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THE CHEMISTRY AND MINERALOGY OF THE METEORITES OF SOUTH AUSTRALIA AND ADJACENT REGIONS

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Frontpiece : Commemorative column in the main street of the Karoonda township

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SUMMARY

This thesis is divided into two parts: A and B.

PART A details the experimental methods employed, the results obtained and descriptions of several previously undescribed meteorites. The chapter treating the experimental methods includes the derivation of a method for the calibration of standards for X-Ray Fluorescence analysis and a description of a modified technique for the X.R.F. determination of major and minor elements in stony meteorites. An examination of the suitability of various techniques for the analysis of iron meteorites is included. A method of calculating normative mineral compositions for the ordinary chondrites is also described.

PART B of the thesis involves an examination of the analytical results and their application to meteorite classification. Problems encountered in attempting to effect these classifications highlighted significant features of several meteorites. Chemical and/or mineralogical characteristics so revealed may have important genetic implications and so these studies lead to a closer examination of the nature and origin of these meteorites. The applicability of several techniques of multivariate analysis to the classification of meteorites is examined. The unusual stony meteorites Brachina and Moorabie are examined in some detail and their classification discussed, as is the carbonaceous chondrite Adelaide. Examination of this latter meteorite leads to the definition of a new group of carbonaceous chondrites while a critical re-examination of the other South Australian carbonaceous chondrite, Karoonda, suggests that the highly metamorphosed carbonaceous chondrites cannot be separated into chemical subgroups on the basis of major element chemistry. This and the fact that such a distinction can be made using trace element abundances leads to important conclusions concerning the origins of the carbonaceous chondrites.

The undescribed achondrite Muckera is examined and shown to be the first recorded Australian polymict howardite. The exact classification of the mesosiderite Pinnaroo is examined and a third recovery of the Millbillillie fall is described in passing and its classification as a eucrite confirmed. The terminology "cognate achondrite", embracing the diogenites, eucrites, howardites and mesosiderites, is introduced. The relationship between the various achondrite and iron meteorite groups is examined and comment made on their possible origins.

The new iron meteorite Kapunda is examined and further points raised concerning the classification of Mount Sir Charles and Yardea, while Cowell and Kyancutta are shown to belong to the same fall.

The meteoritic Ca/Al ratio is examined and its constancy or otherwise discussed as is the relationship between lunar, terrestrial and meteoritic material.

A new chondrule definition is proposed and some points raised concerning the the origin of these and other textural features of the chondrites. The nature and composition of several chondritic glasses is examined as is the possible asteroidal origin of the meteorites examined in this work.

Appendix A is devoted to a study of the terrestrial history of the meteorites under examination in order to establish their authenticity. The first major section includes much previously unpublished material and provides the first compilation of this material in such detail while the final section consists of an annotated account and bibliography of previous work carried out on these meteorites.

STATEMENT OF ORIGINALITY

The material contained in this thesis has not been previously submitted by me for the award of any degree or diploma at any University and to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

ACKNOWLEDGEMENTS

Many people have assisted the author in the course of this work and their help is gratefully acknowledged. Few people are specifically mentioned here but my gratitude to those not named is none the less real.

First and foremost, I wish to acknowledge the help and guidance of my supervisor, Doctor J.B. Jones, who was ready with timely advice at all stages of this project. My thanks are also due to Professor R.W.R. Rutland, the Head of the Department of Geology and Mineralogy in the University of Adelaide.

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GENERAL INTRODUCTION

The earliest accounts of Australian meteorites occurred under such headings as "native iron" in mineral listings. Most subsequent Australian meteorite research has appeared in the form of accounts detailing the chemistry, mineralogy and petrography of individual meteorites. In 1953 Urey and Craig examined the published analyses of some 300 chondritic meteorites. For various reasons they rejected 192 of them as being unreliable, accepting only 94 as "superior analyses". Unfortunately the rejected analyses included all those published to that date for South Australian meteorites. Great care has been taken with analytical technique in this study in the expectation of producing a set of "superior analyses" for a large sample of Australian meteorites.

This work represents the first comprehensive attempt to study and correlate data for Australian meteorites on a regional basis, although, of course, geographical proximity does not necessarily imply either chemical or genetic affinity.

The major aim of this work was to gain further information concerning the nature and origin of meteorites and thereby add to our knwoledge of the genesis of the solar system. In order to provide a basis for this several approaches were adopted. Chemical and mineralogical analyses were chosen as the primary data base for the study and to this end detailed chemical and mineralogical analyses were carried out on as many South Australian and Northern Territory meteorites as possible. The reasons for this geographical selection are detailed in Chapter A1. Correlation of this and other information enabled attempts to be made to classify the meteorites. Either success or failure in this endeavour led to important conclusions concerning the adequacy of the classification technique and also suggested limits or constraints on theories of genesis. An examination of textural relationships in several of the meteorites furthered this end. Reference to the results of others enabled the conclusions of this work to be extended even further. Before such results could be used they had first to be located and, secondly, the authenticity of the meteorites so examined had to be ensured. The extensive results of Appendix A give an account of this authentication and present tabulations of all documented previous work.

The results of this work are discussed in the following sequence - the ordinary followed by the carbonaceous chondrites, the stony and stony-iron achondrites, and the iron meteorites, all of this being followed by an examination of some textural relationships. The results of the work are then summarized in Chapter 12.

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A: EXPERIMENTAL METHODS AND RESULTS

Chapter 1

INTRODUCTION

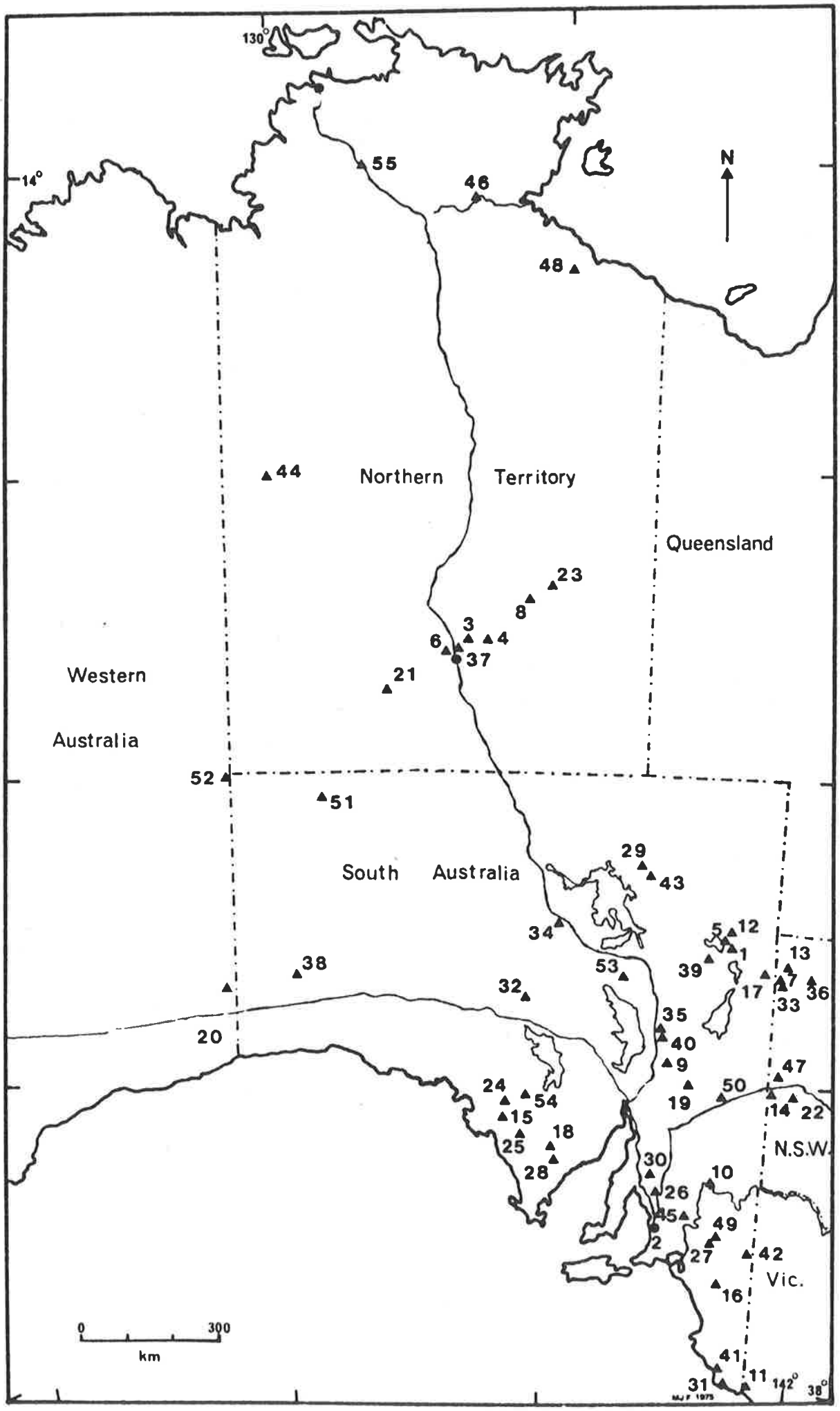
The meteorites discussed in this work were recovered within South Australia and the Northern Territory or in close proximity to the borders of these States. The historical background to this choice is detailed fully in Chapter A1. Table 1.1 lists the meteorites with their general classification and numbers in the Collection of the Tate Museum in the School of Geology in the University of Adelaide. The numbers in Figure 1.1, which shows the geographical distribution of most of the meteorites, correspond to the code numbers in Table 1.1. The Carraweena specimen 17269 is a sample of the outer, weathered zone of the meteorite and the reasons for its inclusion are given in Section 6.6.1. Chemical, mineralogical or petrographic data are given in this work for those meteorites marked with an asterisk.

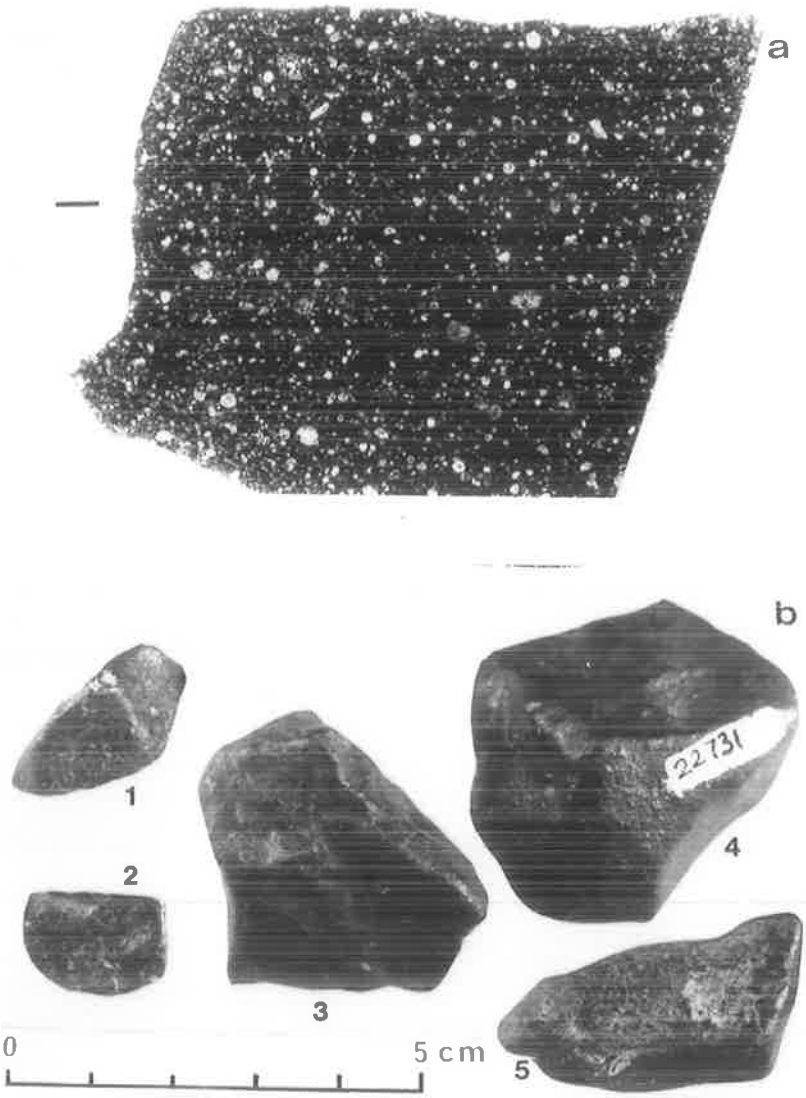
Six other meteorites from outside the region were also examined. Three "foreign" ones, Allende (20539), Forsyth County (22579) and Plainview (1917) (19061) were used as analytical standards while three Australian meteorites from outside the central region of the country were also studied. The analytical results for the latter three - Millbillillie No.3 (22867), Mossgiel (22585) and Oberon Bay (22576) - will be found in Appendix B. Because of their geographical remoteness these meteorites are discussed in full elsewhere (Fitzgerald 1979b,c,d), but occasional mention will be made of them for comparative purposes in such sections as those devoted to the multivariate techniques. One of the problems encountered both in the preparation of this table and the remainder of this work was that of meteorite nomenclature. Several authors (Hey 1966, Huss 1971 and Buchwald and Wasson 1972) have considered the major problem encountered here, viz. the naming of several pieces of meteorite found in the one area. The suggestion of Hey concerning the use of numbers to distinguish specimens of the same fall appears to be the best solution and is adopted here. This usage also appears to be in line with recommendations made by the Committee on Nomenclature of the Meteoritical Society as reported by Olsen et al (1978). Thus in those cases where at least two falls seemed to be represented, members of supposed different falls were given diverse major names while supposed members of the same fall were numbered in the order of their recognition as meteorites. Such numbers have not been appended to the names of pieces that were produced by fragmentation on impact, but rather to individuals with more or less complete fusion crusts. The nature of these individuals varies from the situation where their shape suggests that they are pieces of one mass which broke up during atmospheric flight, but sufficient time was available for the production of a fusion crust, to that where there is no obvious relationship between them. The material recovered in the Kybunga and Cockburn areas illustrate these points and will be discussed later.

Table 1.1 : Meteorites of the central region of Australia, their classification and numbers in the Tate Museum in the School of Geology, University of Adelaide, where applicable.

Locn. No.	Meteorite	Classification	Museum No.
1	Accalana*	L-chondrite	17270
2	Adelaide*	C-chondrite	23114
3	Alikatnima	Ataxite	
4	Arltunga	Ataxite	
5	Artracoona*	L-chondrite	17290
	Basedow Range	Medium octahedrite	
6	Bond Springs	H-chondrite	
7	Boolka	Chondrite	
8	Boxhole	Medium octahedrite	
9	Brachina	Anomalous chondrite	
10	Cadell*	L-chondrite	17265
11	Caroline	H-chondrite	
12	Carraweena*	L-chondrite	22588
12	Carraweena*	L-chondrite	17269
13	Cartoonkana*	L-chondrite	17266
14	Cockburn No.1*	L-chondrite	21287
14	Cockburn No.2*	L-chondrite	20245
14	Cockburn No.3*	L-chondrite	22731
14	Cockburn No.4*	L-chondrite	22732
14	Cockburn No.5*	L-chondrite	22733
14	Cockburn No.6*	L-chondrite	22873
14	Cockburn No.7	?L-chondrite	
15	Cocunda*	L-chondrite	22589
16	Coomandook No.1*	H-chondrite	15128
16	Coomandook No.2	H-chondrite	
17	Coonana*	L-chondrite	22580
18	Cowell*	Medium octahedrite	18295
19	Crocker's Well	Chondrite	
19	Ethiudna	Chondrite	
20	Forrest Lakes	LL-chondrite	
	Gallipoli Station	Medium octahedrite	
	Glen Helen	Medium octahedrite	
	Hart Range	Medium octahedrite	
21	Henbury*	Medium octahedrite	17289
22	Hollmayer No.5*	H-chondrite	22987
22	Hollmayer No.6*	H-chondrite	22988
23	Huckitta Pallasite		
24	Kaldoonera Hill*	H-chondrite	22586
25	Kappakoola	H-chondrite	
26	Kapunda*	Medium octahedrite	22587
27	Karoonda*	C-chondrite	18792
28	Kielpa*	H-chondrite	22933
	Kingoonya	L-chondrite	
29	Kittakittaooloo	H-chondrite	
18	Kyancutta*	Medium octahedrite	22578
30	Kybunga No.1*	L-chondrite	S.A.M.
30	Kybunga No.2	L-chondrite	
30	Kybunga No.3*	L-chondrite	22583
31	Lake Bonney*	L-chondrite	22575
32	Lake Labyrinth*	LL-chondrite	22980
	Monte Colina*	L-chondrite	22890
33	Moorabie*	L-chondrite	
34	Moorumbunna*	Medium octahedrite	18294
35	Motpena*	L-chondrite	22981
36	Mount Browne*	H-chondrite	A.N.U.
37	Mount Sir Charles*	Fine octahedrite	22577
38	Muckera*	Howardite	22581
39	Murnpeowie	Anomalous Iron	
	Naretha	L-chondrite	
40	Nilpena	Chondrite	
22	Nine Mile*	L-chondrite	22985
41	Nora Creina*	L-chondrite	22727
	Nutwood Downs	Medium octahedrite	
42	Pinnaroo*	Mesosiderite	14190
43	Poonarunna*	H-chondrite	22730
22	Popilta*	L-chondrite	22986
22	Popio*	L-chondrite	22983
44	Rabbit Flat	H-chondrite	
45	Rhine Villa*	Coarse octahedrite	17273
46	Roper River	Medium octahedrite	
47	Silverton*	L-chondrite	A.N.U.
	S.A. Beta*	Medium octahedrite	22930
48	Tawallah Valley	Ataxite	
14	Thackaringa No.1*	H-chondrite	22982
14	Thackaringa No.2*	Chondrite	23006
22	Twin Wells*	H-chondrite	22984
	Un-named Stony Iron	Uncertain	22917
49	Vincent*	L-chondrite	22728
50	Weekeroo Station*	Coarse octahedrite	22931
51	Wilbia*	H-chondrite	22729
52	Wingellina	H-chondrite	
53	Witchelina*	H-chondrite	21604
13	Yandama*	L-chondrite	17272
54	Yardea*	Coarse octahedrite	22574
55	Yenberrie	Coarse octahedrite	

Figure 1.1 : Map of recovery sites. Numbers correspond to code numbers in Table 1.1.


130°
14°
N
55
46
48
44
Northern Territory
Queensland
23
8
3
4
6
37
21
Western
Australia
52
51
South Australia
29
43
34
5
12
1
13
39
7
17
33
36
53
38
32
35
20
40
9
47
24
54
50
19
14
22
15
18
25
28
30
N.S.W.
10
26
45
49
2
27
42
Vic.
16
41
11
31
142°
38°
0
300
km


a
b
1
2
3
4
5
22731
0
5 cm
c
d

Chapter 2

SEVERAL NEW AND/OR UNDESCRIBED METEORITES

2.1 INTRODUCTION

This chapter contains brief descriptions of several new or previously undescribed meteorites. In some instances these descriptions are provided for the sole reason that the meteorites are undescribed, in other cases, they are necessary to establish whether two or more meteorites may be members of the same fall.

2.2 ADELAIDE

2.2.1 General description

A comprehensive description of Adelaide is given by Davy *et al* (1978). Several additional points should be made . Mineral grains which commonly have crystal terminations can be seen quite plainly protruding from a fractured surface. Similar terminated olivine crystals have been reported in Murchison (Fuchs *et al* 1973, Olsen and Grossman 1978). Rounded grains can be seen quite clearly on a cut surface but these are not abundant and the meteorite is mainly a mixture of silicate grains and a darker, fine grained material dispersed both in and between the silicate grains. The tarnish on some of the matrix suggests that it is a sulfide mineral, while the abundance of soft black grains may indicate the presence of carbon, iron oxides and possibly layer structure silicates.

2.2.2 Petrography

In thin section (Figure 2.1 a) the overall texture and relative abundance and size of chondrules and inclusions is very similar to that of Murchison (Van Schmus and Hayes 1974). Davy *et al* (1978) suggested a resemblance to the Vigarano section figured by Van Schmus (1969a) but chondrule size and abundance suggests this is not so. Some limonitic staining of the silicates can be seen especially in the smaller grains and along fracture planes in the olivine. Although most of the silicates are present as isolated grains, radiating and occasional barred chondrules can be found as can inclusions of porphyritic material. Many of the silicate grains are irregular in shape and have a spongy appearance. Pink glass present in the porphyritic material attests to the low petrologic grade of the meteorite. Some of this glass has been devitrified.

2.3 CADELL

The chondritic texture in this meteorite is almost completely obliterated and many of the silicates are stained with limonite. Large anhedral grains of olivine and orthopyroxene are present with many of the former having limonitic stains on their fracture planes. The olivine grains commonly enclose small pyroxene grains and many show undulatory extinction with some possessing a mosaic texture. Exsolution lamellae are present in some of the orthopyroxene grains.

2.4 COCKBURN No.1

Ten meteorites, Cockburn No.1 to No.7, Silverton and Thackaringa No.1 and No.2 have all been recovered in the vicinity of the town of Cockburn (See also Section A2.2). Various observations have been carried out on most of these meteorites in order to ascertain whether some or all of them belong to the same fall.

The Cockburn specimens Nos.1, 2, 4 and 5 are all pyramidal in shape as is Thackaringa No.2. Spencer (1934a) likewise described Silverton as being pyramidal but with one convex face. The external morphology of the first five Cockburn specimens is shown in Figure 2.1 b. All of the Cockburn and Thackaringa specimens show the effects of weathering in the form of prominent limonitic staining. In the case of Silverton, which was probably recovered nearly a century ago, weathering effects are confined to limonitic haloes around metal

Figure 2.1 a. Thin section of Adelaide. Scale bar 2mm.
b. Cockburn recoveries, Nos.1 to 5.
c. Thin section of Cockburn No.1. Scale bar 2mm.
d. Thin section of Cockburn No.3. Scale bar 2mm.

and sulfide grains.

2.4.1 General description

Johnson and McColl (1967) described this specimen as a bipyramid with a trapezoidal base. A cut surface shows many irregular metal grains up to 1mm in diameter along with smaller grains of troilite. Limonitic staining is related to the metal grains except for a fracture which passes almost completely through the meteorite between the apices of the two pyramids. The silicate grains are uniform in size with no trace of a chondritic texture.

2.4.2. Petrography

Thin section examination shows the silicates have been extensively recrystallized, chondrule boundaries being virtually absent (Figure 2.1 c). Several barred chondrules which can still be recognized show evidence of recrystallization both of the bars and the glassy mesostasis. Devitrification of apparent former porphyritic material has resulted in subhedral olivine grains set in a granular matrix. Some of the larger olivine grains exhibit undulatory extinction and in some cases possess a mosaic texture.

2.5 COCKBURN No.2

2.5.1 General description

There is some evidence of flow lines radiating from one of the vertices of this specimen. Limonitic staining is most evident in the vicinity of irregular patches of metal up to 1mm in diameter which can be seen on a cut surface. Troilite occurs as more elongate grains or aggregates. Some evidence of chondritic structure can be seen in the silicates, rounded grains frequently being bounded by grains of troilite or dark matrix material.

2.5.2 Petrography

The textures of this (Figure 2.1 d) and Cockburn No.1 are very similar with chondrule outlines being obliterated by extensive recrystallization, no obvious glass being present.

2.6 COCKBURN No.3

2.6.1 General description

This specimen has an approximately rhombohedral shape being about 3x3x2cm in size. There appear to be recognizable front and rear surfaces to the specimen. The latter is marked with many shallow regmaglypts and may represent an earlier fracture surface. The anterior surface is much smoother being quite regular with three faces of approximately equal area sloping away from the major axis. The intersection of these faces is quite prominent and gives an indication of the orientation of the meteorite during its passage through the atmosphere.

The metal and troilite grains are smaller and more evenly distributed than in either Cockburn No.1 or 2. The overall appearance is much darker due to greater oxidation. A colour zonation, apparently connected with the sulfide distribution and the weathering of this, can be seen on the cut surface. Chondrules are not apparent.

2.6.2 Petrography

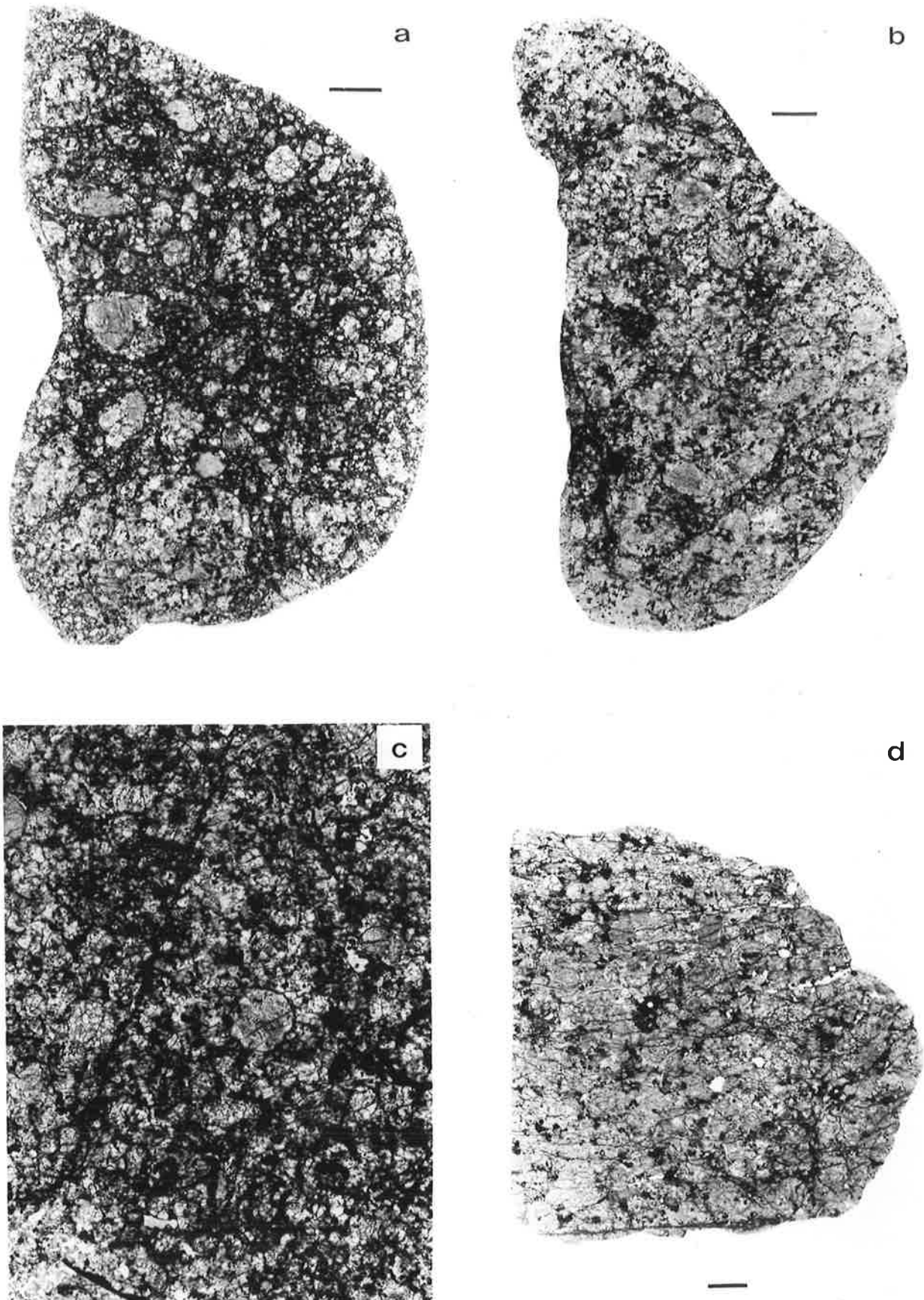
Extensive recrystallization has generally removed most traces of a chondritic texture (Figure 2.2 a) but in some places it is clear and more marked than in any of the other Cockburn material. Some of this material contains skeletal grains with devitrified and recrystallized interiors. The proportion of opaque minerals is higher than in Cockburn No.1 or 2. Devitrified porphyritic material is present as angular to rounded clasts producing an overall chondritic appearance.

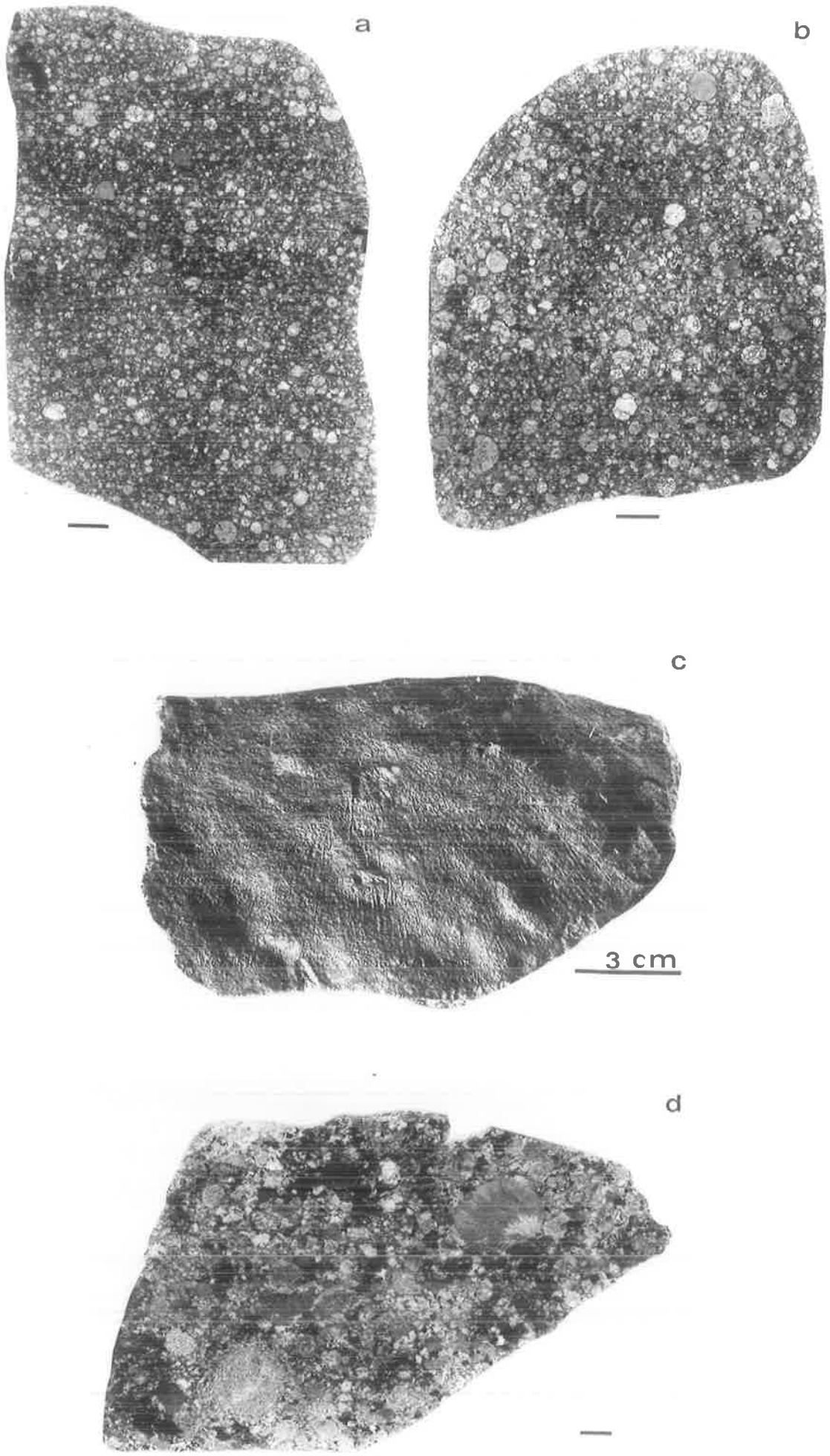
2.7 COCKBURN No.4

2.7.1 General description

This specimen is approximately tetrahedral in shape with a height of about 3.5cm. The base is gently indented while the other surfaces are much smoother. Thus this specimen also appears to be an oriented individual. Like the other Cockburn specimens it has a complete fusion crust and hence fragmentation must have occurred prior to the formation of at least a thin crust. Much of the cut surface shows limonitic staining commonly centred around the numerous metal grains of up to 1mm in diameter. Isolated rounded grains are obvious but otherwise there is no pronounced structure in the silicates. The unstained material is white to grey implying the absence of fine sulfide inclusions.

Figure 2.2 a. Thin section of Cockburn No.3. Scale bar 2mm.
b. Thin section of Cockburn No.4. Scale bar 2mm.
c. Thin section of Cockburn No.5. Scale bar 2mm.
d. Thin section of Cockburn No.6. Scale bar 2mm.


a
b
c
d


a
b
c
3 cm
d

2.7.2 Petrography

Extensive recrystallization has removed much of the chondritic texture (Figure 2.2 b) although some areas do show remnants of barred and radiating structures and the former glassy mesostasis has been devitrified. Many of the larger olivine grains have an undulatory extinction and many exhibit a pronounced mosaic texture.

2.8 COCKBURN No.5

2.8.1 General description

One face of this specimen is much smaller than the other three. The vertex is about 2.5cm above the lower surface which shows evidence of pockmarking. The upper three surfaces are quite smooth and, as is the case with Cockburn Nos. 3 and 4, show evidence of flow away from the vertex. The fusion crust is penetrated with chondrules, as in the preceding four Cockburn specimens. The specimen is broken, possibly by impact on landing, and about 15% is missing.

The metal grains are smaller than those in Cockburn No.1, 2 or 4. Most of the silicates are stained with limonite but some chondrules are visible. A colour zonation, not directly related to oxidation, can be seen as in Cockburn No.2. Numerous metal grains, not necessarily surrounded by alteration products, are present.

2.8.2 Petrography

The overall texture (Figure 2.2 c) is very similar to No.1 and 2 with little evidence of chondritic structure. Devitrified and recrystallized porphyritic material and large subhedral to anhedral grains of olivine are present. Evidence of shock in the form of undulatory extinction and mosaic textures is much less pronounced than in the other Cockburn specimens.

2.9 COCKBURN No.6

2.9.1 General description

Only a small piece of this meteorite was available for examination. The material is heavily altered, extensive weathering having taken place along a series of fractures which are sub-parallel to the outer surface. Very small and widely distributed grains of metal and troilite can be seen as in No.2. The specimen is not only heavily stained with limonite but there are also numerous pockets of ferruginous material suggesting extensive replacement of opaque minerals. Some chondrules are obvious, penetrating the limited fusion crust, although few were seen on a cut surface.

2.9.2 Petrography

Although recrystallization has effectively obliterated chondrule boundaries (Figure 2.2 d) the internal structures of some of the chondrules remain and some structures present can be correlated with different chondrule types. The olivine grains are generally more fractured in this specimen and the glassy mesostasis has undergone less devitrification.

2.10 COCUNDA

This meteorite has been completely recrystallized and little evidence of chondrule outlines remains. Large anhedral grains of olivine, mostly fractured, are present. Inclusions which were once probably porphyritic material now consist of olivine megacrysts set in a fine granular matrix. Parts of the section examined are free of limonitic staining while other parts are heavily stained. Within the areas so affected the fracture planes of the olivine grains are stained with limonite. Many of the olivine grains have trains of small bubbles running through them. Fibrous pyroxenes, which have possibly formed by devitrification of glasses, contain numerous opaque grains.

2.11 COOMANDOOK No.1

There is abundant matrix present in this meteorite with little evidence of a chondritic texture. Most of the silicates appear to be fragments of pyroxene or olivine with the latter commonly exhibiting a mosaic texture. The olivine grains, which in nearly every case are extensively fractured, have a limonitic stain on their fracture planes. There are occasional anhedral fragments of olivine or pyroxene set in a devitrified matrix.

2.12 HOLLMAYER No.5

As detailed in Chapter A2, over 50 meteorites have been recovered to the south east of Broken Hill by Mr. Werner Hollmayer. These meteorites are being documented by the Bureau of Mineral Resources, Canberra. Brief petrological descriptions only of six specimens (Hollmayer No.5, Hollmayer No.6, Nine Mile, Popilta, Popio and Twin Wells)

Figure 2.3 a. Thin section of Hollmayer No.5. Scale bar 2mm.
b. Thin section of Hollmayer No.6. Scale bar 2mm.
c. Kybunga No.3.
d. Thin section of Kybunga No.3. Scale bar 2mm.

made available for this work are given.

An obvious chondritic texture can be discerned in Hollmayer No.5 (Figure 2.3 a). The section shows evidence of "fusion" of barred chondrules. Porphyritic material occurs both as angular and rounded fragments. Many of the chondrules contain skeletal crystals. Former glassy material is commonly devitrified producing "feathery" and "wheatsheaf" textures.

2.13 HOLLMAYER No. 6

This meteorite has a well defined chondritic texture (Figure 2.3 b) with both complete and broken barred and radiating chondrules present. Several of the barred chondrules are "overgrown". Porphyritic material occurs both as rounded and angular grains. Glassy chondrules are present and like the other chondrules have well defined boundaries. Many of the chondrules contain skeletal pyroxene crystals set in a devitrified glass.

2.14 KALDOONERA HILL

Extensive recrystallization has occured in this meteorite. Nonetheless, several partly rounded grains which are possibly chondrule fragments, are present. Several of these consist of subhedral to anhedral megacrysts of olivine set in a granular pyroxenic groundmass which may have been produced by devitrification. In other cases the megacrysts are set in devitrified material characterized by radiating textures. Limonitic staining is present on the fracture planes of many of the olivine grains.

2.15 KAPUNDA

The shape of this meteorite is similar to that of Murnpeowie (Spencer 1935a). It is a relatively flat, shield-like body of sides of approximately 7, 8 and 10cm having an average thickness of 2.5cm. The flatter of the two surfaces is marked with numerous regmaglypts about 1cm in diameter and 1 to 2mm deep. The other surface is quite irregular being characterized by odd shaped protrusions and large, irregular shaped, shallow pits. A prominent peak rises from the surface near one corner. Etching of a polished surface produced a prominent Widmanstatten pattern. Several small troilite nodules, varying in diameter from 0.5 to 1mm in diameter, can be seen on a cut surface.

2.16 KYBUNGA No.1

The main mass of this meteorite could not be examined, however, a thin section was made available by the S.A. Museum for a bried examination to compare it with Kybunga No.3.

Nearly every large grain in the section examined displayed a mosaic texture in direct contrast to the section of Kybunga No.3 examined in this work. The section shows a fairly well developed chondritic texture with barred and radiating chondrules and porphyritic inclusions being visible. In addition there are some granular aggregates present as well as rare grains of clinopyroxene.

2.17 KYBUNGA No.3

2.17.1 General description

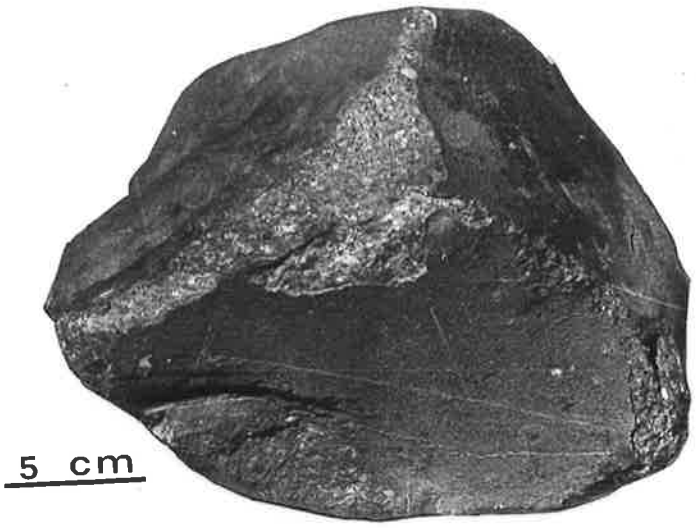
This specimen has a rectangular base and stands about 7cm high (Figure 2.3 c). It is completely covered with a fusion crust. Lines can be seen on the upper surface radiating from the centre of one edge and also on the bottom surface which is patterned with numerous regmaglypts. Numerous chondrules can be seen penetrating this lower surface but very few are visible on the upper one.

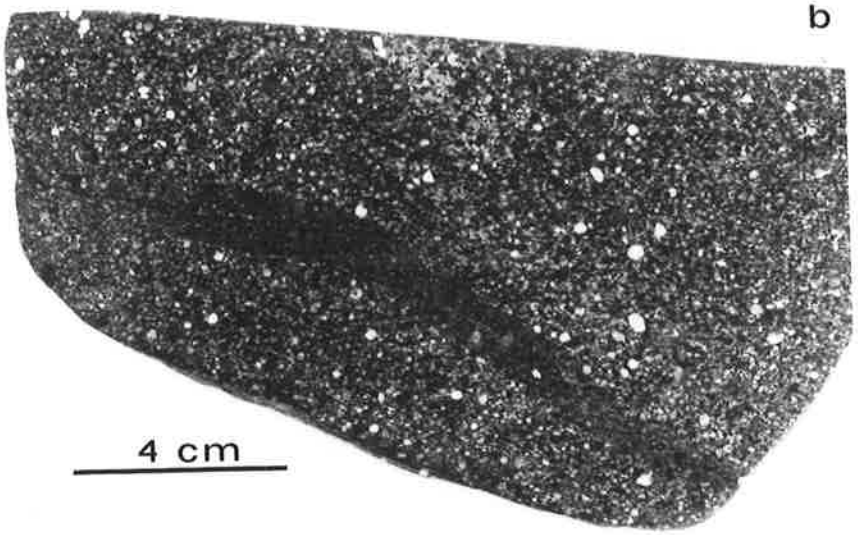
The unweathered material is grey in colour with a slight green tinge but many of the numerous metal and troilite grains are surrounded by brown limonitic stains. A chondritic texture is moderately obvious, particularly on a polished surface. The chondrules are generally about 1mm in diameter but larger rounded grains up to 1cm in diameter are present. They are all generally set in a silicate matrix.

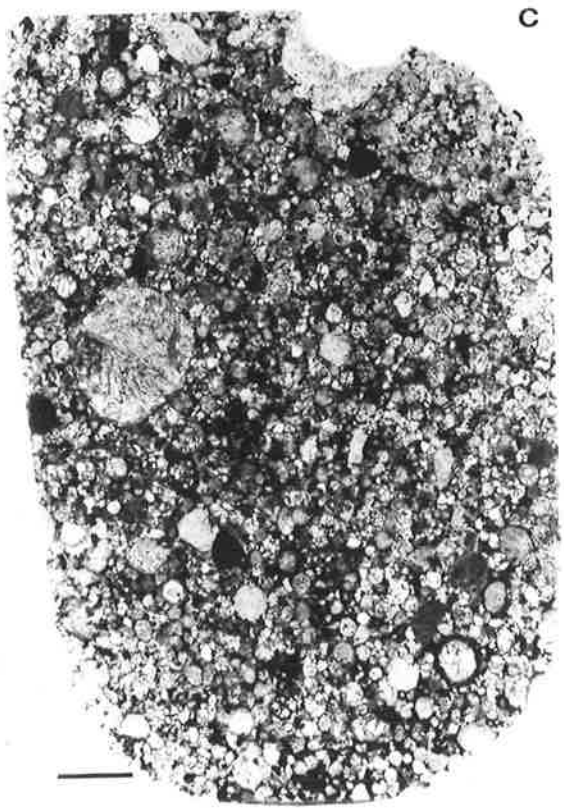
2.17.2 Petrography

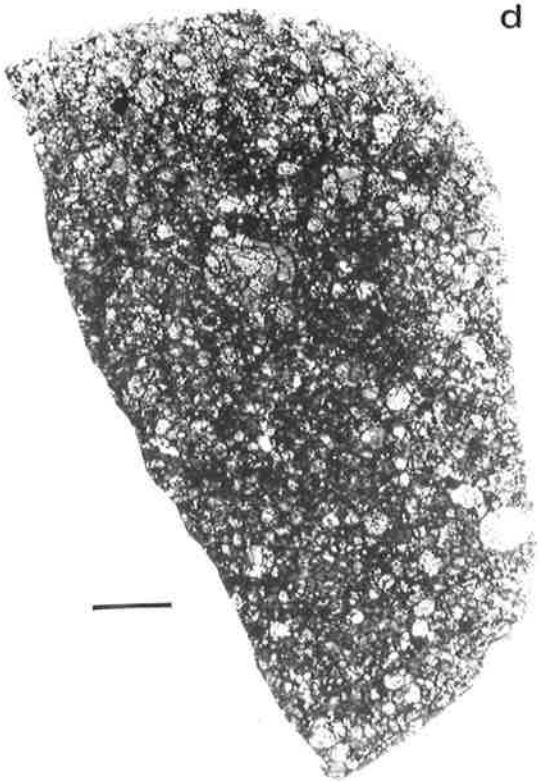
Thin section examination reveals the presence of numerous barred and radiating chondrules as well as devitrified glassy ones (Figure 2.3 d). Some porphyritic material showing moderately extensive matrix devitrification to fibrous pyroxene is present. being fibrous pyroxene. An overall chondritic texture is clearly visible. Nevertheless, there are areas where chondrules are rare, possibly because of recrystallization.

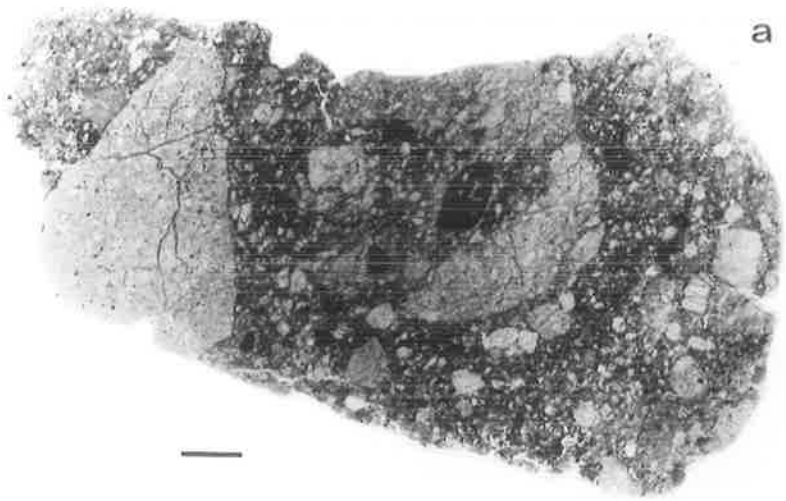
Figure 2.4 a. Moorabie.
b. Vein development in Moorabie.
c. Thin section of Moorabie. Scale bar 2mm.
d. Thin section of Poonarunna. Scale bar 2mm.

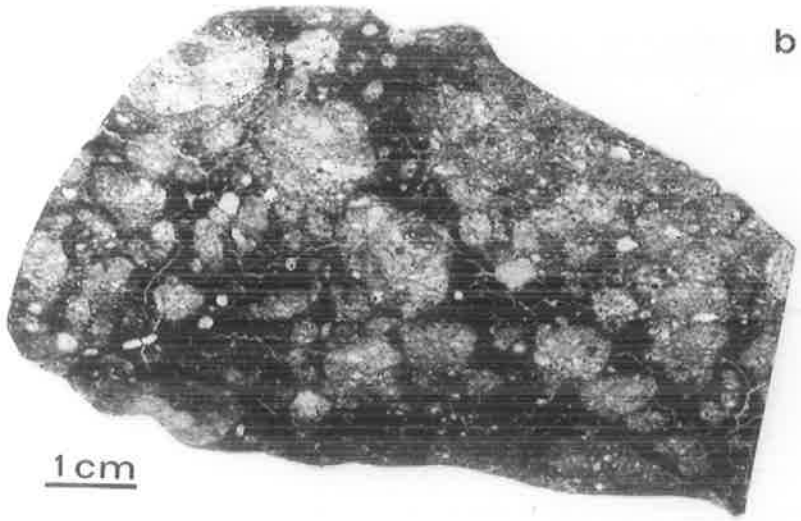

a
5 cm

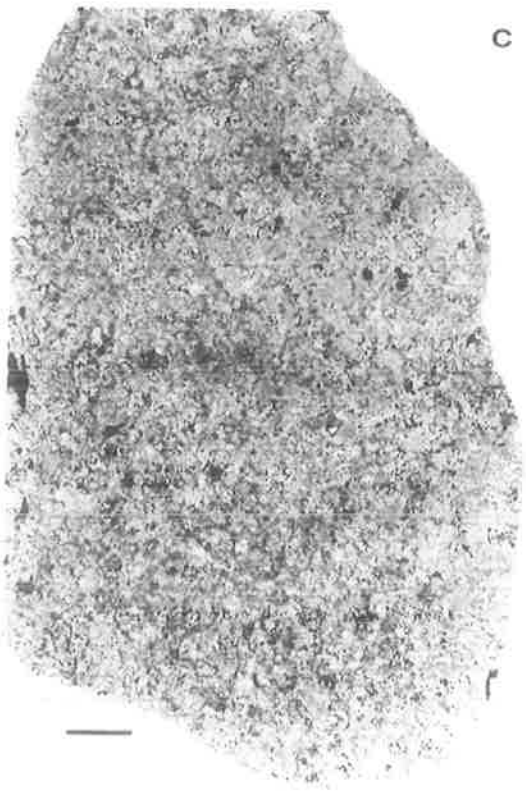

b
4 cm

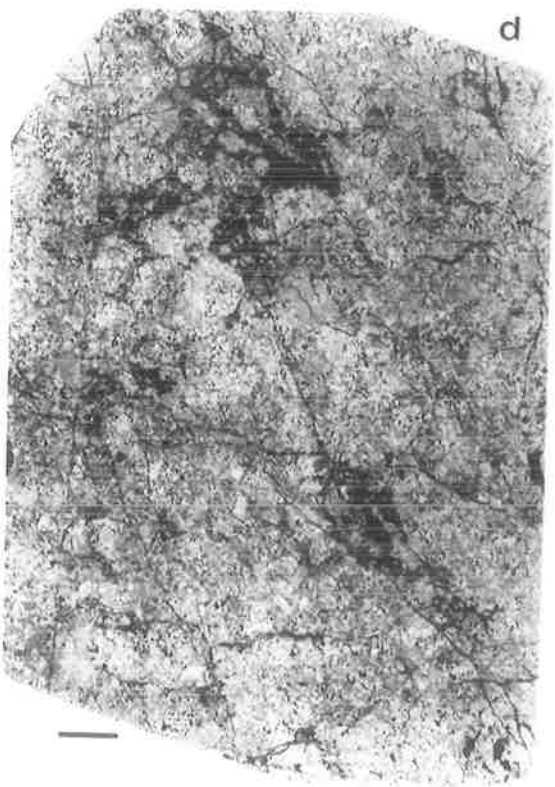

c


d


a


b
1 cm


c


d

2.18 MOORABIE

2.18.1 General description

This meteorite is approximately tetrahedral in shape with the apex being about 20cm above the base (Figure 2.4 a). Much of the surface is covered with a fusion crust penetrated by chondrules. The latter are less obvious here than on an outer non-crusted surface. Fresh metal grains about 1mm in diameter are scattered abundantly through the meteorite. Numerous grains of troilite are present many being equal in size to the metal grains while others are smaller. Chondrules are commonly wholly or partly surrounded by metal or troilite and there are abundant fine grained sulfide grains dispersed through the matrix. There is no pronounced limonitic staining associated with the metal grains although light and dark areas are present. The silicates in the light region are grey while those in the darker region are brown probably due to the weathering of sulfides which assume a spongier and more tarnished appearance in these areas.

There is at least one prominent vein of dark material associated with a fracture running through the meteorite (Figure 2.4 b). The darkening is probably a weathering feature but there also appears to be a lighter vein running through the meteorite.

2.18.2 Petrography

A chondritic texture is clearly developed, most of the silicates being present either as whole or broken chondrules and inclusions (Figure 2.4 c). All recognized chondrule types are present. Most of the silicates are stained with limonite, as are some of the fracture planes of larger olivine grains, which are commonly skeletal. Numerous grains of polysynthetically twinned clinopyroxene are present in the porphyritic regions. The glassy matrices of these areas generally show little devitrification, many being transparent pink glasses. Nonetheless, some porphyritic material has matrix material which has apparently been completely devitrified and recrystallized leaving little glass. The lack of general recrystallization is evidenced by the arrangement of discreet chondrules and fragments in the opaque matrix.

2.19 MUCKERA

2.19.1 General description

This meteorite is approximately ellipsoidal in shape with dimensions of about 10, 8 and 5cm. Some brown fusion crust containing several small white mineral grains is still preserved but is red-brown in colour as a result of terrestrial weathering. A cut surface shows rounded and sub-rounded white to grey clasts set in a black matrix (Figure 2.5 a). Small grains of nickel-iron and sulfide, surrounded in most cases by weathering haloes, are present. Commonly the nickel-iron is confined to the clasts, while the dark colour of the matrix is apparently due to the presence, among other things, of fine grained tarnished sulfides and glass. Numerous fractures and vughs, many of which are lined with, and commonly filled by, a soft yelllow to pale brown mineral resembling calcite are present. In some cases this filling is layered parallel to the cavity walls.

Many of the silicate grains are white to pale cream, others are colourless and transparent. The clast size varies from a millimetre or so to more than 3cm in diameter. Many are aggregates of smaller sub-rounded clasts which in turn are composed of angular and sub-rounded mineral fragments.

2.19.2 Petrography

Petrographic examination reveals a brecciated texture (Figure 2.5 b). The ground mass, containing abundant glass, is dark grey to black while the fragments are generally light grey. Several different types of clasts are present, ranging from mineral fragments through monomineralic aggregates to polymineralic lithic ones.

The monomineralic fragments include both angular pyroxene and large plagioclase grains many of which are are strongly shocked and broken but have not been disaggregated. The monomineralic aggregates include fragments which in terrestrial rocks would be referred to as orthopyroxenites and anorthosites, while the lithic fragments include rock types such as basalts. There are also numerous fine, even grained clasts composed of angular to sub-rounded grains. Pyroxene is more abundant than plagioclase

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Figure 2.5 a. Section of Muckera showing brecciated texture.
b. Thin section of Muckera. Scale bar 2mm.
c. Thin section of Nine Mile. Scale bar 2mm.
d. Thin section of Popilta. Scale bar 2mm.

in these pre-existing breccias and a glassy mesostasis is commonly present. Furthermore, the "clast within clast" relationship described in the previous section can be seen clearly. In these cases there is generally little matrix material separating the small clasts which have been incorporated into the larger ones. Muckera is thus a polymict breccia with a clast to matrix ratio of about 5:1, the latter being composed mainly of small grains exhibiting a wide variation in grain size and composition.

Olivine and calcium rich pyroxene present in Muckera are generally confined to the dark matrix which has a high glass content, while most of the calcium poor pyroxenes occur in the clasts (See also Section 8.4).

2.20 NINE MILE (Hollmayer No.3)

This specimen is extensively recrystallized, rare chondrules only being found (Figure 2.5 c). The average grain size and texture is similar to that of Popio.

2.21 POONARUNNA

2.21.1 General description

A small (ca. 5cm), partly fusion crusted, specimen was examined. Occasional grains of metal and sulfide can be seen on one cut surface. Sulfide is also abundantly disseminated throughout the matrix while many veins of dark material, probably sulfide, less than 0.1mm width and about a centimetre long, run through the specimen.

Deep weathering has occurred along fractures. Most of the silicates have a brown limonitic stain. However, there is no such obvious staining associated with the metal or sulfide grains. Many of the chondrules are white or grey being unaffected by oxidation and so are readily visible against the darker matrix. Some dark, fine-grained fragments can also be seen. Rare chondrules penetrate the fusion crust.

2.21.2 Petrography

Chondrules are not abundant but there are many isolated grains of olivine and pyroxene, the former generally being anhedral to subhedral and the latter anhedral (Figure 2.4 d). There is abundant limonitic staining along the fracture planes in the olivine grains. The presence of many grains of porphyritic material, varying in shape from angular to rounded, heightens the impression of a chondritic texture. Occasional grains of polysynthetically twinned clinopyroxene are present in these inclusions.

2.22 POPILTA (Hollmayer No.4)

Recrystallization has obliterated most traces of chondritic texture in this specimen (Figure 2.5 d). The grain size is similar to that of Popio (c.f. Figure 2.6 a). Isolated grains of olivine are present.

2.23 POPIO (Hollmayer No.1)

This specimen has been extensively recrystallized and in ordinary light few chondrules can be seen (Figure 2.6 a). There is no glassy material and little opaque matrix present. Most of the larger olivine grains are euhedral.

2.24 SILVERTON

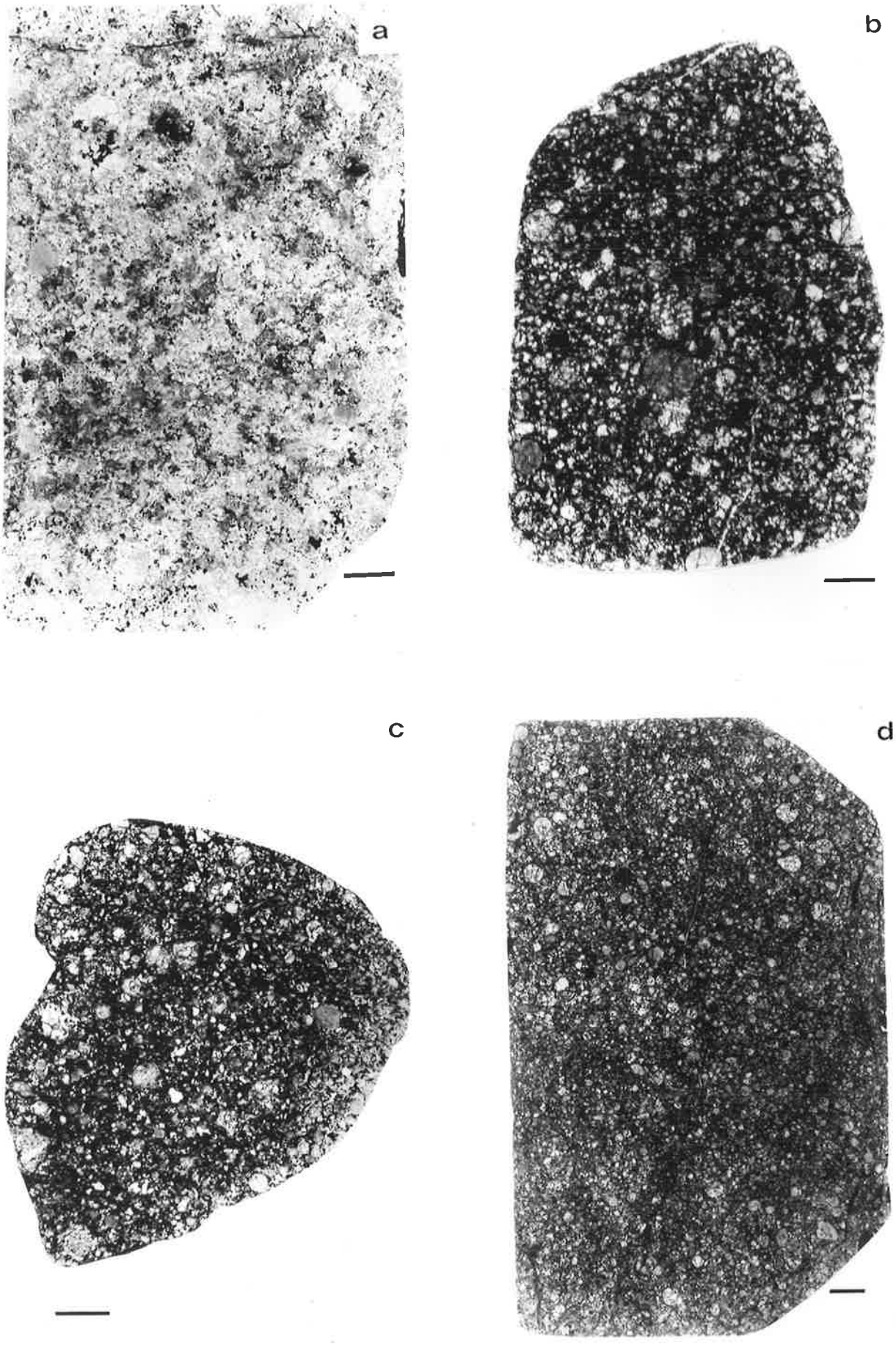
A small fragment of Silverton was examined for comparison with the Cockburn meteorites. It is composed of fresh white silicate grains in which are dispersed abundant discrete grains of metal and troilite, many of which are surrounded by limonitic staining. Chondritic structure is not obvious as there is no marked colour difference between the fresh chondrules and the silicate matrix although isolated grey chondrules could be discerned. The white matrix, the distribution of the metal and troilite and the appearance of staining around the grains of these minerals is quite similar to that observed in Cockburn Nos. 1, 2, 4 and 5. Thin sections of these and Silverton are very similar also. These features are consistent with the Cockburn specimens being part of the same fall as Silverton except for the more extensive weathering.

2.25 THACKARINGA No.1

2.25.1 General description

Only a small piece was available for examination. A chondritic texture is clearly visible, numerous grey to brown chondrules being set in a matrix of red, iron-stained silicates, black iron oxides and other weathering products. Metal and troilite grains are extremely rare, presumably having been altered to iron oxides. Weathering effects are far more pronounced in the vicinity of several fractures which pass through the sample.

Figure 2.6 a. Thin section of Popio. Scale bar 2mm.
b. Thin section of Thackaringa No.1. Scale bar 2mm.
c. Thin section of Thackaringa No.2. Scale bar 2mm.
d. Thin section of Twin Wells. Scale bar 2mm.


a
b
c
d

2.25.2 Petrography

Limonitic staining is less pronounced than in the Cockburn specimens. Numerous well preserved barred olivine and radiating pyroxene chondrules are present (Figure 2.6 b). Additionally, there are numerous subhedral to anhedral grains of olivine dispersed throughout the section. There is less porphyritic material than in the Cockburn specimens. The matrices of these porphyritic inclusions are all extensively devitrified and recrystallized. Little evidence of shock can be seen in the olivine megacrysts. The specimen has a higher opaque content than the Cockburn material.

2.26 THACKARINGA No.2

2.26.1 General description

This specimen resembles a triangular bipyramid in shape with the apices of the pyramids about 14mm apart. It is covered with a fusion crust from which several chondrules protrude. Some areas of the crust and a cut surface are penetrated by numerous small holes possibly produced by the alteration of metal or sulfide grains. The cut surface is very similar to that of Thackaringa No.1, metal and sulfide grains being rare while well defined chondrules are seen set in a matrix of reddish iron-stained silicates and dark oxidation products.

2.26.2 Petrography

Several well rounded chondrules are present and only minimal devitrification and recrystallization of glassy areas appears to have occured (Figure 2.6 c). There are many isolated olivine and pyroxene fragments dispersed throughout the opaque matrix. The relative amount of matrix is similar to Thackaringa No.1.

2.27 TWIN WELLS (Hollmayer No.2)

A chondritic structure is more obvious in this meteorite than the other Hollmayer specimens but recrystallization has occurred (Figure 2.6 d). Glassy chondrules and porphyritic inclusions are present with some of the latter containing skeletal crystals. Most of the chondrules are broken, those with radiating structures commonly having both rounded and angular outlines, while most of the porphyritic material is angular.

2.28 VINCENT

Chondrule boundaries are generally clear in this meteorite and the chondrules, in general, are less iron-stained than the surrounding material. The matrices of porphyritic inclusions have been devitrified. Chondrules include barred and radiating types. Olivine is generally present as anhedral grains and in some cases the fracture planes are stained with limonite. Many of the isolated olivine grains exhibit an undulatory extinction.

2.29 WILBIA

This meteorite has been strongly recrystallized and little evidence of chondrule boundaries remains. Many of the olivine grains are badly fractured, commonly showing undulatory extinction and some exhibiting a mosaic texture. No recognizable chondrule remains are present but porphyritic inclusions can be seen. Many of the silicate grains are stained with limonite, especially the finer grains.

Chapter 3

EXPERIMENTAL METHODS

3.1 INTRODUCTION

Because of the nature of the specimens the techniques used in the analysis of the stony meteorites differed from those for the iron meteorites.

Two major groups of techniques were employed, wet chemical methods and X-ray fluorescence analysis. Wet chemical methods were used when it was found that either the analyses could not be performed using X-ray techniques or that the results were more reproducible.

3.2 SAMPLE PREPARATION

Sample preparation depended on whether the meteorite was an iron or stony one.

In the case of the irons, samples were obtained by cutting pieces of the appropriate meteorite with a hacksaw and collecting the cuttings. Due care was taken to avoid any major visible troilite nodules (see also Section 4.1 below). Any grains of foreign material were removed from the cuttings by handpicking. Previous tests had shown that the saw blade produced no contamination of significance for the present study.

The stony meteorites were treated in an entirely different manner. Slabs of meteoritic material were cut and then lightly ground to remove any metal particles left behind by the saw. All traces of the fusion crust (see also Section 4.1 below) were removed. The slabs were then crushed with a pounding action, without any grinding, using a hardened steel rod and plate. The samples were passed through a 44-mesh nylon sieve and quartered. One half of this powder was preserved for mineralogical determinations and the other was placed in a tungsten carbide Siebtechnick mill and ground for one minute. The tungsten carbide was chosen in preference to others available on the basis that cobalt was the only likely contaminant. Since it was not intended to use these powders for cobalt determinations this contamination seemed preferable to that which would result from the use of steel, chrome plated, agate or alundum vessels.

3.3 CHEMICAL COMPOSITION FROM WET CHEMICAL TECHNIQUES

3.3.1 Reagent preparation

In all the following techniques reagent solutions were prepared with "AR" or better grade chemicals. Weighings were carried out on an electric balance calibrated to the nearest 0.1mg where sensitivity was necessary; in other cases a "top pan" balance weighing to 0.1g was used. When necessary "green line" volumetric glassware was used, otherwise, a measuring cylinder.

3.3.2 Gravimetric analysis

A gravimetric procedure was adopted for the determination of nickel in all of the iron meteorites studied. The standard method involving the precipitation of the red nickel (II) dimethylglyoximate complex (Vogel 1962) was used.

Generally the determinations were done in triplicate using about 0.6 g of meteorite. In some cases additional analyses were performed.

3.3.3 Volumetric analysis

Volumetric techniques were used for the determination of the iron content of some of the iron meteorites, and the examination of the Fe(II) content of some fused glass buttons. In both instances the same basic procedure was employed.

a. Iron content of iron meteorites

About 0.5g meteorite samples were used and after dissolution in hydrochloric acid the iron content was determined by titration with standardized potassium dichromate (Vogel 1962).

b. Fused button examination

A method, similar to that of Maxwell (1968), was used to examine the nature of the oxidation state of the iron in fused buttons. A button was dissolved by boiling in a mixture of hydrofluoric and sulfuric acids, the platinum crucible and its contents then being placed in a mixture of

boric and sulfuric acids and titrated with potassium dichromate as described above.

3.3.4 Spectrophotometric analysis

Attempts were made to use spectrophotometric methods to measure the concentration of nickel and iron in the iron meteorites. A similar process was also used to examine the weathering products of a stony-iron meteorite. All the measurements were made with a Shimadzu QV-50 spectrophotometer.

a. Procedure for iron in the iron meteorites

This determination was based on the intense red colour of the iron (III) thiocyanato complex produced by the addition of a solution of potassium thiocyanate to one containing iron (III) ions using the method of Vogel (1962).

Approximately 0.2g of meteorite were dissolved in acid, oxidised, and the optical density of the coloured solution measured after the addition of potassium thiocyanate. The results, however, were unsatisfactory due to the magnitude of the dilution which was necessary prior to determination of the optical density.

b. Procedure for nickel in the iron meteorites

The method of Mitchell and Milton (1945) involving the oxidation of nickel (II) to higher oxidation states and the subsequent formation of a red coloured, soluble complex with dimethylglyoxime was investigated. Preliminary results obtained from a set of standards were so erratic that further measurements involving meteoritic material were not attempted.

c. Procedure for weathered iron in a stony-iron meteorite

A set of standard solutions prepared from ammonium iron (II) sulphate hexahydrate was buffered with sodium acetate and after adding o-phenanthroline their optical densities were measured at 515nm (Vogel 1962).

About 0.05g of meteorite were treated with a mixture of sodium bicarbonate, citric acid and sodium dithionate to reduce any non-silicate iron (III) compounds to the iron (II) citrate complex. This solution was treated with an acetic acid/sodium acetate buffer and o-phenanthroline and its optical density measured at 515nm.

Calculations enabled the amount of non-silicate iron extracted from the original sample to be measured.

3.3.5 Flame photometric analysis

An EEL Flame Photometer was used to measure the sodium and potassium content of all the stony meteorites studied.

Approximately 0.016g of sample were placed in a teflon beaker (platinum crucibles could not be used on account of the method of digestion) and treated with nitric, hydrochloric and hydrofluoric acids. These solutions were then diluted to appropriate volumes.

3.4 CHEMICAL COMPOSITION FROM X-RAY TECHNIQUES

3.4.1 X-ray fluorescence analysis

a. Theoretical considerations

The phenomenon of X-ray fluorescence, i.e. the absorption of primary X-rays and their re-emission as secondary or fluorescent radiation, is well documented and will only be discussed briefly.

The intensity of this fluorescent radiation is a function of several factors such as particle size and the mass absorption coefficient of the sample being examined. Precautions recommended by Claisse (1956), Rose et al (1962) and others were taken to either minimize or eliminate these effects.

Norrish and Chappell (1967) studied a series of multicomponent systems and derived a set of correction factors which were linearly related to the concentrations of the elements present. They showed that the observed intensities could be corrected by use of the following equation:

$$C_i = C_i'(M_i + \sum_i x_i C_i') - B_i$$

where C_i are the true concentrations of the elements,

C_i' are the observed, or nominal, concentrations,

M_i are the normalized values of the mass absorption coefficients of the flux for the appropriate wavelengths,

x_i are the normalized differences between the mass absorption coefficients of each of the elements and the flux, and,

B_i are the background values for each element.

They published values of M_i and x_i for the major elements (as oxides) encountered in silicate analysis. These were updated by Norrish and Hutton (1969,1970) and subsequent work by these authors extended the values to include eight other common elements (K. Norrish, pers. comm.).

The first cycle of this calculation

involves the computation of a set of corrected concentrations for all of the elements under consideration. For the next cycle the C_i inside the parentheses are replaced by the corrected concentrations obtained from the first cycle without, however, replacing those outside. This produces another set of corrected concentrations which are better approximations to the true values. This cyclic process is continued until the results converge.

The background values are determined on samples which are free of the element under consideration and in this case the above equation reduces to

$$B_i = C_i'(M_i + \Sigma_i x_i C_i')$$

The background values thus have, in turn, to be corrected for absorption and enhancement effects prior to their use in the matrix correction calculations.

Magnesium provides a further problem if an ADP analysing crystal is used because interfering fluorescent radiation is also produced by it. Norrish and Hutton (1969) calculated a set of factors to allow for this. This correction should be applied prior to the use of the main equation described above. This order is not the one suggested by Norrish and Hutton (1969) but Hutton (pers. comm.) agrees that the method suggested and used by the author is correct.

b. Preparation of fused buttons

i. Counting standards

Three main counting standards FS11, FS65 (Fluorescence Standards Nos.11 and 65) and NCS2 (Nickel-chrome Standard No.2) were used. The two F standards were supplied by C.S.I.R.O. Division of Soils, Glen Osmond, S.A., while the NC standard was prepared by the author. The F standards had been made from a 0.56g sample containing oxides of Fe, Mn, Ti, Ca, K, P, Si, Al, Mg, and S. In the preparation of these standards the lanthanum oxide normally added to the fusion mixture was omitted from the flux to increase the count rates. The NC standard was prepared using the ordinary flux and a 0.28g sample comprised of 85% silica, 10% nickel (II) oxide, and 5% chromium (III) oxide, all materials being "spectpure".

ii. Sample buttons

Initially some fused buttons were made using the "recipe" and method of preparation of Norrish and Chappell (1967) viz:

1.50g lithium borate/lanthanum oxide flux
0.02g sodium nitrate
0.28g sample.

On counting these trial buttons at the iron wavelength and then crushing, refusing and recounting, a considerable variation in count rate was found. This was probably due to high iron concentrations resulting in a viscosity increase thereby causing micro-segregation of the lanthanum and hence a variation in the mass absorption of the button. For this reason the above "recipe" was modified and only 0.14g of sample used. As it was intended that these buttons should be used for the measurement of sulfur as well as other elements it was important that not only should it all be retained but also that it should be in the same oxidation state (cf. Elsheimer and Fabbi 1973). To this end the sample weight deficit was made good with an oxygen source to oxidise any sulfides present. Various oxygen suppliers were tried including sodium nitrate, sodium peroxide and boric acid. Sodium nitrate gave the best results and so the "recipe" adopted for all sample button preparation was:

1.50g flux
0.404g sodium nitrate (this is equivalent to the original 0.02g plus 0.384g which supplies 0.14g of sodium oxide)
0.14g sample.

This is one of the modifications of Norrish and Hutton (1970).

As a further aid to this oxidation process the fusions, which were performed in a gold-plated platinum crucible, were made in an electric furnace rather than over a burner. It was found that not only was the sulfur retained by this technique but also all of the iron was present in the +III oxidation state. The latter was established by the redox titration described in Section 3.3.3 b. Weight changes during the fusions were also recorded.

To check whether this extra oxidation produced erroneous results for the other elements, sample of 22 meteorites were ignited at 1000°C for 24 hours prior to button preparation. (All specimens were initially dried at 110°C for 3 hours.) The results indicated that the sulfur oxidation had not affected the results for the other elements and so these results were combined with the earlier ones to give a better estimate of the true concentrations.

As a further refinement, the molten glass, after fusion, was poured on to a cold graphite disc rather than a hot one as suggested by Norrish and Hutton (1969). Since the liquid, when poured on to hot discs apparently adhered to them, cracking as it cooled, the change to cold discs was

made. This change, suggested by Hutton (pers. comm.), effectively solved the problem.

Several U.S.G.S. geochemical standards were also analysed as checks on technique. As these standards had neither the same high iron nor sulfur contents, fused buttons containing them were prepared using the standard technique.

iii. Blank buttons

Buttons for background measurements have to be free of the element being measured. Two main sets of buttons were prepared - one containing 0.28g of sample and the other 0.14g. A set of the half-weight blanks had the weight deficit made good with sodium oxide and another with potassium oxide. The inert substances used were quartz and calcium oxide (provided in the form of the carbonate). For the calcium oxide buttons only 0.028g of calcium oxide were used the remaining sample weight being flux.

c. Experimental procedure

All measurements were carried out using a Philips PW1540 X-Ray Spectrograph with modified electronics. The crystal chamber was evacuated and all measurements were performed in an argon-methane atmosphere using a flow-proportional counter. Table 3.1 gives some of the experimental conditions. Other variables such as the goniometer angle, X-ray tube current and voltage and the value of the E.H.T. supplied to the detector were adjusted in each instance to maximize the count rate, subject to the condition that it did not exceed 20,000 c.p.s., thus ensuring that the counts recorded fell well within the range in which they could be corrected for dead-time losses by assuming a constant correction factor.

The design of the sample holder was such that four specimens could be analysed sequentially. Accordingly, a standard and three samples were placed in the holder, the counting sequence being: standard - three samples - standard - three samples - standard - three samples - standard, so allowance could be made for machine drift.

Some complications arose in the measurement of chromium as the chromium K_α peak could not be adequately resolved from the lanthanum L_{β_2} peak. The chromium K_β peak was also near the lanthanum L_{γ_1} and L_{γ_2} peaks as well as the manganese K_α peak. The lanthanum peaks were far enough away from the chromium K_β not to cause problems while Measurements on a series of buttons containing manganese, but not chromium, suggested that chromium measurements could be performed using the chromium K_β peak without any significant manganese interference given the likely manganese content of the meteorites to be analysed. Matrix correction factors for chromium K_α X-rays were used to correct the chromium K_β radiation for matrix effects.

Table 3.1 : X.R.F. analytical conditions.

Element	*Line*	*X-ray Tube*	*Analysing Crystal*	*Collimator*	*Count Time (s)*
Fe	*Kα*	*Cr*	LiF_{200}	*Coarse*	*40*
Mn	*Kα*	*Au*	LiF_{200}	*Coarse*	*40*
Ti	*Kα*	*Cr*	LiF_{200}	*Coarse*	*40*
Ca	*Kα*	*Cr*	LiF_{200}	*Coarse*	*40*
K	*Kα*	*Cr*	*P.E.*	*Coarse*	*40*
P	*Kα*	*Cr*	*Ge*	*Coarse*	*100*
Si	*Kα*	*Cr*	*P.E.*	*Coarse*	*40*
Al	*Kα*	*Cr*	*P.E.*	*Coarse*	*40*
Mg	*Kα*	*Cr*	*A.D.P.*	*Coarse*	*100*
Ni	*Kα*	*Au*	LiF_{200}	*Coarse*	*40*
S	*Kα*	*Cr*	*Ge*	*Coarse*	*100*
Cr	*KB*	*Au*	LiF_{220}	*Fine*	*100*

d. Calculations

i. Nominal percentages

Nominal, or uncorrected, percentages were calculated by multiplying the ratio of the sample counts to those of the standard, for a given element, by the appropriate calibration factor, both count rates having been corrected for dead time and drift.

ii. Calibration of standards

The FS standards were calibrated when received but these factors had changed with time (cf. Le Maitre and Haukka 1973). FS65 had been subject to little irradiation when this work was begun and FS11 was recalibrated on the basis of its calibration factors. These new factors were subsequently modified on the basis of results obtained for six U.S.G.S. standards.

In the case of NCS2 calibration factors had to be determined. To do this a series of nickel (II) oxide/silica and chromium (III) oxide/silica buttons were prepared. These buttons and the standards were irradiated and the intensity of nickel and chromium X-rays measured. Approximate calibration factors were assumed so preliminary nominal percentages could be calculated. More exact factors were then calculated on the basis of the composition of the calibration buttons.

For a button composed only of nickel and silicon oxides the matrix correction equation reduces to

$$C_{Ni} = C'_{Ni}(M_{Ni} + C'_{Ni}x_{Ni} + C'_{Si}x_{Si}) - B_{Ni}$$

for nickel. Since an infinite number of

iterations will give the correct value of C_{Ni}, it can be assumed that the value obtained after one less cycle will be extremely close to the true value. After an infinite number of cycles the above equation can be written as

$$C_{Ni} = C'_{Ni}(M_{Ni} + C^*_{Ni}x_{Ni} + C^*_{Si}x_{Ni}) - B_{Ni}$$

where the C^*_i are the corrected concentrations after infinity less one cycles. On the assumption that this value is an extremely good approximation to the true value the above can then be rewritten as

$$C_{Ni} = C'_{Ni}(M_{Ni} + C_{Ni}x_{Ni} + C_{Si}x_{Si}) - B_{Ni}$$

and it was on this basis that the theoretical nominal percentage of the calibrating buttons were calculated after calculating B_{Ni} on the basis of the assumed calibration factor.

By comparing these theoretical nominal percentages with the calculated ones, a better approximation to the calibration factor was obtained. On the basis of this, the background and nominal percentages were again calculated and the latter compared to the theoretical value. Three cycles of this process were sufficient to cause the value of the calibration factor to converge. A similar approach was adopted for chromium.

iii. Calculation of results

Since the calculations involved in the processing of the correction equations are long and tedious the computer programme, SILIAN, had been used prior to this work, to perform corrections for eleven elements. This programme was completely rewritten, with many modifications, by the author. The new version, METEAN, processed data for thirteen elements in addition to the weight loss recorded during fusion. The correction to the magnesium calculations for fluorescence of the ADP analysing crystal was changed as described in Section 3.4.1 a and the concentration factors inside the parentheses of the matrix correction equation were only changed at the completion of each cycle. (SILIAN changed these factors after each individual calculation.) The programme also takes into account any weight change that occurs if the sample is ignited to constant weight at 1000°C prior to button preparation thus calculating the analysis of the original specimen and not the ignited material. An initial check was carried out on the convergence of the calculation and no significant difference was detected between the results from two cycles and those from three and so two only were used in subsequent calculations. Appendix D contains a full listing of METEAN.

3.4.2 Mass absorption analysis

The phenomenon of mass absorption is well documented. Measurement of attenuation can be used as the basis for the calculation of the composition of a system composed of essentially only two components.

a. Direct measurements

When two components of a system have markedly different absorptive powers for a given incident radiation, changes in composition can readily be detected (Moore 1969, Mastins et al 1972).

A series of mixtures of nickel (II) oxide and iron (III) oxide, ranging in composition from 100% nickel (II) oxide to 100% iron (III) oxide, at intervals of 20% in composition, were prepared. Samples of these oxide mixtures were then mixed with boric acid in the ratio of 1:5 and mass absorption buttons prepared using Method b. of Mastins et al. Their technique of measuring and calculating the mass absorption of these oxide mixtures for nickel radiation was also used with the plot of measured values of μ vs composition being essentially linear.

Iron meteorite samples were converted to the oxide by dissolving them in nitric acid, evaporating to dryness and igniting (Schmidt 1969). The resulting solid was used to prepare mass absorption buttons, but their mass absorption, however, was much greater than expected, implying, among other things, that the sample consisted only of iron (III) oxide. This suspicion was confirmed by a powder diffraction examination of the sample. The boiling point of nickel (II) nitrate is 137°C and so it appears it was lost in toto during the decomposition. Since this and several other transition element nitrates have low boiling points this method of sample preparation is unsuitable for iron meteorites.

Another series of meteorite samples were dissolved in hydrochloric acid and the solution carefully neutralized with ammonia solution so precipitating the metals as hydroxy compounds. After filtering and washing, the precipitates were ignited. Mass absorption buttons prepared from the residues also gave meaningless results.

b. Differential measurements

The method of Bertin et al (1964) involving the measurement of the mass absorption coefficient of an element at two different wavelengths, one above and one below its absorption edge, was investigated. Nickel and cobalt radiation were chosen to measure the mass absorption coefficients for

iron. Since the method involves the measurement of relative rather than absolute values it is superior to the method described above ,but it has a disadvantage in that standards of known concentration are required. The method ought to work for iron meteorites as iron and nickel are the only major constituents.

Measurements were first made on iron-free samples in the form of boric acid buttons. After measuring standards of known iron concentration at the two wavelengths the measurements were repeated on several meteorites. The results, using the method of calculation of Bertin et al were unsatisfactory. The method is apparently quite adequate for two component systems in which the two members are present in somewhat equal proportions but it becomes unsatisfactory when one member constitutes only about 10% of the system.

c. Compton scattering measurements

The determination of mass absorption coefficients by the Compton scattering method (Reynolds 1963,1967) was also investigated.

The time to accumulate 400,000 counts using the Compton peak of the molybdenum tube as primary radiation was measured. Some 65 chemical compounds in the form of "pressed mounts" (Norrish and Hutton 1964) were used as samples. The calculated mass absorption of these compounds (from Tables) was plotted against the time to accumulate the counts. The graph was linear for compounds containing elements of atomic number less than 25 (Mn) but as the iron absorption edge was approached linearity was lost. This method is therefore also unsuitable for the analysis of iron meteorites.

3.5 RARE EARTH ELEMENT ANALYSIS

The rare earth elements (REE) were determined by the isotope dilution method using a fully automated 12 inch radius 90°-sector solid source Thomson mass spectrometer (Sun and Nesbitt 1978). One gram of sample was used for the determination. The analytical precision for each REE is estimated to be better than 2% for all the elements except gadolinium for which it may be as high as 5%.

3.6 MINERAL COMPOSITIONS USING X-RAY TECHNIQUES

3.6.1 X-ray diffraction analysis

a. Theoretical considerations

The cell parameters of olivine, as with many other minerals, vary with composition (Yoder and Sahama 1957). These authors measured the 130 spacings of a series of olivine samples and calculated the following equation relating the composition to these spacings:

$$Fo(\text{mole }\%) = 4233.91 - 1494.59d_{130}$$

with an error range of ± 3 mole percent.

Mason (1963a), using this method to measure olivine composition in chondritic meteorites, claimed an accuracy of ±1 mole percent. The technique was extended by Pollack and Chi (1972) to measure the quantity of olivine present.

This method of composition determination is strictly only applicable to the "equilibrated" chondrites as the result it produces is an average one (Dodd 1968).

b. Sample preparation

About 0.09g of specimen was mixed with about 0.01g of zinc oxide powder. The mixture was ground under acetone and spread, as a slurry, on a quartz slice cut so as to eliminate diffraction from the quartz over the interval of interest.

c. Instrumental calibration

All measurements were carried out using a Philips X-Ray Powder Diffractometer equipped with a monochromator. Generating conditions of the order of 36 kV and 20 mA were used to produce copper radiation. Half degree slits and a goniometer drive speed of a quarter of a degree per minute were used in conjunction with a proportional detector.

As an internal standard was being used, the absolute positions of the standard and olivine peaks were not important but rather their angular separation. As this was expressed as a distance on the plotted output the relationship between these two quantities is significant.

The chart recorder was calibrated by recording a silicon spectrum and examining the trace. With a goniometer drive of a quarter of a degree per minute, and a nominal chart speed of 10mm per minute the relationship ought to be 40mm to the degree. Measurement of the distance between the 111 (unresolved) and the 220 doublet peaks of the silicon trace showed that an angular displacement of one degree was equivalent to a linear one of 40.024mm.

d. Standard technique

Sample spectra in the range 31-33° 2θ were scanned several times in both directions. The double directional scan was to compensate for distortions due to instrumental aberrations. The 2θ range permitted measurements of both the 130 peak

of olivine and the 110 one of zinc oxide.

The distance between the olivine and zinc oxide peak on the trace was measured in each instance and by assuming that the zinc oxide peak occured at 31.79° the olivine angle was calculated. The calculated d_{130} spacing of the olivine was substituted in a modified form of the Yoder and Sahama equation, viz.

$$Fa(\text{mole \%}) = 1494.59 d_{130} - 4133.91$$

e. An alternative method

In the case of some specimens it was found that there was a significant overlap of the olivine and zinc oxide peaks and so silicon was substituted as an internal standard. The 111 peak of silicon was assumed to have an angular value of 28.442_0 and the spectra were scanned in the range 28-32° 2θ. The calculations were performed as before.

3.6.2 Microprobe analysis

a. Introduction

The compositions of various mineral phases in some twenty meteorites were determined using a Technisch Physiche Dienst (T.P.D.) electron microprobe fitted with modified electronics.

b. Standard technique and calculations

The specimens, in the form of doubly polished thin sections, were coated with a 20nm carbon layer. "Aquadag" was used to provide an electrical connection between the coating and the sample holder. The latter, in electrical contact with the microprobe, was aligned so that both the incident and take-off angles were equal to 45°. A Leitz microscope (x320) enabled the specimen to be viewed with either transmitted or reflected light. An accelerating voltage of 15 kV and a beam current of 3 nA were used for all determinations. The beam current was checked, and adjusted if necessary, before every analysis.

Table 3.2 : Lines analysed and channels integrated during electron microprobe analysis.

Element	*Line*	*Integrated Channels (Channel width: 20 eV)*
Na	$K\alpha$	*50 - 56*
Mg	$K\alpha$	*60 - 66*
Al	$K\alpha_1+\alpha_2$	*71 - 74*
Si	$K\alpha_1+\alpha_2$	*85 - 91*
Ar (bgd)	$K\alpha_1+\alpha_2$	*144 - 152*
K	$K\alpha_1+\alpha_2$	*162 - 169*
Ca	$K\alpha_1+\alpha_2$	*181 - 188*
Ti	$K\alpha_1+\alpha_2$	*222 - 229*
Cr	$K\alpha_1+\alpha_2$	*267 - 274*
Mn	$K\alpha_1+\alpha_2$	*291 - 299*
Fe	$K\alpha_1+\alpha_2$	*316 - 324*
Ge (bgd)	$K\alpha_1+\alpha_2$	*487 - 506*

The X-rays so produced were processed with a lithium-drifted silicon detector (Ortec 77016-40165S) and the output fed to an Ortec main amplifier and a Northern Scientific NS710 multichannel analyser. The main amplifier time constants were set to 6 s and the base line restorer to the "low" position. Appropriate Ortec units were employed to ensure pulse pile-up rejection and a "live-time" system. Counting times of 100 seconds and count rates of 4-5000 c.p.s. were employed.

Integrated peak counts from twelve sets of channels (Table 3.2) were processed directly by a Hewlett-Packard 2116B computer using the methods of Reed and Ware (1973,1975).

The integrated counts were corrected for background, peak overlap and matrix effects.

The corected counts were converted to elemental weight fractions using conversion factors calculated from standards of known composition.

To ensure accurate processing of count data the calibration of the analyser was periodically checked by examining the spectrum of a synthetic nickel silicide standard. This standard was used as the energies of the comparable Si and Ni K peaks are widely separated. The positioning and separation of these peaks enabled any changes to the zero adjustment or gain of the main amplifier to be calculated. The stability of the instrument was such that these checks were performed infrequently and then any changes were of a minor nature only.

Small changes in calibration appeared as consistent variations from 100% in the analytical total - these drifts were corrected by multiplying the conversion factors by an appropriate drift factor.

Due care was taken to ensure that the area analysed was clear of cracks and other surface blemishes. Likewise, areas in the immediate vicinity of troilite or metal grains were generally avoided.

The energy spectrum was displayed on a C.R.T. and a brief inspection usually enabled the distinction to be made between olivine, pyroxene and feldspar enabling the correct number of oxygen atoms per mineral molecule to be input to the computer. The analysis was calculated on the basis of this number. The output included both the number of atoms of each cation and the total number of cations as well as selected atomic ratios.

Results were rejected if either the number of Si(+Al) cations or the total number of

cations differed by more than ± 0.05 from the following:

Mineral	Si(+Al)	Total Cations	Oxygens
Olivine	1	3	4
Pyroxene	2	4	6
Feldspar	4	5	8

Essentially pure silica was detected in some cases and in these instances the analyses were calculated on the basis of 2 oxygen atoms.

In the case of glassy areas the analyses were always initially calculated on the basis of a pyroxenitic composition - some were also recalculated as olivines and/or feldspars. In most cases the glasses were non-stoichiometric.

Every attempt was made to avoid grains showing heavy limonitic staining. Analysis of such areas produced high "totals" as the programme assumed all the iron to be Fe (II) - i.e. an iron to oxygen ratio of 1:1. (Ratios involving iron were likewise inaccurate.)

A limit of detection of three standard deviations of the background value applied to all elements. Reed (1973) suggested that in the most favourable circumstances an accuracy of ± 1% could probably be achieved while ± 2% was probably more realistic for many analyses. Mason (1974), in discussing the accuracy of his measurements on this same machine, stated that he was quoting his analytical results to one decimal place, given, however, that this decimal figure was of doubtful validity due to sample inhomogeneities and experimental uncertainties. Following Mason's lead, results in this work are quoted to one decimal place but with the same limitations.

An indication of the reproducibilty of the instrument is given by iron and calcium results obtained over a period of several days for the same pyroxene grain in a section of Muckera. The results obtained were as follows:

Fe	: 26.7	27.0	26.9
Ca	: 3.2	3.2	3.0

These results are expressed as moles per cent calculated by use of equations such as Fe = 100Fe/(Fe+Mg+Ca) where each chemical symbol indicates the cation composition of the analysed grain.

3.7 CONCLUSION

The results obtained will be found in the next chapter and a full discussion of them in Section B.

Chapter 4

ANALYTICAL RESULTS

4.1 INTRODUCTION

Adequacy of sampling is a continual problem in analytical studies of meteorites. Although ordinary chondrites represent fractions which have formed by random partitioning (Kiesl et al 1967) estimates of the amount necessary for representative elemental analysis vary from 0.5g (Wasson 1974) through 1g (Schmitt et al 1972) up to one kilogram (Greenland and Lovering 1965).

Sample sizes used in this work ranged from 5 to 150g, the smaller coming from meteorites for which only limited material was available. Although care was taken to make allowance for grain size and homogeneity in selecting sample size, sampling errors must be present.

In the case of very small samples the fusion crust is important but it was removed from the sample in every case. Since it is generally a glass containing fragments of refractory components its inclusion must introduce bias and certainly in the case of small meteorites errors which may arise from its omission are outweighed by those which would arise from its inclusion.

Variation in the physical properties of the constituent minerals is also a possible source of sample inhomogeneity.

Most of the meteorites analysed were weathered and in each case the analysis presented is that of this material. Every attempt has been made to produce an accurate analysis of the available material, but whether it is an accurate analysis of the whole unweathered material is another matter. Whether the "original unweathered meteorite" is the body as it landed on the earth's surface, a sample of the meteor prior to any ablationary sculpturing, or of the original parent body is a moot point. Kiesl et al (1967) summed up the situation by stating that the result of any analysis is only absolutely true in respect to the ratios in the material of the sample which has actually been used and hence generalizations made from the results should only be done with care. Accordingly comparison of absolute results obtained by different workers for the same meteorite are somewhat difficult but comparison of relative values is valid. This highlights the need expressed by Schmidt (1969) and others for meteoritic standards. Recent progress has been made in this direction using samples of Allende (Jarosewich and Clarke 1971, Mason 1975b).

For iron meteorites, the traditional practice has been to choose, for analysis, sections free of troilite or other inclusions. This obviously gives a more "accurate" analysis of the nickel-iron component but equally obviously gives a less representative one. Thus Schmidt (1969) commented on the low value for sulfur in his analysis of Cowell. Further cutting of this meteorite, after his work, revealed the presence of large troilite nodules, perhaps accounting for his result. In this work the iron meteorites were analysed in the form of cuttings and so included fragments of any minor nodules encountered during cutting.

4.2 THE CHONDRITES AND THE ACHONDRITES

Forty three chondrites and achondrites and six rock standards were analysed by X-ray fluorescence and other methods.

4.2.1 The method of reporting meteorite compositions

Mason (1962b), among others, pointed out that the reporting of meteorite analyses in terms of oxides involved several assumptions, none of which was fully justified. Iron provides the major problem. Attempts to "partition" the iron between silicate, sulfide and metal phases produces certain difficulties. To circumvent some of these problems, the results in this work are reported in the elemental form. The results then lack information in that no attempt has been made to determine the amount of iron in the metal phase but since most of the specimens are weathered such determinations would be of limited value. By reporting the iron as "total iron" this error is eliminated and at the same time the weathered iron is not aggregated to the silicate iron during "difference" calculations and the uncertainty in any FeO

Table 4.1 : Analytical results for the analysed U.S.G.S. standards.

	AGV-1		BCR-1		DTS-1		G-2		GSP-1		PCC-1	
	1	2	1	2	1	2	1	2	1	2	1	2
Fe	6.83	6.76	13.58	13.40	8.85	8.64	2.63	2.65	4.25	4.33	8.36	6.35
Mn	0.100	0.097	0.16	0.18	0.14	0.11	0.034	0.034	0.041	0.042	0.13	0.12
Ti	1.09	1.04	2.31	2.20	0.016	0.013	0.50	0.50	0.68	0.66	0.015	0.015
Ca	5.03	4.90	7.04	6.92	0.101	0.15	1.94	1.94	2.00	2.02	0.52	0.51
K	2.98	2.89	1.77	1.70	0.001	0.001	4.53	4.51	5.51	5.53	0.035	0.004
P	0.60	0.49	0.41	0.36	0.12	0.002	0.31	0.14	0.33	0.28	0.001	0.002
Si	59.79	59.00	54.51	54.50	40.36	40.50	69.13	69.11	67.27	67.38	42.10	41.90
Al	17.36	17.25	13.59	13.61	0.19	0.24	15.49	15.40	15.00	15.25	0.65	0.74
Mg	1.52	1.53	3.46	3.46	49.32	49.80	0.77	0.76	0.96	0.96	43.52	43.18

References: 1. This work 2. Abbey (1978)

determinations is eliminated (Deuser 1968). The reporting of meteorite analyses in this manner is not without precedent - e.g. Von Michaelis et al (1969) and Wiik (1969).

4.2.2 Analytical controls

Analytical results for the U.S.G.S. standards, listed below, which were analysed to monitor the accuracy of the analytical techniques, are reported in conventional form in Table 4.1. The results of Abbey (1978) are included for comparative purposes.

Table 4.2 lists results obtained for the analysis of fragments of Allende and Plainview (1917) from the Tate Museum, University of Adelaide, with comparative results of other workers.

Table 4.2 : Analytical results for Allende and Plainview (1917).

	Allende		Plainview (1917)			
	1	3	1	5	4	2
Fe	23.36	23.6	26.62	27.65	26.54	25.94
Mn	0.16	0.15	0.25	0.22	0.25	0.24
Ti	0.103	0.090	0.072	0.059		0.072
Ca	1.94	1.85	1.21	1.16	1.17	1.22
K	0.053	0.025	0.136	0.074		0.083
P	0.11	0.11	0.115	0.11		0.109
Si	16.05	16.0	17.01	16.61	17.07[6]	16.22
Al	1.81	1.74	1.14	1.07		1.16
Mg	15.20	14.9	14.46	14.00		13.45
Ni	1.46	1.42	1.77		1.71	1.59
S	1.97	2.10	2.04			2.08
Cr	0.30	0.36	0.32		0.34	0.36
Na	0.44	0.34	0.62			0.50

References:
1. *This work*
2. *Fodor and Keil (1976)*
3. *Mason (1975b)*
4. *Nichiporuk et al. (1967)*
5. *Von Michaelis et al. (1969)*
6. *Wing (1964)*
7. *Yates et al. (1968)*

4.2.3 Major and minor elemental abundances

Table 4.3 lists the analytical results obtained in this work for South Australian and Northern Territory specimens. The results for three other meteorites which were recovered well away from the study area are given in Appendix B.

4.2.4 Rare earth element abundances

Rare earth element abundances for the chondritic meteorite Adelaide are listed in Table 4.4. These results were obtained by the isotope dilution technique as described in Section 3.5 and the analyses were carried out in this Department by Dr. S.-S. Sun to whom thanks are due.

4.2.5 Mineralogical compositions

a. Preamble

X-ray diffraction and electron microprobe methods were used to measure olivine, pyroxene and feldspar compositions. Dodd and Van Schmus (1965) reported that when such methods were compared, the olivine and pyroxene results for the equilibrated meteorites agreed well but not so the unequilibrated ones, as the diffraction method produces an average value while the microprobe gives grain to grain values. They also reported that when the results

Table 4.4 : REE composition of Adelaide.

Element	Abundance (p.p.m.)
La	0.399
Ce	0.957
Nd	0.678
Sm	0.225
Eu	0.0836
Gd	0.309
Dy	0.387
Er	0.237
Yb	0.239

Table 4.3 : Analytical results for the meteorites examined in this work (elemental percentages).

Meteorite	Fe	Mn	Ti	Ca	K	P	Si	Al	Mg	Ni	S	Cr	Na
Accalana	17.98	0.29	0.081	1.30	0.089	0.079	19.10	1.18	15.22	1.07	1.55	0.31	0.61
Adelaide	21.69	0.19	0.080	0.94	0.027	0.143	15.68	1.46	14.99	1.50	1.77	0.23	0.29
Artracoona	20.19	0.26	0.074	1.19	0.113	0.105	17.91	1.09	14.04	1.13	1.84	0.31	0.61
Cadell	21.56	0.37	0.056	1.23	0.032	0.100	18.86	1.11	15.69	1.29	2.25	0.28	0.53
Carraweena	18.91	0.28	0.081	1.36	0.109	0.090	19.44	1.21	15.46	1.09	2.05	0.33	0.70
Carraweena Fragment	19.42	0.27	0.087	1.30	0.086	0.065	18.98	1.23	16.23	1.10	2.19	0.32	0.55
Cartoonkana	20.04	0.28	0.093	1.17	0.088	0.120	18.42	1.09	14.43	1.46	1.39	0.43	0.57
Cockburn No.3	20.61	0.25	0.089	1.18	0.071	0.062	17.62	1.12	15.01	1.04	1.48	0.29	0.68
Cockburn No.4	21.74	0.27	0.092	1.25	0.108	0.075	18.29	1.17	15.99	1.25	2.29	0.34	0.80
Cockburn No.5	20.86	0.26	0.093	1.23	0.083	0.064	18.24	1.18	15.33	1.04	1.88	0.33	0.70
Cockburn No.6	22.59	0.30	0.104	1.24	0.133	0.124	17.91	1.27	14.15	1.03	0.34	0.34	0.76
Cocunda	20.04	0.27	0.094	1.32	0.093	0.071	18.80	1.20	16.06	1.05	2.15	0.36	0.70
Coomandook No.1	24.82	0.25	0.100	1.15	0.127	0.132	16.59	1.21	13.80	2.12	1.73	0.35	0.59
Coonana	24.87	0.22	0.084	1.03	0.074	0.087	15.85	1.08	13.40	1.60	1.74	0.31	0.50
Hollmayer No.5 (HO5)	23.54	0.28	0.062	1.05	0.095	0.136	16.71	1.07	13.35	1.62	1.36	0.25	0.68
Hollmayer No.6 (HO6)	23.22	0.28	0.064	1.17	0.104	0.130	16.83	1.07	13.62	1.60	1.46	0.29	0.76
Kaldoonera Hill	24.78	0.24	0.068	1.13	0.070	0.109	16.18	1.01	13.39	1.66	1.78	0.29	0.53
Karoonda	23.86	0.15	0.103	1.71	0.039	0.104	15.89	1.57	14.51	1.50	1.38	0.30	0.39
Kielpa	25.16	0.24	0.070	1.11	0.084	0.106	16.08	1.01	13.40	1.68	1.77	0.30	0.67
Kybunga No.3	20.12	0.26	0.056	1.31	0.130	0.092	18.98	1.20	15.11	1.13	2.11	0.32	0.64
Lake Bonney	20.63	0.28	0.078	1.28	0.112	0.080	18.00	1.09	14.39	1.19	2.64	0.38	0.67
Lake Labyrinth	19.70	0.31	0.073	1.41	0.103	0.157	19.37	1.42	16.03	1.20	2.00	0.31	0.86
Monte Colina	19.07	0.27	0.084	1.28	0.054	0.103	18.99	1.25	16.10	1.10	2.32	0.31	0.60
Moorabie	22.68	0.29	0.072	1.32	0.073	0.118	18.67	1.19	15.05	1.37	2.28	0.31	0.68
Motpena	21.02	0.29	0.066	1.42	0.109	0.121	17.88	1.16	14.70	1.23	2.32	0.27	0.75
Muckera	13.85	0.40	0.248	5.06	0.060	0.029	23.20	4.32	8.95	0.09	0.27	0.37	0.21
Nine Mile (HO3)	21.28	0.30	0.068	1.25	0.119	0.129	18.59	1.22	14.05	0.84	0.66	0.24	0.76
Nora Creina	19.69	0.28	0.079	1.26	0.092	0.088	18.54	1.14	14.83	1.12	2.26	0.29	0.65
Pinnaroo*	24.81	0.29	0.142	3.54	0.043	0.428	17.55	3.38	6.76	0.95	7.39	0.34	0.22
Popilta (HO4)	20.00	0.31	0.068	1.22	0.105	0.117	18.68	1.19	15.20	1.29	1.72	0.29	0.77
Popio (HO1)	21.34	0.29	0.071	1.31	0.114	0.135	18.64	1.23	15.23	1.33	2.52	0.32	0.82
Poonarunna	23.88	0.24	0.076	1.08	0.091	0.095	16.51	1.05	13.01	1.41	1.53	0.27	0.58
Thackaringa No.1	24.93	0.25	0.065	1.11	0.101	0.153	16.50	1.08	11.49	1.35	0.21	0.30	0.81
Twin Wells (HO2)	22.98	0.25	0.067	1.03	0.110	0.136	16.62	1.09	13.23	1.52	1.49	0.24	0.66
Vincent	21.45	0.26	0.089	1.25	0.070	0.069	17.83	1.14	15.84	1.23	2.35	0.32	0.70
Wilbia	23.30	0.24	0.085	0.98	0.062	0.088	16.60	1.08	14.32	1.67	1.68	0.33	0.46
Witchelina	24.44	0.22	0.069	1.13	0.058	0.105	16.25	1.00	13.19	1.63	1.66	0.27	0.46
Yandama	20.77	0.27	0.078	1.28	0.100	0.099	17.78	1.08	14.01	1.22	1.50	0.31	0.66

*cf. Recalculated analysis below.

differed, the diffraction ones were generally about 1% higher in iron content for the equilibrated meteorites and even higher for the unequilibrated ones. For ten of the eleven meteorites examined by both methods in this study, the converse situation was found. This trend agrees with that shown by the results of Mason (1963a,1967a,1974). The earlier of these results were diffraction ones while the 1974 results were obtained with the microprobe used in this study. Nwe (1976), in a study of Skaergaard olivines, found that microprobe results were always more iron rich than those given by optical methods.

The olivine and pyroxene compositions in the unequilibrated chondrites are highly variable and various parameters have been calculated to measure this variation (Dodd and Van Schmus 1965, Dodd et al 1967). Since it involves the unbiased standard deviation and hence can be used for extrapolation to the meteorite as a whole, the coefficient of variation, (CV), was used as a measure of mineralogical composition variablity in this work. The CV was calculated as follows:

$$CV = 100s/\bar{X}$$

where s is the unbiased standard deviation of the measurements and $\bar{X}$ is the average composition. s gives the best unbiased measure of variance.

Not all of this variance is due to variations in mineral compositions since some of it arises from errors in the

determinations. In Section 3.6.2.b a value of ± 2% was suggested as a reasonable estimate of the analytical accuracy. Values of CV were calculated for average compositions ranging from 15 to 35 mole percent in steps of 2.5 and differing numbers of determinations to examine the effect of this error. The more pessimistic estimate of error produced a CV of about 2% for ten or more measurements while a more optimistic error estimate of ± 1% produced a CV of approximately 1%. When 2% is subtracted from the calculated CV's, they are reduced to zero or very small values for most of the specimens. For others, the coefficient is quite high and so gives an accurate indication of intrinsic compositional variation. The approach of Dodd et al (1967) resembled that taken in this work. These authors estimated their overall precision to be ± 2.5% for olivine and ± 5% for pyroxene and then stated that a specimen with a PMD (percent mean deviation - their measure of variance) less than these values was considered to have homogeneous silicates. The considerable variation between the rim and centre in many chondrules in the Hallingeberg chondrite noted by Dodd (1974) suggests that some of the variation measured by the CV may reflect such variation in addition to chondrule to chondrule ones.

The pyroxenes examined in this work generally showed a greater degree of inhomogeneity than the olivines - i.e. given that the cooling rates were the same the homogenization of the olivine appears to be more rapid that that of the pyroxene. Some meteorites had homogeneous olivine associated with inhomogeneous pyroxene. Similar trends were reported by Dodd et al (1967). These authors examined two of the meteorites discussed in this work (Baratta and Carraweena) and their results are included for comparative purposes. The absolute values of the olivine and pyroxene compositions are similar and in both cases lie within error limits. The CV has a greater value than their PMD but the orders of magnitude are quite similar.

b. X-ray diffraction results

Table 4.5 shows the results obtained. The methods employed and the accuracy expected were described in Chapter 3.

c. Electron microprobe results

Compositions of olivine, pyroxene and feldspar measured with this equipment are listed in Table 4.5 along with the parameter CV. Average values only are presented in this table. The complete results are available from the author.

As described in Section 3.5.2 a, all microprobe analyses were initially processes by an "on-line" computer, a decision having been made as to the tentative identification of the component. After recalculation on the basis of 4, 6 or 8 oxygen atoms the cation sum was examined and generally it did not depart significantly from 3, 4 or 5. In those cases where it did, there was evidence, in some instances, of machine error and the analysis was discarded. The remaining analyses were considered to represent non-stoichiometric glass phases.

Meteoritic glasses have variously been described as mafic (Dodd and Van Schmus 1965) and siliceous (Dodd et al 1967). Almost without exception the glasses examined in this work contained less than 65% silica and so can be described as mafic. These glasses showed a wide range in composition which may indicate that in some instances more than one grain was being analysed. The range was so great that an "average" composition was meaningless and accordingly results are tabulated in full in Appendix C only. These results are discussed in Section 11.3.

4.2.6 Normative mineral calculations

Mason (1962b) pointed out that normative calculations of mineral compositions for stony meteorites are fraught with assumptions of dubious validity. Nonetheless, such calculations do reflect fairly accurately the mineralogical composition of the meteorite. Furthermore, gross differences between normative and modal compositions are of diagnostic value.

One of the main reasons that these calculations are more subject to error than similar terrestrial ones is the iron problem, i.e the manner in which it is distributed between various minerals.

In this work, a conventional approach was used for various glassy phases analysed with the microprobe and a modified one for the meteorite bulk analyses.

a. Meteorite glasses

The analytical results for these phases were all processed by the computer programme CIPWNM (Fitzgerald 1975) which was originally written by I. Van Wielen on the basis of the work of Kelsey (1965).

Since the normative olivine and pyroxene molecules are of very restricted composition, such calculations must be treated with caution. Thus, for example, cations such as Al may be an integral part

Table 4.5 : Mineralogical compositions.

Meteorite	Olivine				Pyroxene			Feldspar		Silicate Homogeneity			
	X.R.D.		Probe		Probe			Probe		Olivine		Pyroxene	
	Fa[1]	Fa[3,4]	Fa[1]	Fa[5]	Fs[1]	Wo[1]	Fs[5]	An[1]	Ab[1]	CV[1]	PMD[2]	CV[1]	PMD[2]
ACCALANA	24.9	24		24.8									
ADELAIDE	0.7 42.4												
ALLENDE	16 48												
ARTRACOONA	25.2	24		25.6									
BARATTA		25	23.8	24.0 23.7[2]	17.8	1.5	16.7 16.7[2]			3.0	4.2	30	23
CADELL	25.7			25.5									
CARRAWEENA	24.9	24	25.3	24.8 24.9[2]						14	6.0	30	20
CARRAWEENA FRAGMENT	25.0												
CARTOONKANA	24.0	24		25.7									
COCKBURN No.1			26.2		22.8	1.5				1.7		0.1	
COCKBURN No.2			26.4		22.8	1.5				0		0.7	
COCKBURN No.3	24.7												
COCKBURN No.4	25.4												
COCKBURN No.5	26.1		26.6		23.2	1.7				0.4		3.1	
COCKBURN No.6	25.5			25.1			21.5						
COCUNDA	25.2	24		25.8									
COOMANDOOK No.1	19.0	19		18.8									
COONANA	18.9	19		19.2									
HOLLMAYER No.5	18.9		19.8		17.5	1.0				0		0	
HOLLMAYER No.6	15.1		18.0		16.7	1.2				0		0.6	
KALDOONERA HILL	18.1	19		18.7									
KAROONDA	32.2		34.5							0.4			
KIELPA	18.3			18.9									
KYBUNGA No.3	25.2			25.0									
LAKE BONNEY	25.7	24		24.5									
LAKE LABYRINTH	29.5			25.9									
MONTE COLINA	25.2	25											
MOORABIE	15.6		15.7		12.4	0.8				9.0		42	
MOTPENA	25.3		25.9		22.0	1.5	21.7			0		0	
MOUNT BROUNE		17	18.8	18.1	17.0	1.3	16.5			0		0.2	
MUCKERA			27.4					88.0	11.3	5.6			
NINE MILE (HO3)	23.5		26.9		23.4	1.4				0		3.8	
NORA CREINA	25.6	24		25.1									
PINNAROO	10.8		18.2		31.2 36.0[6]	4.5 4.5[6]		90.7	8.7	1.9		8.7	
POPILTA (HO4)	25.0		25.6		22.8	1.3				1.8		3.8	
POPIO (HO1)	23.9		26.2		22.4	1.5				0.5		1.0	
POONARUNNA	18.1		19.9		17.8	1.5				2.8		7.6	
SILVERTON		25	25.8	25.4	21.5	1.6	21.0			0		0	
THACKARINGA No.1	17.2												
TWIN WELLS (HO2)	18.9		21.1		17.4	1.0				3.1		0	
VINCENT	23.9	24		24.2									
WILBIA	19.0			19.0									
WITCHELLINA	19.1			19.1									
YANDAMA	25.0	25		25.0									

References:

1. *This work.*
2. *Dodd et al (1967)*
3. *Mason (1963)*
4. *Mason (1967)*
5. *Mason (1974)*
6. *Mason and Jarosewich (1973)*

of the pyroxene lattice and need not be present as other minerals. The norm calculation, however, assigns them to such phases as feldspar, nepheline etc. Similarly, titanium is incorporated into ilmenite, sphene or perovskite rather than pyroxene and likewise chromium appears as chromite while manganese and nickel are "converted" to iron. Despite these limitations, the norm calculations are useful in comparing the basic composition of phases which do not appear to consist entirely of one mineral as they give a possible composition of the assemblage. The various assemblages are discussed in Chapter 11 and the results of the norm calculations are given in Appendix C.

b. Bulk meteorite compositions

The standard CIPW norm calculation was modified on the basis of several additional assumptions and the resulting calculations embodied in the computer programme MINORM (Appendix D) which was used to process the analytical results. The assumptions were :-

a. sulfur is present as stoichiometric troilite (FeS),
b. phosphorus is present as the most abundant meteoritic phosphate, whitlockite $(Ca_3(PO_4)_2$, (Keil 1974),
c. nickel is present as an iron-nickel alloy,
d. any iron not used in troilite or nickel-iron alloys is present as Fe(II) in the silicates,
e. the ratio Fe/Mg differs in the olivine and pyroxene, being greater in olivine.

Assumptions (b) and (c) preclude the presence of any normative schreiberiste, an omission which is probably justified by its apparent rarity in stony meteorites. Assumptions (a) and (d) have also been used by Mason and Wiik (1962a), while Mason and Jarosewich (1973) adopted a similar approach for phosphorus to that detailed in (b). Recent structural determinations (Dowty 1977) have shown that the meteoritic phosphate is merrillite rather than whitlockite. This result was too late to be included in this work but Table 4.6 can be readily modified by substituting the heading "Merrillite" for "Whitlockite" as both minerals have the same composition.

The boundary between H and L chondrites has been taken at 23% total Fe, since many of the meteorites in this study are weathered and weathering will tend to lower the total iron content. This division is supported by the olivine determinations and the probability of classing an L chondrite as H is small.

In order to calculate the normative nickel-iron composition, data compilations of Wood (1963), Anders (1964), Craig (1964), Chou et al (1973) and Dodd (1974) were averaged and nickel and iron were distributed either as $Fe_{11.4}Ni$ or $Fe_{7.2}Ni$ for H- and L chondrites respectively. Likewise the olivine and pyroxene compositional data of Keil and Fredriksson (1964) and Mason (1974) were averaged and the iron distributed between pyroxene and olivine in the ratio of 1:1.117 for the H chondrites and 1:1.178 for the L chondrites.

Comparison of normative values calculated by this method (Table 4.6) and modal values reported by Keil (1962b) show a good correlation.

These calculations were inappropriate for use with the carbonaceous chondrites examined in this work but the results for the two achondrites, Muckera and the recalculated Pinnaroo silicate fraction (Section 8.5), appear to be quite realistic.

4.3 THE IRON METEORITES

Iron and nickel compositions were determined by "wet chemical" methods as described in Chapter 3 while measurements of the width of kamacite lamellae were carried out as below. The nickel and iron composition of the hexahedrite Forsyth County were measured for comparative purposes.

4.3.1 Bulk compositions

Table 4.7 lists the iron and nickel compositions as determined in this work.

Lovering et al (1957) reported a nickel composition of 5.55% for Forsyth County while Wasson (1974) quoted 5.50%. Using Lovering et al's figures, an iron value of 93.95% is obtained by difference for Forsyth County. These figures indicate the accuracy of the results reported in this work.

Table 4.7 : Iron and nickel content of the iron meteorites.

Meteorite	*Iron %*	*Nickel %*	*Total %*
Cowell		*8.13*	
Henbury		*7.45*	
Kapunda	*90.88*	*8.05*	*98.93*
Kyancutta	*90.61*	*8.10*	*98.71*
Mount Sir Charles	*90.79*	*8.35*	*99.14*
"S.A. Beta"		*7.48*	
Yardea	*92.30*	*6.81*	*99.11*
Forsyth County	*93.84*	*5.56*	

Table 4.6 : Normative mineral compositions of analysed meteorites.

	Weight Percent									Molar Percent			
	Nickel-iron	Troilite	Whitlockite	Ilmenite	Chromite	Feldspar	Diopside	Orthopyroxene	Olivine	Ab	An	Fs	Fa
ACCALANA	8.8	4.5	0.4	0.3	0.7	10.2	4.9	35.9	34.4	73.2	20.5	16.7	19.7
ARTRACOONA	9.5	5.4	0.6	0.3	0.7	10.0	4.6	31.2	37.9	76.3	15.5	19.9	23.5
CADELL	10.1	6.2	0.5	0.2	0.6	8.7	3.8	32.3	37.6	71.1	22.3	17.9	21.1
CARRAWEENA	8.7	5.7	0.5	0.3	0.7	10.6	5.3	33.5	34.7	77.9	15.0	16.3	19.2
CARRAWEENA FRAGMENT	8.8	6.1	0.3	0.3	0.7	9.7	4.4	30.2	39.5	66.5	27.4	15.9	18.7
CARTOOONKANA	12.1	4.0	0.6	0.3	1.0	9.5	3.9	38.4	30.3	73.1	20.3	17.0	20.0
COCKBURN No.3	8.6	4.3	0.3	0.3	0.7	10.2	5.1	18.8	51.8	81.4	13.6	20.9	24.6
COCKBURN No.4	9.8	6.3	0.4	0.3	0.7	10.7	5.5	17.6	48.7	86.1	7.1	17.4	20.5
COCKBURN No.5	8.4	5.3	0.3	0.3	0.7	10.4	2.6	21.4	48.1	80.0	14.4	19.9	23.5
COCKBURN No.6	8.3	1.0	0.6	0.3	0.8	11.5	4.6	13.8	59.1	79.3	12.5	27.1	31.9
COCUNDA	8.3	5.9	0.4	0.3	0.8	10.3	5.3	23.6	45.1	76.8	15.0	17.4	20.5
COOMANDOOK No.1	*									68.5	22.3		
COONANA	20.9	5.2	0.5	0.3	0.7	9.3	3.2	32.3	27.7	68.0	26.1	11.9	13.3
HOLLMAYER No.5	21.1	4.1	0.8	0.2	0.6	10.4	3.8	36.0	23.1	82.7	10.5	10.2	11.4
HOLLMAYER No.6	20.6	4.3	0.7	0.2	0.7	10.8	5.0	32.7	25.1	87.3	5.6	9.4	10.5
KALDOONERA HILL	21.5	5.3	0.6	0.2	0.7	9.0	4.0	35.0	23.8	74.0	20.3	10.3	11.5
KIELPA	21.6	5.3	0.6	0.2	0.7	9.9	4.7	29.5	27.6	85.3	8.5	10.7	11.9
KYBUNGA No.3	9.1	5.9	0.5	0.2	0.7	10.3	4.9	31.7	36.7	73.8	17.4	17.9	21.1
LAKE BONNEY	9.8	7.6	0.4	0.3	0.9	10.1	5.5	29.7	35.8	80.4	11.6	17.1	20.1
LAKE LABYRINTH	9.3	5.5	0.8	0.2	0.7	12.2	4.7	25.4	41.2	80.9	13.4	15.9	18.7
MONTE COLINA	8.8	6.5	0.5	0.3	0.7	10.0	4.0	31.9	37.4	70.8	25.5	15.2	17.8
MOORABIE	10.7	6.2	0.6	0.2	0.7	10.1	4.6	27.9	39.1	78.5	16.6	9.8	10.9
MOTPENA	10.1	6.6	0.6	0.2	0.6	10.8	6.0	22.8	42.4	83.5	9.4	17.8	20.9
MUCKERA	0.7	0.7	0.1	0.8	0.8	23.9	11.5	61.0	0.5	10.7	87.5	35.3	2.6
NINE MILE (H03)	6.8	1.9	0.7	0.2	0.5	11.2	4.8	21.2	52.8	81.3	11.2	26.9	31.7
NORA CREINA	9.1	6.5	0.5	0.3	0.7	10.1	5.0	32.3	35.7	77.4	16.2	17.2	20.3
PINNAROO (Silicate)			2.8	0.6	1.0	24.5	2.3	66.9	1.0	7.7	91.4	40.4	4.5
POONARUNNA	18.4	4.6	0.5	0.3	0.6	9.8	4.0	34.0	27.8	75.9	17.2	15.5	17.3
POPILTA (H04)	10.4	4.9	0.6	0.2	0.6	11.0	4.8	28.2	39.2	83.6	9.8	17.0	20.0
POPIO (H01)	10.5	7.0	0.7	0.2	0.7	11.2	5.1	25.9	38.9	84.7	8.4	16.3	19.2
THACKARINGA No.1	17.8	0.6	0.9	0.2	0.7	11.4	4.8	28.0	35.5	90.3	3.0	25.2	28.1
TWIN WELLS (H02)	19.9	4.5	0.8	0.2	0.6	10.6	3.6	36.2	23.7	80.2	12.0	11.0	12.3
VINCENT	9.8	6.6	0.4	0.3	0.7	10.0	5.2	18.8	48.3	81.5	13.7	17.2	20.2
WILBIA	21.5	5.0	0.5	0.3	0.8	9.2	2.8	38.0	22.0	68.4	26.6	6.4	7.1
WITCHELLINA	21.3	5.0	0.6	0.2	0.7	8.6	3.7	38.5	21.4	68.3	26.7	10.8	12.1
YANDAMA	10.2	4.4	0.5	0.3	0.7	10.1	5.4	27.2	41.2	80.6	12.3	20.6	24.3

Apparent excess of nickel precluded norm calculations

4.3.2 Bandwidth measurements

One of the oldest methods for classifying octahedrites is based on the examination of polished and etched sections to determine the width of the kamacite lamellae which are finger to plate shaped crystals of kamacite with an approximate length to height to width ratio of 30:3:1 (Buchwald 1969,1975b). The width of these plates is a function of the nickel content, the cooling rate and the nucleation temperature (Wasson 1974). It is generally assumed that the kamacite lamellae grow in such a fashion that their {110} planes are parallel to the {111} planes of the parent taenite. The nickel content of the plates varies from about 5.5% to 7.5% and their width is not only a function of this but also of the nickel content of the taenite precursor.

Since these lamellae are parallel to four different sets of octahedral planes, the number of sets of lamellae and the size of the angle between them which will be observed when the meteorite is cut is a function not only of the actual bandwidth but also of the orientation of the section.

As pointed out by Frost (1965), methods of classification based on bandwidths assume that not only are the plates parallel to the taenite octahedral planes but also that they have developed to an equal extent in each direction.

However, not all of the lamellae always grow to the same size, and for this and other reasons, Buchwald (1975b) stated that the average width of the largest lamellae ought to be used. He presumably intended that the true width of the lamellae be used, i.e. the width observed on a section cut at right angles to the {111} plane of the taenite. Herein lies the second problem encountered in this work, viz. that of section orientation.

Buchwald overcame this problem by making measurements on mutually perpendicular sections. Since this method was not possible in this work, another approach had to be adopted.

Different solutions have been proposed for the orientation problem. Belaiew (1922,1923) and Buchwald (1969) described different methods of calculating the orientation of the section plane from observations of angles measured on it. From this they applied a correction factor to the observed widths. Frost (1969) simply gave a set of correction factors to be applied to measured widths. These factors were based on the number of sets of lamellae observed and their angular relationships and did not involve the calculation of the actual orientation. Lovering et al (1957) measured the average width of all observed sets of lamellae and omitted those measurements which were more than twice as big as the smallest one. This method possibly resulted in an under approximation of the true width.

In this work, the approach of Frost was adopted and correction factors applied to the widths measured according to his method to obtain the true widths. Table 4.8 lists the results so obtained. Values quoted by Buchwald (1975b) are included for comparison.

These results tend to be slightly less than the corresponding ones of Buchwald, possibly due to an average rather than the maximum width being used. The difference is small enough to ignore.

Table 4.8 : Bandwidths.

Meteorite	*Bandwidth (mm)*	
	This work	*Buchwald (1974b)*
Boxhole	*0.93*	*1.00*
Cowell	*1.13*	
Henbury	*0.92*	*0.95*
"S.A. Beta"	*0.94*	*0.95**
Kapunda	*0.93*	
Kyancutta	*0.98*	*1.05*
Moorumbunna	*0.90*	*0.95*
Mount Sir Charles	*0.22*	
Rhine Villa	*1.33*	*1.40*
Weekeroo Station	*2.29*	*2.5*
Yardea	*2.08*	*2.0*

**Buchwald pers. comm. 1974.*

B: METEORITE CLASSIFICATION AND GENESIS IN THE LIGHT OF THIS WORK

Chapter 5

THE CHEMICAL CHARACTERIZATION OF METEORITES

5.1 INTRODUCTION

This chapter is concerned with the basis of classification used for the meteorites studied; both those which are being examined for the first time and those for which some results have already been published. Relevant data available from previous work is listed in Table 5.1. All the meteorites have been critically re-examined by several methods to determine their correct classification.

As mentioned in the main introduction to this work, many different classification schemes have been applied to meteorites. Most early schemes were based on visual and petrological properties, e.g Brezina (1904). In 1916, Prior drew attention to the importance of composition to any classification scheme, while in 1956 Yavnel wrote that "the primary classifying characteristic of meteorites should be their chemical composition followed by the mineral composition and then by other characteristics". In the following year (Yavnel 1957), he re-emphasised the importance of chemical composition as the primary characteristic.

In the light of these and similar comments, an attempt has been made in this work to use chemical composition as the basis for all classification methods. This has been supplemented, where necessary, by mineral compositions and textural features as used by Van Schmus and Wood (1967) and other authors.

Chayes (1960) discussed the problems inherent in studying variables which added to a constant sum. Oxide data in a chemical analysis provide an excellent example of such a set of variables. The result in all such cases is that the sum of the covariances of a variable is equal to the negative value of its variance and accordingly there is a bias towards negative correlations even between unrelated variables. On the surface, it would appear that the method adopted in Chapter 4, namely the re-expression of analytical results as elemental percentages with the omission of oxygen, might alleviate this problem since the variables no longer sum to a constant figure. Percentages, however, are proportions or ratios and are subject to the limitations of such quantities. Thus the closure effect can be eliminated by the formation of ratios but this does not solve the problem as ratio formation removes the specific restraint inherent in closure by replacing it with a more general set of restraints inherent in ratio formation (Chayes 1971).

The fundamental problem is that even if the numerators and denominators of the ratios are completely uncorrelated, there will be a correlation between many pairs of the ratios formed from them; as a result, there is no single, or readily apparent null value against which to test the significance of the correlation between ratios formed from percentages. In the case, however, of two ratios formed from percentages but containing no common term, the expected correlation between them would be zero (Chayes 1971).

Notwithstanding these comments, there is still some information to be gained from studying both absolute and relative elemental abundances provided the correlations and relationships are subjected to careful scrutiny. As Chayes pointed out, the major problem is the estimation of the extent of the correlation produced by the calculation of percentages and the subsequent calculation of ratios from these percentages. The solution to this problem is quite complex and in most cases it has been ignored - a procedure which does not eliminate the problem.

5.2 DIFFERENTIATED AND UNDIFFERENTIATED METEORITES

The traditional division of meteorites into irons, stony-irons, chondrites and achondrites sometimes tends to conceal fundamental aspects of meteorite chemistry and genesis (Wasson 1974). Wasson accordingly advocated that in any meteorite classification scheme an initial distinction ought to be made between the differentiated and the undifferentiated meteorites, the

Table 5.1 : Summary of previous work.

	Bulk Analysis	Trace Element Analysis	Olivine Composition	Pyroxene Composition	Petrographic Description	Chemico-petrologic Group
ACCALANA		X	X			X
ADELAIDE	X	X	X	X	X	X
ARTRACOONA	X		X	X	X	X
BRACHINA	X	X	X	X	X	-
CADELL		X	X	X		X
CARRAWEENA	X	X	X	X	X	X
CARTOOONKANA			X	X	X	X
COCKBURN No.1			X	X	X	X
COCKBURN NO.2						
COCKBURN No.3						
COCKBURN No.4						
COCKBURN No.5						
COCKBURN No.6			X	X		X
COCUNDA		X	X	X		X
COOMANDOOK No.1			X	X		X
COOHANA			X	X	X	X
HOLLMAYER No.5						
HOLLMAYER No.6						
KALOONERA HILL		X	X	X		X
KAROONDA	X	X	X	X	X	X
KIELPA	X		X	X	X	X
KYBUNGA No.3			X	X		X
LAKE BONNEY			X	X	X	X
LAKE LABYRINTH	X	X	X	X	X	X
MONTE COLINA	X		X			X
MOORABIE						
MOTPENA			X	X	X	X
MOUNT BROWNE	X	X	X	X	X	X
MUCKERA						
NINE MILE (H03)						
NORA CREINA			X	X	X	X
PINNAROO	X	X	X	X	X	-
POONARUNNA						
POPILTA (H04)						
POPIO (H01)						
SILVERTON		X	X	X	X	X
THACKARINGA No.1						
THACKARINGA No.2						
TWIN WELLS (H02)						
VINCENT		X	X	X		X
WILBIA			X	X		X
WITCHELLINA	X	X	X	X	X	X
YANDAMA	X		X	X	X	X

former being meteorites with non-volatile elemental abundances similar to that of the sun. Of all the meteorites, only the chondrites have not been produced by differentiation of primitive "cosmic" material. Despite this, close studies of the chondrites suggest that the material of which some of them are composed has undergone some fractionation but to a much lesser degree than that of the differentiated meteorites. Various authors have argued that the composition of the C1 chondrites closely approximates to that of the sun, and, for this reason, the compositions of other meteorites are compared with the C1 chondrites to determine to what degree they are differentiated.

The classification of typical irons and stony-irons as differentiated meteorites is generally not difficult, nor is the classification of the chondrites as undifferentiated ones. However, the classification of meteorites containing a large percentage of silicate-rich material which does not possess a chondritic texture is not so clear as the absence of such a texture does not necessarily imply that the meteorite is differentiated as is evidenced by the C1 chondrites, none of which contains chondrules. That the state of differentiation cannot be determined by textural considerations alone is another example of the importance of bulk chemistry in the determination of a meteorite's classification.

To distinguish between the differentiated and undifferentiated meteorites, Wasson divided the atomic abundances of each element (first normalized to silicon) by those of the average abundances for the C1 chondrites. He then stated that for a meteorite to be undifferentiated these ratios should generally fall in the range 0.5 to 1.0. He plotted the elements under consideration in order of decreasing "incompatability" (i.e. tendency to concentrate in the liquid phase of a silicate melt) and found that the chondrites generally fell within this range. The "curves" for the diogenites, eucrites and howardites indicated that the most incompatible elements were markedly depleted in the diogenites, whereas they were generally enriched in the howardites and eucrites. Iron and magnesium were depleted in all three groups. Similar fluctuations occured for the other two major achondrite groups, the aubrites and the ureilites.

In this work, an undifferentiated meteorite is defined as one whose relative atomic abundances relative to C1 abundances generally fall in the range 0.4 to 1.3. In practice, the ratios for K, Al, Ca, P and Ti give a good indication of this classification. If more than one of these ratios departs markedly from this range, then differentiation should be suspected. Thus, after the calculation of atomic

Table 5.2 : Values of ratios used to determine "state of differentiation".

	K/0.42	Al/8.5	Ca/7.21	P/0.96	Ti/0.2775	Fe/83.0
ACCALANA	0.80	0.76	0.66	0.40	0.89	0.57
ADELAIDE	0.30	1.02	0.58	0.86	1.08	0.84
ARTRACOONA	1.08	0.74	0.65	0.55	0.87	0.69
CADELL	0.29	0.72	0.63	0.50	0.63	0.70
CARRAWEENA	1.24	0.76	0.68	0.44	0.88	0.59
CARRAWEENA FRAGMENT	0.78	0.80	0.66	0.32	0.97	0.62
CARTOOONKANA	0.81	0.73	0.62	0.62	1.06	0.66
COCKBURN No.3	0.69	0.78	0.63	0.34	1.06	0.71
COCKBURN No.4	1.01	0.79	0.67	0.39	1.06	0.72
COCKBURN No.5	0.78	0.80	0.66	0.33	1.08	0.70
COCKBURN No.6	1.27	0.87	0.68	0.66	1.22	0.77
COCUNDA	0.84	0.78	0.68	0.36	1.05	0.65
COOMANDOOK No.1	1.31	0.89	0.67	0.75	1.28	0.91
COONANA	0.80	0.83	0.63	0.52	1.12	0.96
HOLLMAYER No.5	0.98	0.79	0.61	0.77	0.79	0.86
HOLLMAYER No.6	1.06	0.78	0.68	0.73	0.80	0.84
KALDOONERA HILL	0.74	0.76	0.68	0.64	0.88	0.93
KAROONDA	0.37	1.18	1.02	0.63	1.32	0.91
KIELPA	0.89	0.77	0.67	0.62	0.93	0.95
KYBUNGA No.3	1.17	0.77	0.67	0.46	0.63	0.65
LAKE BONNEY	1.06	0.74	0.69	0.42	0.92	0.70
LAKE LABYRINTH	0.91	0.90	0.71	0.77	0.79	0.62
MONTE COLINA	0.49	0.80	0.66	0.51	0.94	0.61
MOORABIE	0.67	0.78	0.69	0.60	0.82	0.74
MOTPENA	1.04	0.79	0.77	0.64	0.78	0.72
MUCKERA*	0.45	2.28	2.12	0.12	2.26	0.36
NINE MILE (H03)	1.10	0.80	0.65	0.66	0.78	0.70
NORA CREINA	0.85	0.75	0.66	0.45	0.90	0.65
PINNAROO*	0.42	2.36	1.96	2.30	1.70	0.86
POONARUNNA	0.95	0.78	0.63	0.54	0.97	0.88
POPILTA (H04)	0.96	0.78	0.64	0.59	0.77	0.65
POPIO (H01)	1.05	0.81	0.69	0.68	0.80	0.70
THACKARINGA (No.1)	1.05	0.80	0.65	0.88	0.84	0.92
TWIN WELLS (H02)	1.13	0.80	0.60	0.77	0.85	0.84
VINCENT	0.67	0.78	0.68	0.36	1.06	0.73
WILBIA	0.64	0.80	0.57	0.50	1.08	0.86
WITCHELLINA	0.61	0.75	0.68	0.61	0.89	0.92
YANDAMA	0.96	0.74	0.70	0.53	0.92	0.71

*Differentiated

abundances relative to 100 silicon atoms, the following ratios were computed:
K/0.42, Al/8.5, Ca/7.21, P/0.96, Ti/0.2775. The results of Cameron (1973) were used to calculate the divisors of these ratios. If the values fell in the specified range, the meteorite was given an undifferentiated classification. In cases where there was any doubt, the ratio Fe/83.0 for iron was also calculated. The results are shown in Table 5.2.

5.3 CLASSIFICATION BASED ON ABSOLUTE CHEMISTRY

Mason (1962b) and other authors have commented on the "quantization" of iron in meteorites, with Wiik (1969) suggesting that in the case of the stony meteorites certain values of iron were "avoided". Ahrens (1964) pointed to a silicon quantization. Table 5.3 shows the method adopted in this work of subdividing meteorites on the basis of their absolute chemistry. The differentiated and undifferentiated meteorites are divided into the traditional categories. The pallasites and mesosiderites, which are often grouped together as stony-irons, have not initially been separated from those meteorites usually known as the achondrites. The reason for this is explained more fully in Chapter 8. It is sufficient to state at this stage that such a subdivision conceals important genetic relationships. The ordinary chondrites cannot be completely characterized here and, in addition, the usual border problems arise. Use is made in

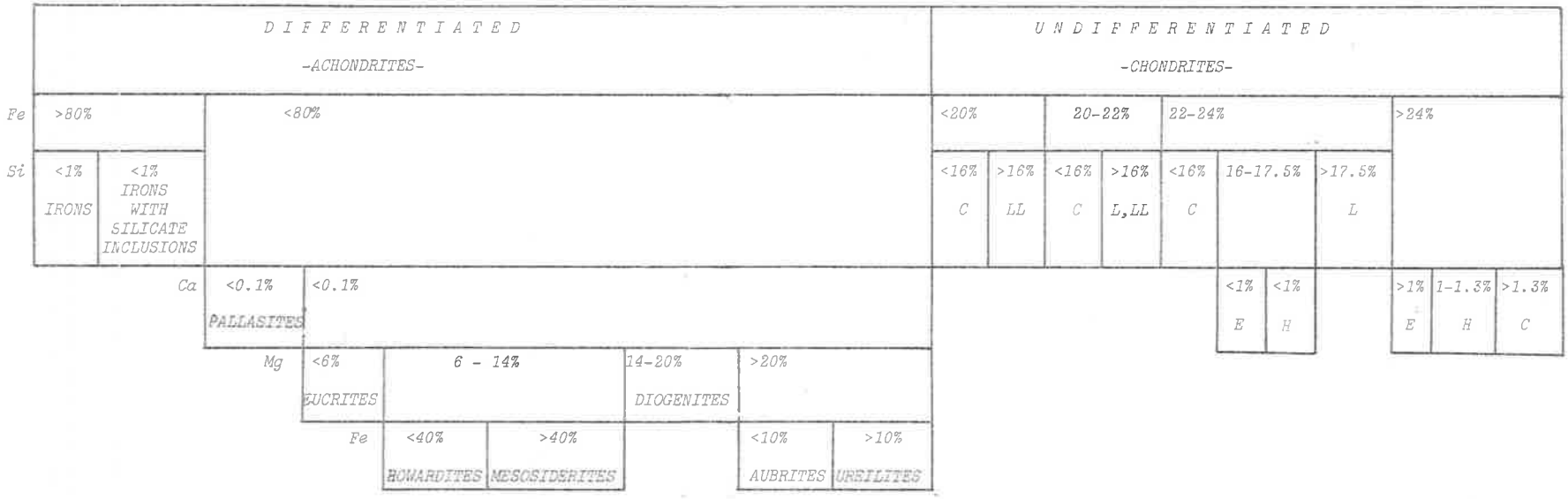


Table 5.3 : The classification of meteorites on the basis of absolute elemental abundances.

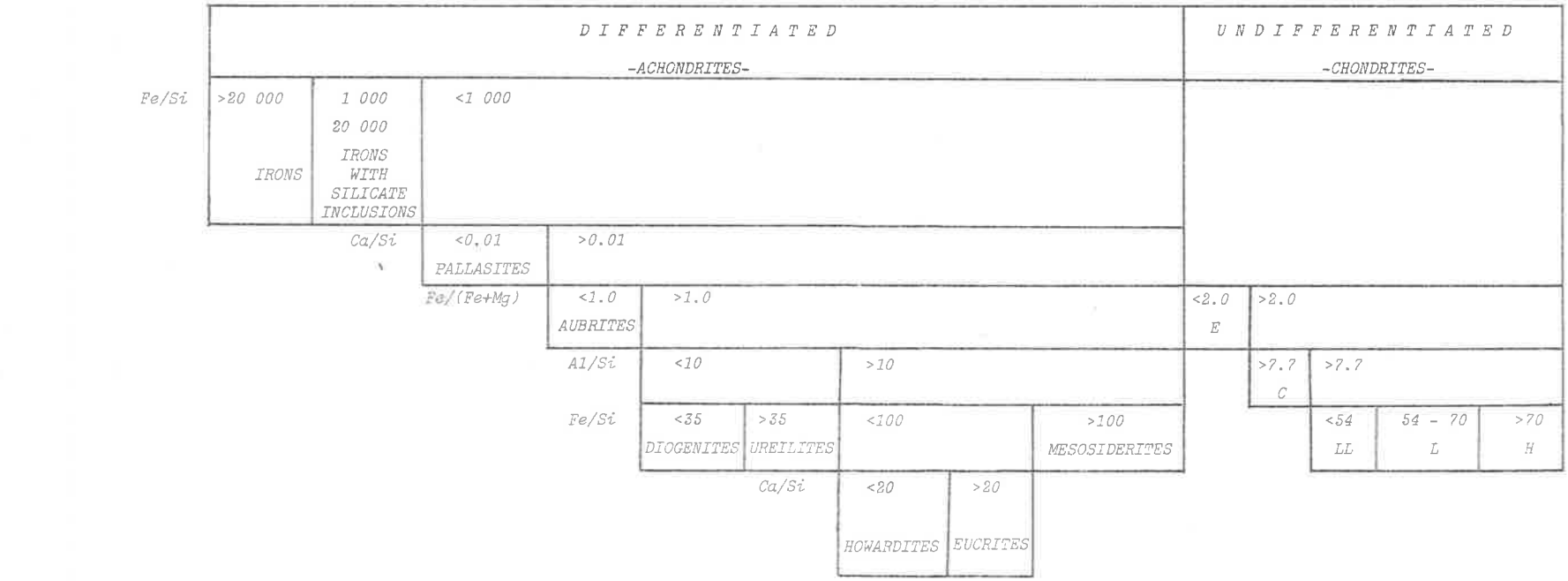


Table 5.4 : The classification of meteorites on the basis of relative elemental abundances.

the table of the terminology of Mason (1962b) and Van Schmus and Wood (1967).

If only the silicate phases of the mesosiderites or pallasites are considered, the pallasites will still be uniquely defined, while the mesosiderites will be grouped with the howardites.

5.4 CLASSIFICATION BASED ON RELATIVE CHEMISTRY

In spite of the comments made above concerning ratio correlations, the calculation of these quantities is a worthwhile exercise and many of them are of taxonomic significance. Intuitively, the expression of these ratios of an atomic basis appears to offer greater potential information and they are calculated in this manner throughout this work unless otherwise stated.

Ahrens (1964) drew attention to the behaviour of silicon in the ordinary chondrites and suggested that a study of various inter-element ratios would be a useful exercise. He initially referred all his ratios to silicon but subsequently he, and other workers, considered many other elemental pairs such as calcium and aluminium.

Probably one of the earliest users of ratios in a taxonomic context was Deuser (1967) who distinguished between four groups of the achondrites on the basis of the ratios Fe/Mg, Fe/Al and Mg/Al. Different elemental ratios have been used in this and other works to distinguish the main meteorite groups, the basic requirement being that the ratio shows a narrow range of values within any one meteorite group which is distinct from that for another group (Wasson 1974). Not only can these ratios be used to distinguish between different meteorite classes, but some can also be used to discriminate between lunar, terrestrial and meteoritic material (See also Chapter 10).

Table 5.4 shows the ratios used in this work to classify meteorites. In this case, the ordinary chondrites can generally be completely characterized but border problems do arise. Once again, if only the silicate phases of the mesosiderites or pallasites are considered, the pallasites will be uniquely defined and the mesosiderites will again fall with the howardites.

5.5 DEFINITION OF CHONDRITE GROUPS

The simple schemes outlined in the previous two sections usually result in the correct classification of a meteorite with the possible exception of borderline cases.

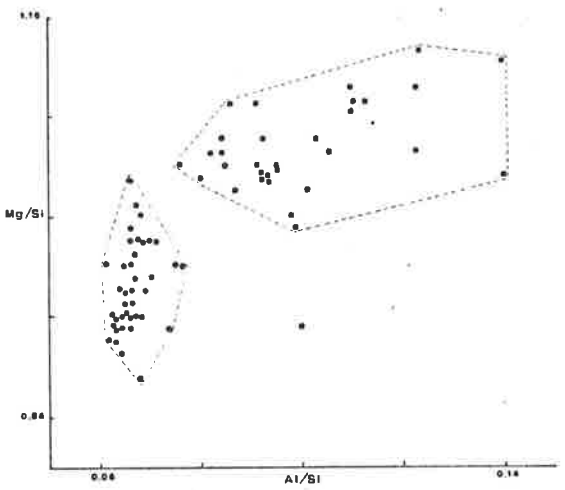
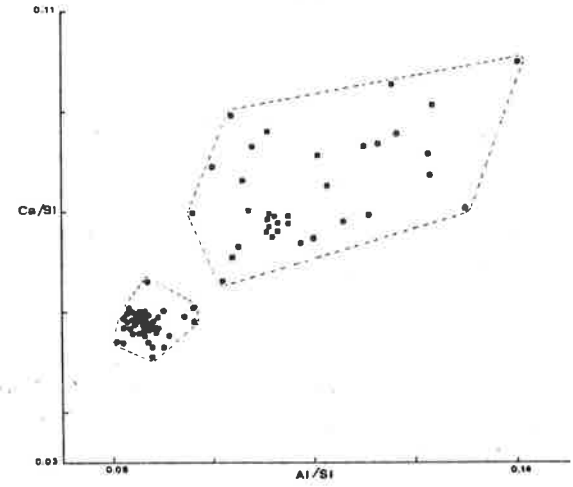


Figure 5.1 : Mg/Si vs Al/Si for ordinary and carbonaceous chondrites. ● : ordinary, this work; ■ : carbonaceous, this work and literature values (Table 7.3).

The dichotomous nature of these schemes can aggravate this problem. More extensive definitions will usually cope with all cases.

There is presently a dearth of definitions based on chemical parameters for the various chondrite classes. Nagy (1975) commented that satisfactory criteria to completely distinguish the carbonaceous chondrites were lacking but did not propose any. The criterion of Mason (1971a), Osborn et al (1974) and others that a Mg/Si ratio of greater than 1 is characteristic of the carbonaceous chondrites is subject to overlap. Wasson (1974) suggested that the ratios Al/Si or Ca/Si would equally separate the carbonaceous from the ordinary chondrites. Of the three, Al/Si appears to be the best discriminator (Figures 5.1 and

Figure 5.2 : Ca/Si vs Al/Si for ordinary and carbonaceous chondrites. ● : ordinary, this work; ■ : carbonaceous, this work and literature values (Table 7.3).



5.2). The main chondrite groups are set out below in terms of these and other selected ratios, all of which are expressed on a percentage basis.

Enstatite chondrites

Ca/Mg	in the range	3.0 to 7.0
Fe/(Fe+Mg)	in the range	0.04 to 2.0
Al/Si	in the range	4.5 to 6.0
Ca/Si	in the range	1.0 to 3.8

Ordinary chondrites

Ca/Mg	in the range	3.0 to 10.0
Fe/(Fe+Mg)	in the range	15 to 60
Al/Si	in the range	4.5 to 8.0
Ca/Si	in the range	3.8 to 5.5

Carbonaceous chondrites

Ca/Mg	in the range	3.0 to 10.0
Fe/(Fe+Mg)	in the range	15 to 60
Al/Si	in the range	8.0 to 15
Mg/Si	in the range	100 to 120

The definition proposed and given here for the carbonaceous chondrites has also been used by Fitzgerald and Jones (1977).

The use of four ratios to define a group usually ensures that the values of two or more of the ratios will indicate a consistent classification. The ordinary chondrites can be further subdivided on the basis of the Fe/Si ratio as shown in Table 5.4, while further subdivisions of the carbonaceous chondrites will be discussed in Chapter 7.

The value of the ratio Ca/Mg is a function of the mean solidification temperature of the residual melt if a process of magmatic segregation has been involved and, accordingly, either high or low values are indicative of formation by such magmatic fractionation (Wasson 1974). The intermediate limits chosen for the chondrites then correspond to a non-magmatic origin for them. The value of the ratio Fe/(Fe+Mg) is a function of the degree of oxidation of the silicate minerals. Fractionation of this ratio likewise occurs during magmatic segregation. The ratios Al/Si, Ca/Si and Mg/Si were chosen on more utilitarian grounds and their inter-relationship is discussed further in Chapter 9.

5.6 MULTIVARIATE ANALYSIS

5.6.1 Introduction

The procedures discussed in the preceding sections were generally based on the study of one or two variables at a time. Further information can be obtained by the simultaneous examination of several. Because of the problems involved in visualizing points in multi-dimensional space recourse was had to the techniques of multivariate analysis which are methods of compressing the available information into one, two, or at the most three, dimensions.

Two different approaches were employed, viz. discriminant and classificationary methods. Discriminant analysis involves the comparison of the samples being studied with a priori defined groups, while classification techniques simply involve the comparison of samples with each other to discover any similarities which will allow them to be placed in sub-groups. All of these processes provide convenient methods of displaying complex relationships, but it must be emphasised that if on close inspection the analytical data seems to be at variance with the proposed groupings then the groupings are suspect. It appeared that the results obtained in this work were quite realistic. Some of the computer programmes used to perform these analyses were written by the author while others were adapted from published ones. Extensive use was made of the Biomedical Programme Library (Dixon 1973).

5.6.2 Data normalization

Some of the techniques permit the data to be first normalized or standardized, that is, transformed so that each variable has a mean of zero and a standard deviation of one. This procedure has the effect of giving equal weighting to all variables and is mandatory if major and trace element data are being considered simultaneously. The situation is not quite so clear for major and minor (not trace) elements together and is discussed at several points below.

5.6.3 Multiple discriminant analysis

This technique consists in the definition of two or more groups and the comparison of unknown objects with each of the groups in order to assign them to one of the groups. The method is limited not only by the adequacy of the initial definitions but also by the assumption that the unknown objects belong to one of the groups. Lower (1966) examined these assumptions and limitation in greater detail.

The simplest and best known form of discriminant analysis is that involving two groups, i.e. when an individual is to be placed in one of two defined groups. This type of calculation is well documented. A series of coefficients λ_i are found from the equation

$$[s^2][\lambda] = [D]$$

where s^2 is the pooled variance-covariance matrix for one of the defined groups and D is the vector of differences between the means of the two groups. Another set of coefficients is likewise calculated for the second group. These coefficients are then used to calculate a discriminant function for each of the groups. Evaluation of these functions for each of the unknowns produces disriminant scores for that sample. The discriminant functions have the form

$$DF = \sum_{i=1}^{n} \lambda_i x_i + C$$

where x_i are the data values for an unknown sample and C is a constant (Davis 1973). The unknown is then assigned to the group for which its discriminant score is greater, the procedure assuming that membership of either group is equally probable.

The extension of this technique to three or more groups has not been so fully documented. The basic assumptions and processes are essentially the same, with the unknown again being allocated to the group for which its discriminant score is the greatest (Kendall 1957). Lachenbruch (1973) included a factor to allow for the probability of membership of each of the groups and then stated that a sample should be assigned to the i-th group if

$$p_i f_i(x) = \max p_j f_j(x)$$

where p_j is the probability of membership of any group and $f_j(x)$ is the corresponding discriminant score. It was assumed in this work that these probabilities were equal and so this factor was ignored. The number of samples used to define some of the groups was small and so this also may have further affected the accuracy of the discriminant functions.

The multiple discriminant programme BMD07M (Dixon 1973) was used. The output included the discriminant functions, the discriminant scores for each sample and a "probability of membership" of each group. The latter, which were calculated as follows

$$Pr_i = \frac{Exp(DF_i - DF_{max})}{\sum_i Exp(DF_i - DF_{max})}$$

are relative and not absolute probabilities, that is, they describe the probability of a sample belonging to a group on the assumption that it belongs to one of the groups under consideration.

5.6.4 Principal component analysis

This multivariate technique consists in the extraction of latent roots (eigenvalues) and latent vectors (eigenvectors) of the variance-covariance matrix of the data set and the use of them to calculate a new or transformed data set. The eigenvectors are often called principal components and their elements "loadings". The manipulation is purely mathematical and unlike other methods of multivariate analysis, no assumptions have to be made concerning the distribution of the samples in the hypothetical population from which they have been drawn (Gower 1966), i.e. no assumptions are made as to whether the samples are distributed normally or otherwise.

After the variance-covariance matrix has been calculated, the following equation is solved for X and λ:

$$[A].[X] = \lambda[X]$$

where A is the variance-covariance matrix, λ is the eigenvalue and X is the eigenvector associated with it provided the data has not first been normalized, in which case A is replaced by R, the correlation matrix (cf. Trochimczyk and Chayes 1978). Since both A and R are symmetrical the eigenvalues will always have real solutions and the associated eigenvectors will be orthogonal (i.e. linearly independent). This mathematical manipulation has the other important property that the sum of the eigenvalues will equal the sum of the diagonal elements (i.e. the trace) of either A or R. Since this trace represents the total variance of the data set, the sum of the eigenvectors will also be equal to the total variance and hence the percentage of the variance represented by each eigenvalue can be easily calculated.

It is also a property of this mathematical manipulation that the magnitude of the largest eigenvalue will be greater than that of any of the elements of the trace of A or R. It is this compression of the variance into fewer dimensions which is the source of the power of the technique (McCammon 1966). The eigen values (and their associated eigenvectors) are ordered in decreasing magnitude and the latter used to transform the original data set into principal component scores which correspond to "co-ordinates" referred to the axes in the direction of these eigenvectors. The transformation is carried out as follows:

$$y_{ij} = \sum_{i}^{n} \sum_{j}^{m} \sum_{k}^{m} x_{ij} \alpha_{jk}$$

where y_{ij} are the k new data points and x_{ij} the original ones fror n samples and m variables while the α_{jk} are the elements of the eigenvectors taken in order.

The purely mathematical nature of these computations is the cause of what is sometimes seen as the principal disadvantage of the technique, namely, the fact that no control can be exercised over the spatial orientation of these eigenvectors. Thus May (1974), for example, suggested that it was often difficult to interpret the eigenvectors in geologically meaningful terms and that this disadvantage could at least be partly overcome by the technique of factor analysis. It was felt that this possible advantage was outweighed by some of the disadvantages of that technique.

The computer programme PRINCA (Appendix D) was written to carry out these manipulations making use of two C.D.C. library routines. The output included the original data set, the eigenvalues and eigenvectors both in absolute and percentage terms and the transformed data set.

Since the elements of the eigenvectors are the direction cosines of these vectors, the sum of their squares equals 1, and hence the contribution of each element to the variance of the eigenvector (the eigenvalue) can be calculated. In like manner, the contribution of each element to the total variance can be calculated (cf. Webb and Briggs 1966). Similar loadings in an eigenvector indicate a similarity between the chemical elements represented by those loadings especially if the loadings are close to unity. For a group of elements to be similar to each other, this resemblance should extend to several eigenvectors (Shaw and Harmon 1975, Webb and Briggs 1966). The number of eigenvectors to which this agreement should extend to indicate a correlation is a function of the amount of variance represented by each eigenvector which is in turn a function of whether the data is normalized or not. In the latter case, the first three eigenvectors represent most of the variance and a coherence of loadings in these three eigenvectors is indicative of a strong relationship, whereas if the data is first normalized, then more eigenvectors must be examined as a larger number of them are required to account for the same amount of variance.

As the principal components are orthogonal, there is no correlation between the co-ordinates of the samples referred to the new axes and accordingly, samples which consistently plot togther when referred to these new axes must resemble each other. Caution must be used when discussing the significance of the distance between samples which plot in close proximity to each other as discussed below.

Once the input data has been transformed, the problem of displaying the results arises. The most obvious method is to plot the first two principal components (eg. Le Maitre 1968) but such diagrams can be misleading. Since most of the variation is contained in the first three eigenvectors, the relationships between elements or individual samples will be best displayed if these three components are displayed simultaneously. Kovats and Fraser (1966) suggested stereoscopic models as the most appropriate methods of display. Such models are physically bulky and difficult to reproduce on paper and so they suggested stereo pairs would provide the best compromise and they and other authors (e.g. Sneath and Sokal 1973) have used such diagrams. As they are difficult to use without a stereo viewer, they were avoided in this work. Stephens et al (1975) adapted a molecular model plotting programme to display their results. An analogous method was initially chosen in this work. Since such a programme was not readily available, one was written based on the clinographic projection (Phillips 1963) involving a clockwise rotation of 18° 26' about the vertical axis and an elevation of the line of projection above the normal to the paper of 9° 28'. A major disadvantage was the pronounced forshortening.

Three modifications were made to improve the display: (1) the positions of the individual data points were represented as circles whose radii were functions of the "x co-ordinate" with an increase in the radius corresponding to movement towards the viewer, (2) solid and broken lines were used to indicate whether the circle was above or below the horizontal "x-y plane", and (3) another diagram was produced by rotating the projection 90° in a clockwise direction about the "z-axis". These two diagrams then enabled the three principal components to be viewed simultaneously. This method of display is suitable for both the elements of an eigenvector or principal component scores. In the former case, the weightings for each variable are plotted. In both instances entities which lie in proximity to each other on both plots are similar. When plotting the principal component scores, the first was plotted on the "z-axis" as most of the variation occurs in this direction, the second principal component was plotted parallel to the "x-axis" and the third parallel to the "y". The rotated position was equivalent to viewing the system along the y-axis in the direction of decreasing y. Figure 5.3 shows this method of display for

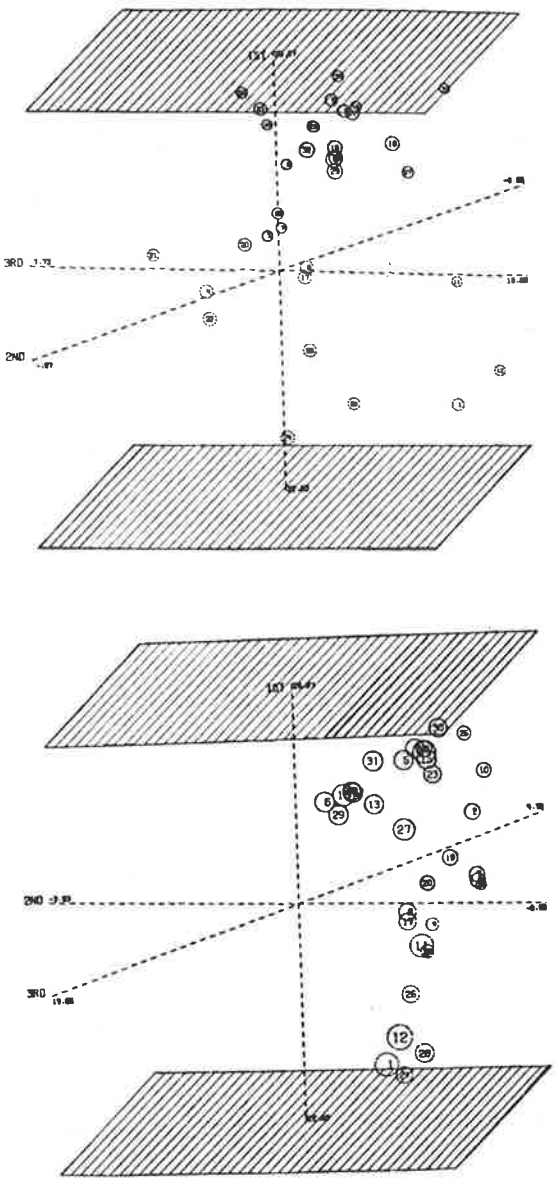


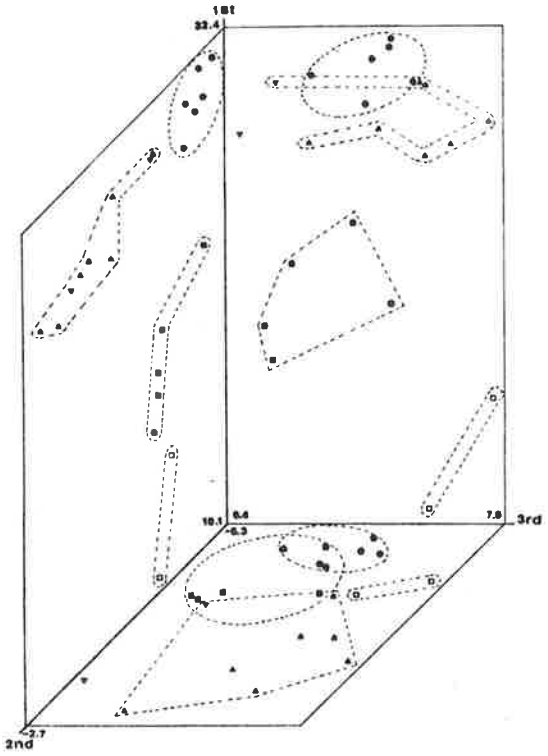
Figure 5.3 : First three principal components for a set of carbonaceous chondrites (Table 7.3).

a set of carbonaceous chondrites.

The above method of display still had some disadvantages and so another method was devised. Plots of the first vs second, first vs third and second vs third principal components were drawn next to each other so that all three could be viewed simultaneously. The angle between the axes representing the first and third vectors was set at 90° and those between these two axes and the one parallel to the third eigenvector were set at 135° (Programme FIRST3 in Appendix D). Figure 5.4, for example, illustrates this technique with a set of 22 carbonaceous chondrites. The lengths of these projection axes ought to be proportional to the magnitudes of the first three eigenvalues, but for ease of computation they were set in the ratio 1.9:1.0:1.0. This choice is somewhat extreme for non-normalized data but not so when the data is first normalized. This multiple plot was generally used in this work, but on some occasions, because of the multiplicity of data, a plot of the first two principal components only is given.

As others (e.g. Till and Colley 1973) have found, more eigenvectors are needed to account for the same amount of variance if the data is first normalized. Thus in this work, in a group of carbonaceous chondrites using the analytical results for thirteen elements the first three eigenvectors accounted for 79.5% of the variance if the data was first standardized and 98.8% if it wasn't. In the case of the non-normalized data, about 92% of the variance represented by the first three eigenvectors arose from the variance of three elements (Fe, Si and Mg) whereas when the variables were first normalized only 19% of the variance was attributed to these three elements which is expected as the magnitudes of the eigenvector loadings are functions only of the variance of the original data. The resultant principal component scores are also affected by the magnitude of the original data and so it is not possible to predict with certainty whether the results from the normalized or non-normalized data will best separate the specimens into groups. Accordingly, in this work both types of analyses were generally carried out and

Figure 5.4 : First three principal components for a set of carbonaceous chondrites (Table 7.3). □ : CI, ■ : CM, ● : CO, ▲ : CV, ▽ : Adelaide and Karoonda.



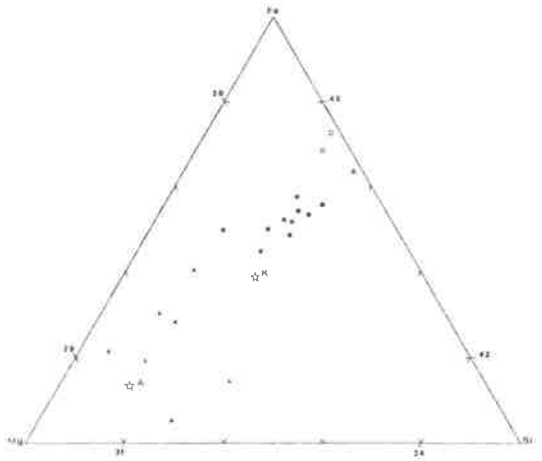


Figure 5.5 : Part of the plot Fe-Si-Mg for a set of carbonaceous chondrites (Table 7.3). □ : CI, ■ : CM, ● : CO, ▲ : CV chondrites, A : Adelaide, K : Karoonda.

the results examined.

The utility of the method of principal component analysis was demonstrated in the case of the carbonaceous chondrite data set by drawing a triangular diagram for Fe, Si and Mg which was found to be less efficient in distinguishing the various groups than the principal component plot (Figure 5.5).

Principal component analysis is characterized by the faithful representation of the distance between groups but frequently gives false distances between close neighbours (Sneath and Sokal 1973) and in this way it is the opposite of cluster analysis (see below) which accurately shows the relationship between adjacent members but distorts the distance between members further away from each other. The two techniques thus complement each other with principal component analysis defining the general distribution of the samples over different groups and cluster analysis highlighting the relationship between members which are very similar to each other.

Closure effects mentioned above in Section 5.1 unfortunately affect principal component analysis also. Butler (1976) showed that by calculating the correlation coefficients brought about by the closure effect alone, a set of "closure principal components" could be calculated for a data set. The magnitude and orientation of these principal components differed from those of the observed data, the implication being that the size and direction of the observed principal components are not solely a function of genetic relationships alone.

5.6.5 Canonical correlation analysis

Canonical correlation analysis is concerned with the relationship between two sets of variables. The variables in each of the two sets are transformed into two new sets of orthogonal variables in such a way as to maximize the correlation between the corresponding variables of each of the new sets and so it can be considered as a sort of "double-barrelled" principal component analysis (Tatsuoka 1971). Thus it generalizes the the normal relationship between two variables expressed by a correlation coefficient to the joint correlation between two sets of variables (Brower and Veinus 1974).

The process is generally used for different groups of variables, Brower and Veinus, for example, used it to inter-relate two different sets of size measurements on Lower Silurian eurypterids; however, the only basic requirement is that the two sets of variables are disjoint. As with other multivariate techniques, its advantage lies in its ability to show a simpler relationship among the observed variables.

The transformed or canonical scores for each of the canonical variables are obtained by multiplying the original data set by calculated coefficients. The magnitude of these coefficients will indicate the extent to which each of the original variables is contributing to the new variable; they are calculated in an analogous manner to the principal component scores described above.

As the correlation between the first canonical variable for each of the two sets of variables has been maximised, a plot of the canonical scores for these first two variables will approximate to a straight line.

Since the results of principal component analysis and cluster analysis suggested that the chemical elements which had been analysed could be split into two groups with a low correlation between them, it appeared to be valid to use the technique of canonical correlation analysis to examine the various meteorite groups. The adequacy of the technique is further discussed below.

The Biomedical Library Programme BMDX75 (Dixon 1973) was used in the computation of the canonical variables and canonical scores, with the first variable of each set of the latter being plotted against each other.

5.6.6 Cluster analysis

Cluster analysis is another method of displaying complex relationships among many objects. The method involves the reduction of the input data to one dimension. A measure of similarity between the objects is

computed and the objects are sorted into groups so that the objects in each group are more similar to each other than to those in other groups (cf. Rhodes 1969). Different measures of similarity and methods of sorting have been advocated by various authors and varying combinations of these may produce different results. Experience in this work has suggested that some methods are consistently "better" than others and these have been used throughout this work. The choice of similarity measure and sorting strategy appears to be dictated, at least partly, by the results, i.e. the best method is the one which gives the "best" results. For these and other reasons, many authors have expressed reservations concerning this method of multivariate analysis. Nonetheless it is a useful technique if used with suitable caution.

Like principal component analysis, cluster analysis can give information concerning the relationship between either samples or the chemical variables which have been measured. Investigation of the variables is called R-mode analysis as the correlation coefficient is used as the similarity measure. In Q-mode analysis the samples are examined and several distance measures can be used. In this work, the Euclidean Distance, which is the modulus of the average algebraic distance between two sample in m-dimensional space, where m is the number of variables, was used as the similarity coefficient. This is calculated as follows:

$$d_{ij} = \frac{\sum_{i}^{m} \sum_{j}^{m} (x_i - x_j)^2}{m}$$

where d_{ij} is the distance between the i-th and j-th objects and x_i and x_j are the values of the m variables taken one at a time. The average value of the distance is used since the absolute distance increases with the number of variables measured (Sneath and Sokal 1973). An (nxn) matrix of similarity coefficients for the n samples is constructed and examined to group the individuals. Several different grouping or "sorting" techniques can be used. In the "weighted group average" method used in this work, the similarity matrix is searched for the value corresponding to the greatest similarity (maximum correlation or minimum distance). After clustering the two individuals, their similarities are replaced in the matrix by that of the cluster relative to the other individuals. These similarities are calculated so as to take account of the number of individuals in the group (cf. Lance and Williams 1967). If samples i, j and k have similarity coefficients d_{ij}, d_{ik} and d_{jk} and if i and j combine to form a group l the similarity d_{lk} is given by:

$$d_{lk} = \frac{n_i}{n_k} d_{ik} + \frac{n_j}{n_k} d_{jk}$$

where $n_k = n_i + n_j$. The process is repeated (n-1) times until all the specimens have been clustered into groups of varying coherency. As more individuals are grouped together, the re-calculated similarity coefficients will become less accurate thereby introducing distortion, the best method being the one with the least distortion (McDonald 1975).

The process of incorporating individuals into already formed groups gives rise to another problem - it can either force individuals into inappropriate groups or it can give rise to spurious groups. The misplaced individuals will be on the periphery of the groups showing that at the level of calculation at which they were added they showed some similarity to the group as a whole but possibly little similarity to any of the individual members of the group.

The results are presented as a "tree-diagram" or dendogram showing the association of individuals into groups. Although the diagram is two dimensional, only the length of the branches has a significance with the origin of the branching giving the magnitude of the similarity coefficient between the individuals or groups. The positioning of the branches along the other axis has limited significance and thus a group of two could be "rotated" through 180° without making the dendogram less accurate. To increase the information conveyed by the dendogram, McCammon (1968) suggested plotting a "dendograph" which placed the "within-group" similarity on the vertical axis and the "between-group" similarity along the horizontal one. Cottle (1976) showed that the proposed method of McCammon and Wenniger (1970) did not produce this result.

The data may be normalized prior to Q-mode analysis but nothing is achieved by normalizing prior to R-mode analysis. For Q-mode analysis, using the Euclidean distance, normalization compresses the samples in m-dimensional space. Sneath and Sokal (1973) suggested that normalization often had little effect on distance coefficients but nevertheless they recommended data normalization. Results obtained in this work suggested that in some cases less distortion was produced if the data was first

normalized but in others more. Kaesler (1970) reported results suggesting the former situation.

Parks (1966), among others, stated that the use of several highly correlated variables could bias the results of Q-mode analysis and suggested that only uncorrelated or least correlated variables be used. Hesp and Rigby (1972) and Hesp (1973) stated that the use of the Euclidean distance required that all the variables be orthogonal. They carried out preliminary R-mode analysis and then chose only one element from each group of elements with correlation coefficients greater than a predetermined value. Rhodes (1969), however, showed that the difference between using all the variables and only some were minimal. Another approach is to use principal component scores since these are orthogonal. Results obtained in this work supported the conclusions of Parks (1966) and Rhodes (1969) that the final pattern using such input data varies little from that from raw data.

Rohlf (1968) suggested that principal component analysis gave a better result than cluster analysis. He had earlier (1967) shown that plots of the first two factors from a method approximating to principal component analysis gave a more satisfactory result. Nevertheless, the technique was considered useful for this work and following the example of Joyce (1973), the complete data set was examined, a modified version of Lance and Williams (1967) being used.

5.6.7 Distortion measures

The production of a dendogram initially involves replacing m variables with one, and so information is lost. Furthermore, in calculating and plotting the dendogram, the value of the similarity measure plotted to represent the first connection for two individuals is the one calculated from the input data, but, on moving away from such initial junctions, successively greater innaccuaracies arise since the junctions represent recalculated similarities. If these apparent similarities, as read from the dendogram, and the true similarities, both expressed as correlation coefficients, are plotted against each other, a strong linear trend will be found for values near 1 and -1 with increasing divergence from linearity away from these points.

As the difference between the true and apparent, or cophenetic, similarities increases the dendogram becomes increasingly distorted in that the relationships portrayed by it become less accurate. Distortion also arises from other factors such as the clustering procedure used and any lack of hierarchical structure in the data (Kaesler 1970). A measure of the overall distortion is given by the cophenetic correlation coefficient of Sokal and Rohlf (1962). This is a product-moment correlation coefficient which compares the corresponding elements of the matrix of true and apparent similarity coefficients. As they are both symmetrical, only half of each matrix is examined. Values run from 1 to -1 and distortion is indicated by non-unit values. Davis (1973) suggested a value of 0.8 or less indicated that the dendogram was misleading while Hesp and Rigby (1972) and Hesp (1973) considered a value of 0.82 to be high and indicative of little distortion.

The cophenetic correlation coefficient is a measure of how much information is lost in the construction of the dendogram and so is somewhat analogous to the eigenvalues of principal component analysis. These indicated the amount of the original variance contained in the eigenvector. For cluster analysis a cophenetic correlation coefficient of 0.8 indicates that 80% of the original information is portrayed by the dendogram but this is an overall average as early linkages are more accurate that later ones. The contention of Kaesler (1970) that less distortion was produced by principal component analysis was examined by calculating an analogous cophenetic correlation coefficient by comparing the matrices of Euclidean distances calculated from the original data and from either the first two or three principal components. Likewise, the transformed scores corresponding to the first canonical variables were compared with the original data. Table 5.5 shows the results obtained from two different data sets:

Table 5.5 : Cophenetic correlation coefficients.

Original Data Compared to	*Cophenetic Correlation Coefficients*	
	Data Set 1	*Data Set 2*
1st 3 Principal Component Scores	*0.9999*	*0.9999*
1st 2 Principal Component Scores	*0.9998*	*0.9997*
1st Canonical Variable Scores	*0.9816*	*0.9891*
Cluster Analysis	*0.8217*	*0.8656*

In each instance, the transformed scores were calculated from raw data. The figures suggest the superiority of principal component analysis but must be treated with caution for, as pointed out by Kendall (1973), the Euclidean distance is invariant under rotation and hence under the

transformation to principal components. The alleged cophenetic correlation coefficient thereby measures little more that the amount of information lost by considering only the first 2 or 3 principal components - information which can be obtained from the eigenvalues.

5.6.8 Application to chondrites and achondrites

The forty three chondrites and achondrites analysed in this work were examined with the techniques described above to establish their basic classifications with the following results.

a. Multiple discriminant analysis

A number of representative analyses of various stony meteorites were chosen from the literature and used to define the groups: achondrite, H, L, E and C chondrites. The meteorites examined in this work were then compared to these groups. As the achondrites stood out quite clearly, they were removed along with the defined achondrite group after the first analysis. The remainder of the samples were then compared with the four other groups and as none of the meteorites being classified showed any affinities for the E-chondrite group it was removed and the process repeated. The analysis clearly divided the specimens being examined into H, L or C groups (Table 5.8).

b. Principal component analysis

A principal component analysis of the analytical results of all the meteorites examined clearly separated the cognate achondrites, Millbillillie No.3, Muckera and Pinnaroo, from the remainder of the data (Figure 5.6). After removing these three meteorites from the data set, the next analysis divided the remaining specimens into two groups, one containing the C and H chondrites and the other the L and LL. The analysis was then repeated using normalized data and it was found that the group which had previously contained the H and C chondrites was split in two with the H chondrites in one group and the C in the other (Figure 5.7).

Examination of the eigenvectors for the whole data set (Table 5.6) shows that the distinction between the achondrites and chondrites is a function of iron, silicon and magnesium content. This is expected as these three elements make up the major part of these meteorites and there are large differences in them between the chondrites and achondrites. In the analysis of the non-normalized chondrite data (Table 5.7), the

Figure 5.6 : First three principal components for all the analysed meteorites. ■ : C chondrites, □ : H chondrites, △ : L chondrites, ▲ : cognate achondrites.

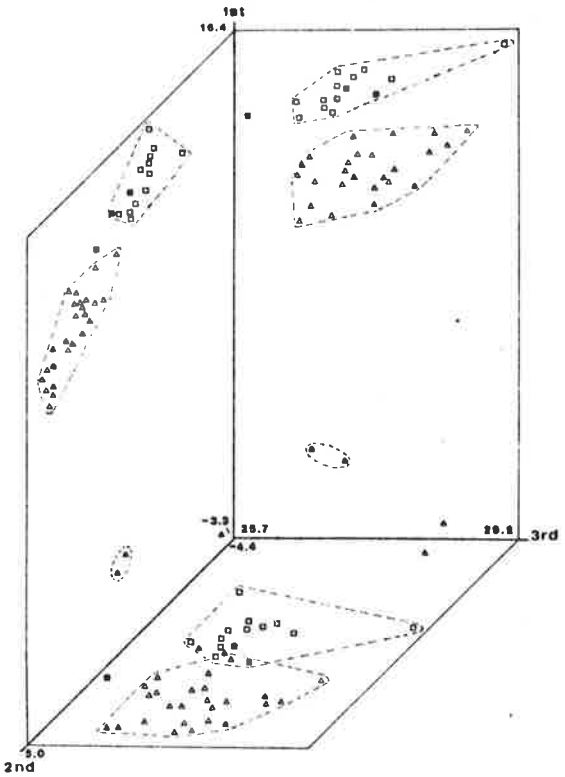


Figure 5.7 : First three principal components for all analysed chondrites, - normalized data. △ : C chondrites, □ : H chondrites, ○ : L chondrites, ◑ : LL chondrites.

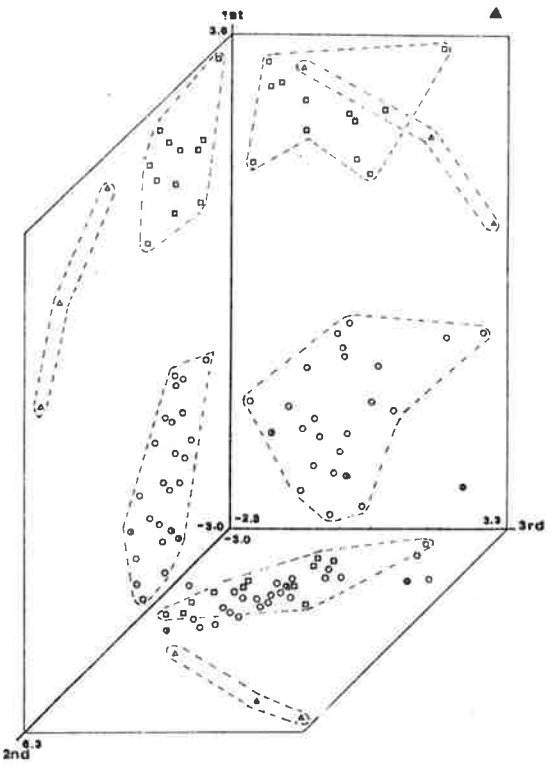


Table 5.6 : Eigenvalues and eigenvectors for all analysed meteorites.

Eigenvalues

Eigenvector	*%age variance*	*Cumulative %age*
1st	*72.6*	*72.6*
2nd	*22.9*	*95.5*
3rd	*2.1*	*97.6*

Eigenvector elements both as absolute values and as percentages of the total variance.

	Non-normalized data					
	1st		*2nd*		*3rd*	
Fe	*0.69*	*34.8*	*-0.52*	*6.3*	*0.41*	*0.3*
Mn	*-0.01*				*0.02*	
Ti	*-0.01*				*0.02*	
Ca	*-0.28*	*5.7*	*-0.22*	*1.2*	*0.36*	*0.3*
K					*0.01*	
P			*-0.01*		*-0.02*	
Si	*-0.46*	*15.5*	*0.13*	*0.4*	*0.55*	*0.6*
Al	*-0.26*	*4.8*	*-0.21*	*1.1*	*0.26*	*0.1*
Mg	*0.38*	*10.4*	*0.76*	*13.3*	*0.24*	*0.1*
Ni	*0.10*	*0.7*	*-0.01*	*0.8*	*-0.01*	
S	*0.10*	*0.7*	*0.18*		*0.52*	*0.6*
Cr			*0.01*			
Na	*0.02*		*0.03*		*0.03*	

first eigenvector is dominated by iron and silicon reflecting the diverse iron contents of the H and C chondrites compared to the L and LL groups along with complementary variations in silicon. The second eigenvector reflects mainly a magnesium variation and, as discussed above, this theoretically separates the H and C chondrites. Overlap precludes the separation of these two groups parallel to this eigenvector.

For the normalized chondrite data (Table 5.7), the first eigenvector again has a significant iron and silicon contribution. Additionally, with all the elements weighted equally, the significance of nickel and magnesium variations becomes apparent. (Nickel and iron fluctuations are, of course, closely correlated.) Several elements contribute to the second

Table 5.7 : Eigenvalues and eigenvectors for all analysed chondrites.

Eigenvalues

	Non-normalized data		*Normalized data*	
Eigenvector	*%age variance*	*Cumulative %age*	*%age variance*	*Cumulative %age*
1st	*83.6*	*83.6*	*32.6*	*32.6*
2nd	*9.0*	*92.6*	*23.8*	*56.4*
3rd	*4.0*	*96.6*	*11.9*	*68.3*

Eigenvector elements both as absolute values and as percentages of the total variance.

	Non-normalized data						*Normalized data*					
	1st		*2nd*		*3rd*		*1st*		*2nd*		*3rd*	
Fe	*0.85*	*60.9*	*0.31*	*0.9*	*0.40*	*0.7*	*0.42*	*5.8*	*-0.02*		*0.07*	*0.1*
Mn	*-0.01*		*-0.01*		*0.04*		*-0.28*	*2.6*	*-0.40*	*3.8*	*-0.04*	
Ti							*-0.07*	*0.2*	*0.39*	*3.7*	*0.14*	*0.2*
Ca	*-0.02*		*0.06*		*0.01*		*-0.17*	*1.0*	*0.31*	*2.3*	*0.45*	*2.4*
K			*-0.01*		*0.03*		*-0.10*	*0.3*	*-0.36*	*3.0*	*0.33*	*1.3*
P					*0.01*		*0.23*	*1.7*	*-0.19*	*0.9*	*0.46*	*2.6*
Si	*-0.41*	*14.1*	*0.01*		*0.88*	*3.1*	*-0.46*	*6.8*	*-0.13*	*0.4*	*0.01*	
Al	*-0.01*		*0.02*		*-0.06*		*-0.06*	*0.1*	*0.42*	*4.2*	*0.46*	*2.5*
Mg	*-0.30*	*7.6*	*0.76*	*5.3*	*-0.04*		*-0.39*	*5.1*	*0.23*	*1.3*	*-0.07*	*0.1*
Ni	*0.08*	*0.5*	*0.04*		*-0.05*		*0.38*	*4.7*	*0.04*		*-0.09*	*0.1*
S	*-0.06*	*0.3*	*0.56*	*2.8*	*-0.17*	*0.1*	*-0.23*	*1.7*	*0.15*	*0.5*	*-0.35*	*1.5*
Cr			*0.01*		*0.02*		*-0.19*	*1.2*	*0.07*	*0.1*	*-0.02*	
Na	*-0.02*		*-0.03*		*0.15*	*0.1*	*-0.21*	*1.4*	*-0.39*	*3.6*	*0.31*	*1.1*

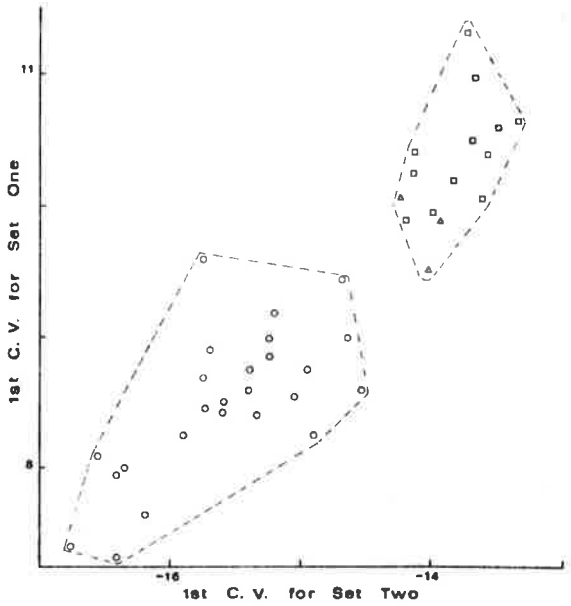


Figure 5.8 : First two canonical variables for all analysed chondrites. △ : C chondrites, □ : H chondrites, ○ : L chondrites.

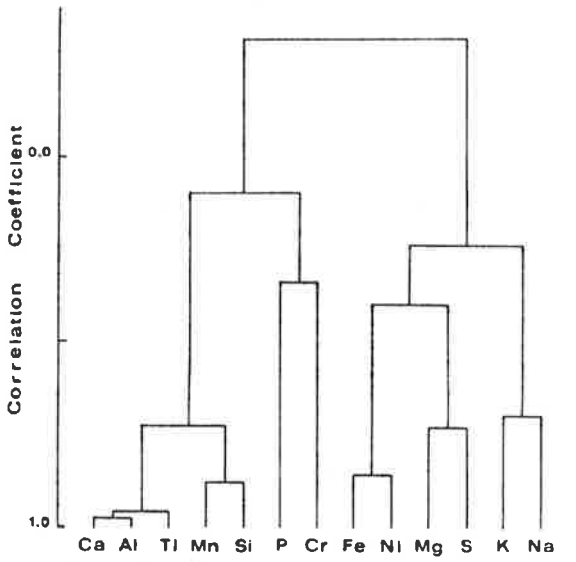


Figure 5.10 : R-mode cluster analysis of all analysed meteorites.

eigenvector which effectively separates the H and C chondrites, the most important being aluminium which was shown above to be the most effective discriminator between the H and C chondrites even on an absolute basis.

c. Canonical correlation analysis

This method also clearly differentiated Millbillillie No.3, Muckera and the silicate fraction of Pinnaroo from the chondritic meteorites. The correlation between the first two canonical variables was 0.97. The elements used for each of the canonical variables were those indicated by the R-mode cluster analyses described below. Removal of the achondrites and repetition of the analysis produced two main groups comprised of the C and H chondrites and the L and LL chondrites (Figure 5.8), the correlation between the first two canonical variables now being 0.92. This reduced correlation is in accord with the lower cophenetic correlation coefficient recorded for the R-mode cluster analysis of the chondrite data set. Thus this process did not distinguish between the C and the H chondrites.

d. Cluster analysis

A cluster analysis of the data set consisting of all the analysed meteorites clearly separated the achondrites from the chondrites (Figure 5.9) with a cophenetic

Figure 5.9 : Q-mode cluster analysis of all analysed meteorites.

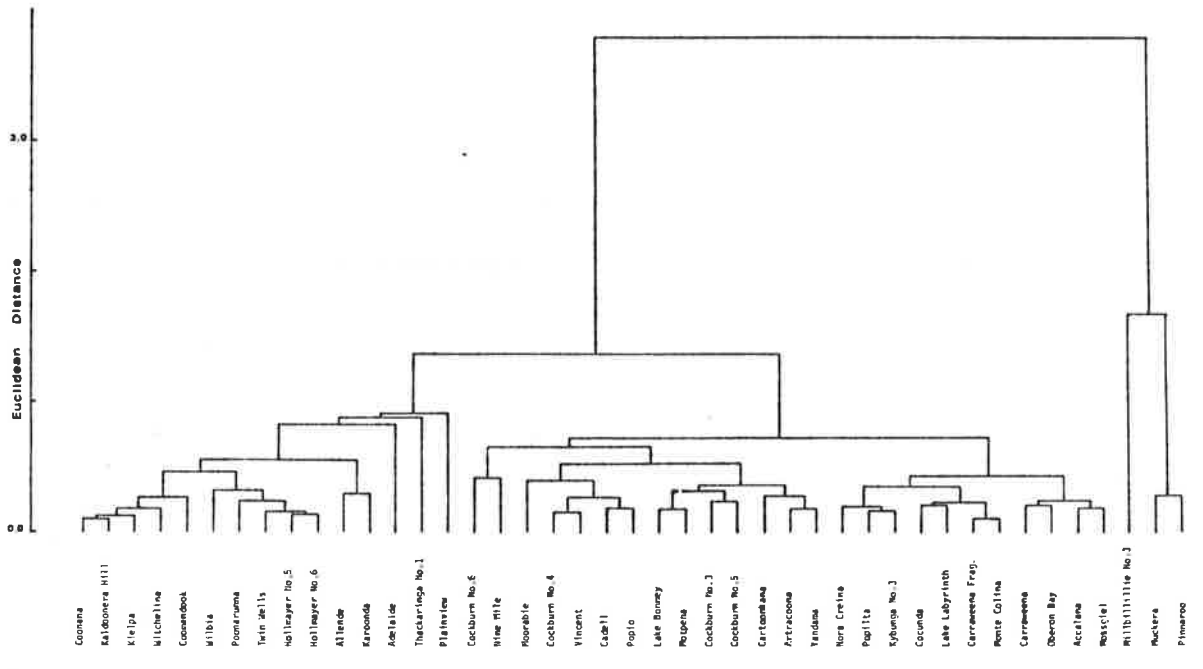
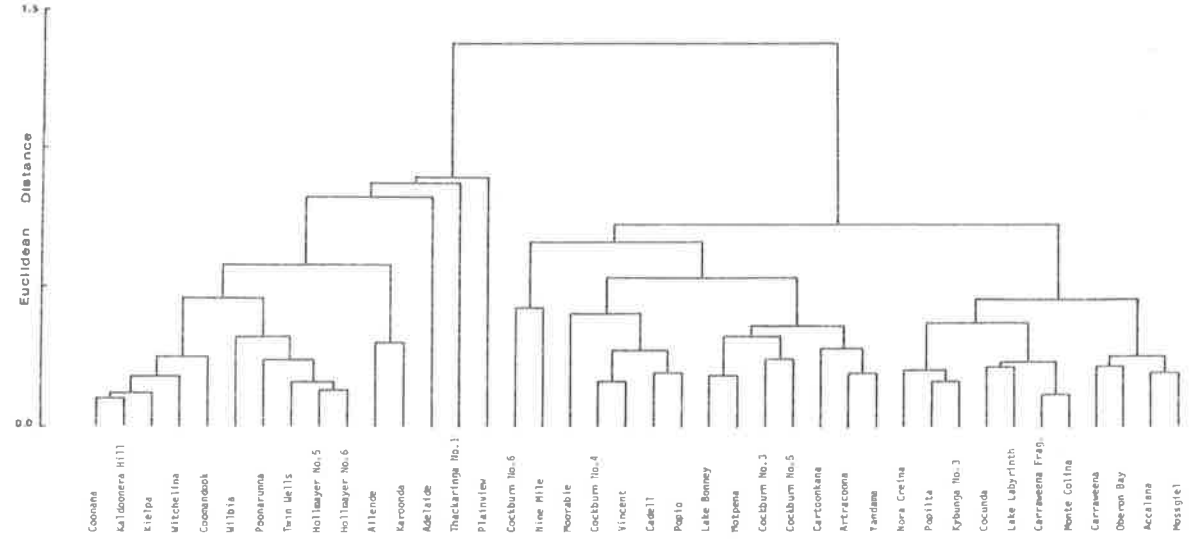


Figure 5.11 : Q-mode cluster analysis of all analysed chondrites.



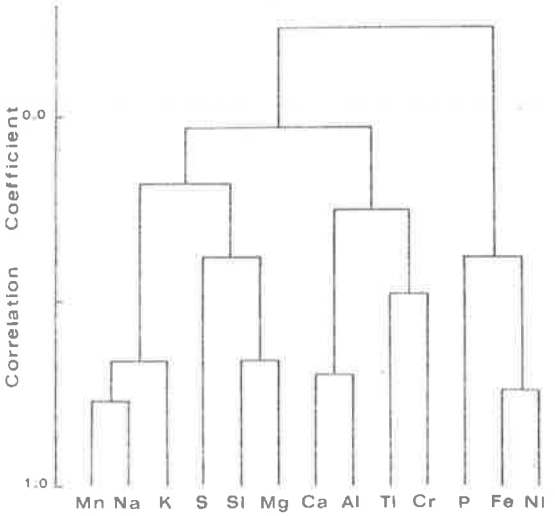


Figure 5.12 : R-mode cluster analysis of all analysed chondrites.

correlation coefficient of 0.94 indicating only minor distortion. An R-mode analysis of the same data (Figure 5.10) split the elements as follows:

1. Ca, Al, Ti, Mn, Si, P, Cr
2. Fe, Ni, Mg, S, K, Na

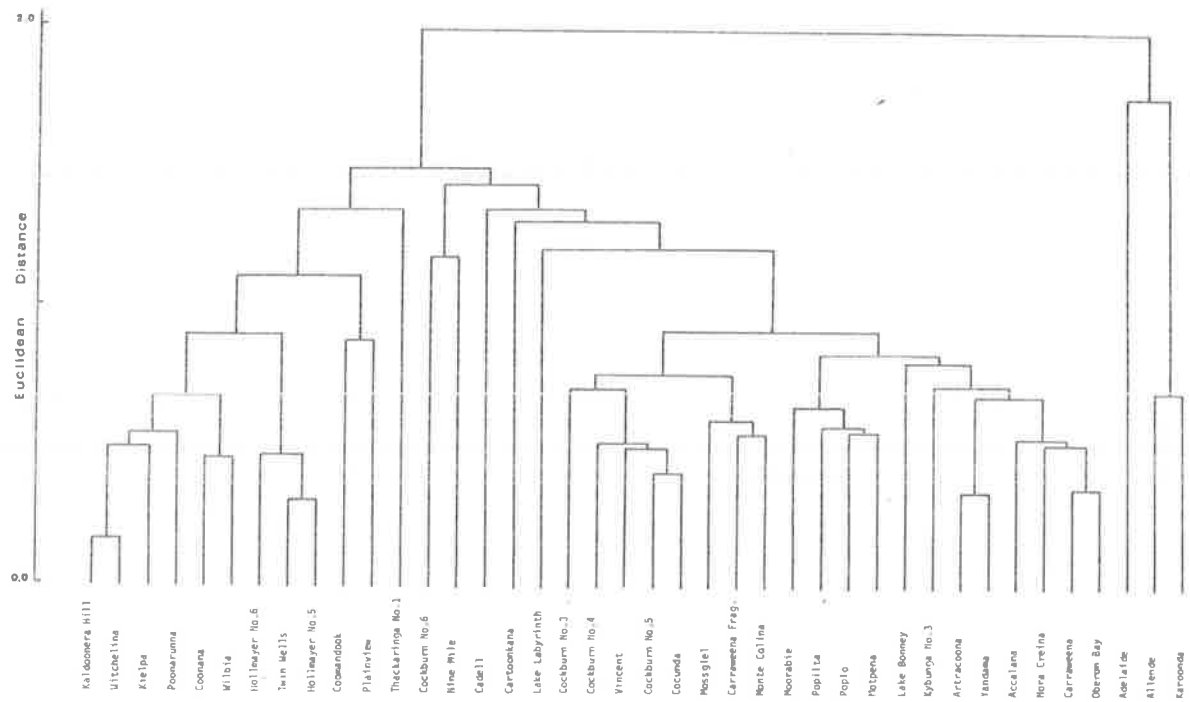
with a cophenetic correlation coefficient of 0.90.

The data set was modified by the removal of the achondrites and the analysis repeated. The cophenetic correlation coefficient for the Q-mode analysis (Figure 5.11) was then 0.80, while that for the R-mode (Figure 5.12) was 0.77. The latter analysis divided the elements as follows:

1. Mn, Na, K, Si, Mg, S, Ca, Al, Ti, Cr
2. Fe, Ni, P

In this instance, the Q-mode analysis divided the samples into two main groups,

Figure 5.13 : Q-mode cluster analysis of all analysed chondrites - normalized data.



one containing the L and LL chondrites and the other the H and C chondrites. When this data set was normalized prior to the analysis, the Q-mode analysis separated the meteorites into three groups - the L and LL, the H and the C chondrites - with a cophenetic correlation coefficient of 0.88 (Figure 5.13).

e. Summary

The overall conclusion is that all four techniques can effectively distinguish between the achondrites and the chondrites as well as between the high total iron and low total iron chondrites. Furthermore, the discriminant analysis distinguished the carbonaceous from the H chondrites as did the principal component and cluster analysis when the data was first normalized. In general, inter-group relationships are best displayed by principal component analysis and intra-group ones by cluster analysis.

It ought to be stressed again that the raison d'etre of these multivariate techniques is the elucidation of trends which are difficult to perceive because of the multiplicity of data and that consequently, if any of the relationships suggested by these methods cannot be substantiated by subsequent examination, in one way or another, of the original data, then the relationships need to be treated with great caution.

5.7 CONCLUSION

Table 5.8 summarizes the classifications given to the meteorites studied in this work on the basis of the methods described in this chapter. Meteorites marked with an asterisk were either previously unclassified or the previous classification has been altered.

Table 5.8 : Summary of classifications.

Section	5.2	5.3	5.4	5.5	5.6.8 a	5.6.8 b	5.6.8 c	5.6.8 d
Technique	Differentiated/ Undifferentiated	Absolute Abundances	Relative Abundances	Extended Definition	Discriminant Analysis**	Principal Component Analysis**	Cluster Analysis**	Canonical Correlation Analysis**
ACCALANA	U	LL	LL	LL	L	L	L	L
ADELAIDE	U	C	C	C	C	C	C	H
ARTRACOONA	U	L,LL	L	L	L	L	L	L
CADELL	U	L,LL	L	L	L	L	L	L
CARRAWEENA	U	LL	LL	LL	L	L	L	L
CARRAWEENA FRAGMENT	U	LL	LL	LL	L	L	L	L
CARTOOONKANA	U	L,LL	L	L	L	L	L	L
*COCKBURN No.3	U	L,LL	L	L	L	L	L	L
*COCKBURN No.4	U	L,LL	L	L	L	L	L	L
*COCKBURN No.5	U	L,LL	L	L	L	L	L	L
COCKBURN No.6	U	L,LL	L	L	L	L	L	L
COCUNDA	U	L,LL	L	L	L	L	L	L
COOMANDOOK No.1	U	H	H	H	H	H	H	H
COONANA	U	H	H	H	H	H	H	H
COWELL	D	IRON	IRON					
HENBURY	D	IRON	IRON					
*HOLLMAYER No.5	U	H	H	H	H	H	H	H
*HOLLMAYER No.6	U	H	H	H	H	H	H	H
KALDOONERA HILL	U	H	H	H	H	H	H	H
*KAPUNDA	D	IRON	IRON					
KAROONDA	U	C	C	C	C	C	C	H
KIELPA	U	H	H	H	H	H	H	H
KYANCUTTA	D	IRON	IRON					
KYBUNGA No.3	U	L,LL	L	L	L	L	L	L
LAKE BONNEY	U	L,LL	L	L	L	L	L	L
LAKE LABYRINTH	U	LL	LL	LL	L	L	L	L
MONTE COLINA	U	LL	LL	LL	L	L	L	L
*MOORABIE	U	L	L	L	L	L	L	L
MOTPENA	U	L,LL	L	L	L	L	L	L
MOUNT SIR CHARLES	D	IRON	IRON					
*MUCKERA	D	HOW	HOW		ACH	ACH	ACH	ACH
*NINE MILE (H03)	U	L,LL	L	L	L	L	L	L
NORA CREINA	U	LL	L	L	L	L	L	L
PINNAROO	D	MESO	MESO		ACH	ACH	ACH	ACH
*POONARUNNA	U	H	H	H	H	H	H	H
*POPILTA (H04)	U	L,LL	L	L	L	L	L	L
*POPIO (H01)	U	L,LL	L	L	L	L	L	L
*"S.A. BETA"	D	IRON	IRON					
*THACKARINGA No.1	U	H	H	H	L	H	H	H
*TWIN WELLS (H02)	U	H	H	H	H	H	H	H
VINCENT	U	L,LL	L	L	L	L	L	L
WILBIA	U	E	H	H	H	H	H	H
WITCHELINA	U	H	H	H	H	H	H	H
YANDAMA	U	L,LL	L	L	L	L	L	L
YARDEA	D	IRON	IRON					

** Note that in these methods no distinction could be made between the L- and LL-groups.

ACH = Achondrite HOW - Howardite MESO - Mesosiderite

Chapter 6

THE ORDINARY CHONDRITES

6.1 DEFINITION AND SUBDIVISIONS OF THE ORDINARY CHONDRITES

The term "ordinary chondrite" encompasses the H, L and LL chondrites of Van Schmus and Wood (1967) and others. No subdivisions other than the petrologic ones of Van Schmus and Wood are currently used for these meteorites. The unequilibrated ordinary chondrites, defined by Dodd et al (1967) as ordinary chondrites containing heterogeneous silicates, are not contained within a single petrologic subdivision but overlap both types 3 and 4 which themselves contain equilibrated examples.

The stony meteorites studied in this work were separated in Chapter 5 into one of the groups ordinary chondrite, carbonaceous chondrite or achondrite. This chapter involves a closer examination of the 34 meteorites classified as ordinary chondrites.

6.2 CLASSIFICATION BASED ON BULK CHEMISTRY

6.2.1 Absolute and relative elemental abundances

Distinctions other than those made in Chapter 5 cannot be made on the basis of either absolute or relative chemistry. Table 6.1 gives values of the elemental ratios used in Section 5.5 to define the ordinary chondrites. Classifications arising from these ratios were summarized in Section 5.7.

6.2.2 Multivariate techniques

a. Multiple discriminant analysis

An attempt to subdivide the ordinary chondrites into H, L and LL groups produced some possibly erratic results suggesting that the similarity between the L and LL groups is such that the distinction between them is beyond the limits of the method of discriminant analysis, probably as a result of the analyses used to define these two groups (Table 6.4).

b. Principal component analysis

A principal component analysis of the ordinary chondrite data readily split it into two groups. Prior normalization of the data produced a better separation of these groups. Thackaringa No.1 and Plainview (1917), both somewhat anomalous prior to data normalization, now closely resembled the other H chondrites. (This deviation was probably produced by apparently anomalous iron and magnesium values respectively for these two meteorites.) Figure 6.1, a plot of the first three principal components for the normalized data, shows that these groupings are real. The diagram shows that principal component analysis cannot adequately distinguish between the L and LL chondrites, however, it is significant that all the chondrites classified as LL chondrites on the basis of relative elemental abundances (Table 5.8), plus the two LL chondrites Mossgiel and Oberon Bay, lie in the region of the L field furthest from the H group.

The eigenvectors for the non-normalized data (Table 6.2) show the importance of iron, silicon and magnesium in distinguishing the ordinary chondrites,

Figure 6.1 : First three principal components for the ordinary chondrites - normalized data. □ : H chondrites, ○ : L chondrites, ◑ : LL chondrites.

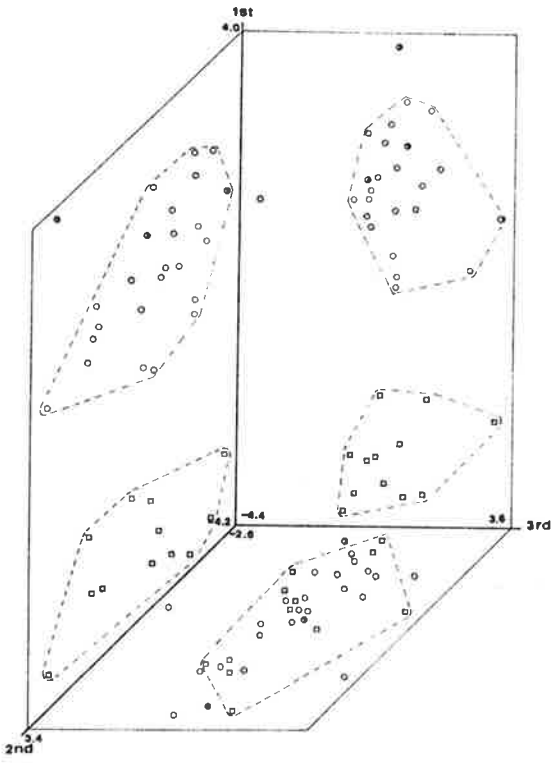


Table 6.1 : Atomic ratios for the analysed chondrites.

	Ca/Mg	Fe/(Fe+Mg)	Al/Si	Ca/Si	Fe/Si	Ca/Al
Accalana	5.2	34	6.4	4.8	48	0.74
Artracoona	5.1	39	6.3	4.7	57	0.74
Cadell	4.7	38	6.1	4.6	58	0.75
Carraweena	5.3	35	6.5	4.9	49	0.75
Carraweena Fragment	4.8	34	6.8	4.8	52	0.71
Cartooonkana	4.9	38	6.2	4.4	55	0.72
Cockburn No.3	4.8	38	6.6	4.7	59	0.71
Cockburn No.4	4.7	37	6.7	4.8	60	0.72
Cockburn No.5	4.9	37	6.7	4.7	58	0.70
Cockburn No.6	5.3	41	7.4	4.9	64	0.66
Cocunda	5.0	35	6.6	4.9	54	0.74
Coomandook No.1	5.0	44	7.6	4.8	76	0.64
Coonana	4.6	45	7.1	4.5	79	0.64
Hollmayer No.5	4.8	44	6.7	4.4	71	0.66
Hollmayer No.6	5.2	43	6.6	4.9	70	0.73
Kaldoonera Hill	5.1	45	6.5	4.9	78	0.75
Kielpa	5.0	45	6.5	4.9	79	0.75
Kybunga No.3	5.3	37	6.6	4.8	54	0.73
Lake Bonney	5.4	39	6.3	5.0	58	0.79
Lake Labyrinth	5.3	35	7.6	5.1	51	0.67
Monte Colina	4.8	34	6.9	4.7	51	0.69
Moorabie	5.3	40	6.6	4.9	62	0.75
Motpena	5.8	39	6.7	5.6	60	0.82
Nine Mile (H03)	5.4	40	6.8	4.7	58	0.69
Nora Creina	5.2	37	6.4	4.8	54	0.75
Poonarunna	5.0	45	6.6	4.6	73	0.69
Popilta (H04)	4.9	37	6.6	4.6	54	0.69
Popio (H01)	5.2	38	6.9	4.9	58	0.72
Thackaringa No.1	5.9	49	6.8	4.7	76	0.69
Twin Wells (H02)	4.7	43	6.8	4.3	70	0.64
Vincent	4.8	37	6.6	4.9	61	0.74
Wilbia	4.1	42	6.8	4.1	71	0.61
Witchellina	5.2	45	6.4	4.9	76	0.76
Yandama	5.5	39	6.3	5.0	59	0.80

while in those for the normalized data, calcium, aluminium and nickel assume an importance.

c. Canonical correlation analysis

Using the two variable sets suggested by an R-mode cluster analysis, the chondrites were clearly separated into two groups (Figure 6.2), with a correlation between the first two canonical variables of 0.94. Lake Labyrinth is not separated from the L chondrites but Plainview (1917) and Moorabie lie somewhat away from their respective groups.

d. Cluster analysis

An R-mode cluster analysis of the ordinary chondrites divided the elements into two groups viz.

1. Fe, Ni, P
2. Ca, Si, Mg, Al, K, Mn, Na, Ti, Cr, S

with a cophenetic correlation coefficient of 0.82. Figure 6.3 shows that the larger group can be split into three smaller ones, namely,

a. Ca, Si, Mg, Al
b. K, Mn, Na
c. Ti, Cr, S

Using Goldschmidt's classification of the elements, it can be seen that the four groups (1;a;b;c) comprise the siderophile elements, the refractory lithophile elements, the volatile lithophile ones, and a group containing two refractory lithophile and a volatile chalcophile element. Phosphorus, however, even though it is described as siderophilic, is mainly present in the chondrites as phosphates (Moore 1971b). Iron, nickel and the refractory lithophile group are generally present in the ordinary chondrites in major amounts, while the others are usually present only in minor amounts.

A Q-mode analysis (Figure 6.4) divided the ordinary chondrites into two groups containing the H and L plus LL chondrites

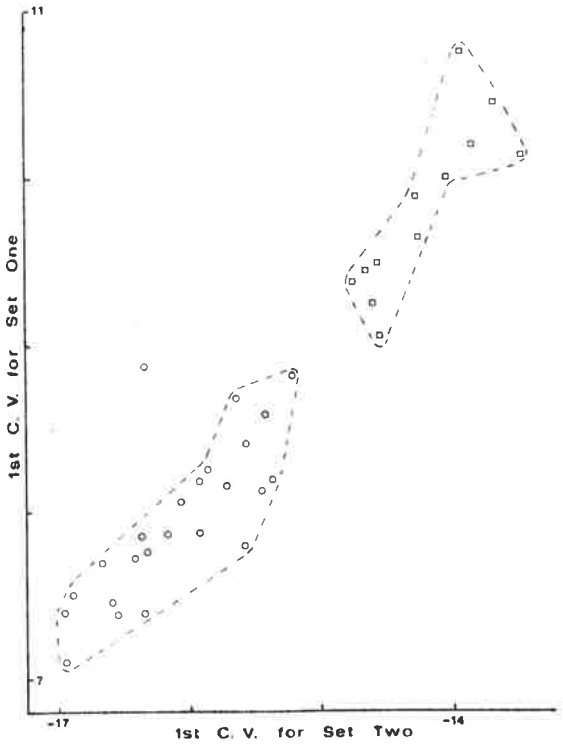


Figure 6.2 : First two canonical variables for the ordinary chondrites. □ : H chondrites, ○ : L chondrites.

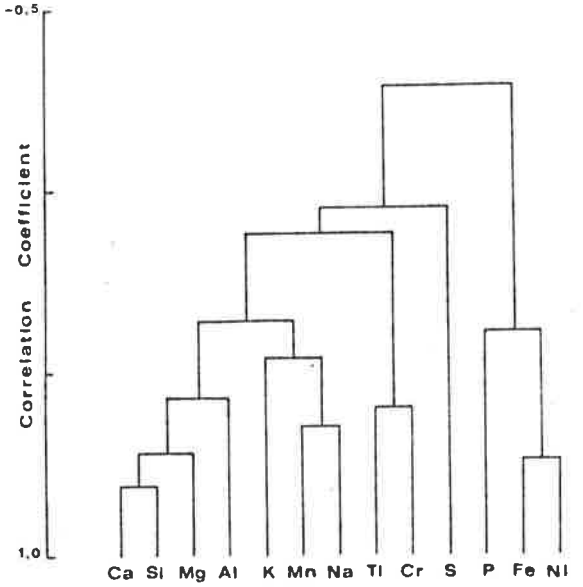


Figure 6.3 : R-mode cluster analysis of the ordinary chondrites.

with a cophenetic correlation coefficient of 0.82. The value of the similarity coefficient at which they were associated was considerably smaller than any other association within the groups indicating their diversity.

Figure 6.4 shows the H chondrites are a cohesive group except for Plainview (1917) and Thackaringa No.1, which again appear somewhat different. The L and LL chondrites are divided into two large groups, one containing Artracoona, Cartoonkana and Yandama, while Monte Colina and the Carraweena fragment, which can be seen to be very similar to each other, are closely associated with Accalana and Carraweena in the second group. Reference is made later to these associations. In fact, this second group contains all of the chondrites classified, on the basis of relative elemental abundances, as LL chondrites in Table 5.8 as well as the LL chodrites Mossgiel and Oberon Bay. Moorabie, while clearly being a member of the L group, did not show sufficient similarity to any other specimen to form one of the initial pairs. Cockburn No.6 and Nine Mile, both with very low sulfur contents, were separated from the other L chondrites.

Figure 6.4 : Q-mode cluster analysis of all analysed ordinary chondrites.

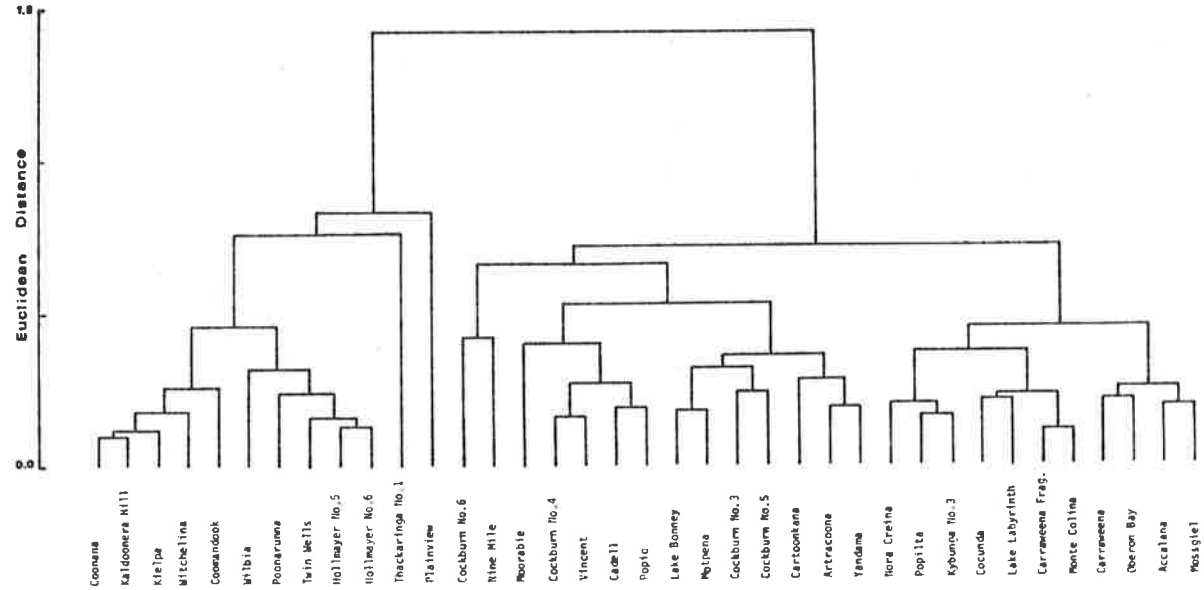


Table 6.2 : Eigenvalues and eigenvectors for the ordinary chondrites.

Eigenvalues

	Non-normalized data		*Normalized data*	
Eigenvector	*%age variance*	*Cumulative %age*	*%age variance*	*Cumulative %age*
1st	*87.1*	*87.1*	*41.1*	*41.1*
2nd	*8.6*	*95.7*	*19.7*	*60.7*
3rd	*2.7*	*98.8*	*12.2*	*72.9*

Eigenvector elements both as absolute values and as percentages of the total variance

	Non-normalized data						*Normalized data*					
	1st		*2nd*		*3rd*		*1st*		*2nd*		*3rd*	
Fe	*0.85*	*62.8*	*0.43*	*1.6*	*-0.28*	*0.2*	*-0.37*	*5.7*	*0.09*	*0.2*	*0.09*	*0.1*
Mn	*-0.01*						*0.27*	*3.0*	*0.28*	*1.6*	*-0.24*	*0.7*
Ti							*0.11*	*0.5*	*-0.31*	*1.9*	*0.57*	*4.0*
Ca	*-0.03*	*0.1*	*0.04*		*-0.06*		*0.37*	*5.6*	*0.14*	*0.4*	*-0.01*	
K					*-0.02*		*0.04*	*0.1*	*0.37*	*2.8*	*0.44*	*2.4*
P			*-0.01*		*-0.02*		*-0.14*	*0.8*	*0.51*	*5.1*	*0.05*	
Si	*-0.39*	*13.2*	*0.19*	*0.3*	*-0.68*		*0.42*	*7.1*	*0.03*		*-0.07*	*0.1*
Al	*-0.02*		*0.03*		*-0.09*	*1.2*	*0.33*	*4.5*	*0.14*	*0.4*	*0.18*	*0.4*
Mg	*-0.34*	*9.8*	*0.76*	*5.0*	*-0.04*		*0.38*	*5.9*	*-0.19*	*0.7*	*-0.07*	*0.1*
Ni	*0.08*	*0.5*	*0.06*		*0.16*		*-0.33*	*4.5*	*-0.04*		*0.09*	*0.1*
S	*-0.08*	*0.6*	*0.43*	*1.6*	*0.64*	*1.1*	*0.19*	*1.4*	*-0.27*	*1.4*	*-0.23*	*0.6*
Cr			*0.01*				*0.13*	*0.7*	*-0.25*	*1.2*	*0.52*	*3.4*
Na	*-0.01*				*-0.1*		*0.17*	*1.2*	*0.45*	*4.1*	*0.19*	*0.4*

6.3 CLASSIFICATION BASED ON MINERALOGICAL CRITERIA

6.3.1 Olivine and pyroxene composition

Many authors have discussed the use of olivine and pyroxene compositions to classify the chondrites. Table 6.3 list some of the proposed ranges.

Mineral compositions measured in this work, Table 4.5, were used for classification purposes and the results are summarized in Table 6.12. The statistic CV, the Coefficient of Variation, was defined in Section 4.2.5 a as a measure of olivine and pyroxene equilibration and values are given for some meteorites in Table 4.5 also. Some comments follow on these results:

Barratta : Dodd et al (1967) described this as an unequilibrated ordinary chondrite on the basis of the large variation in its olivine and pyroxene composition. Results obtained here support this assignment and act as a check on the CV parameter.

Carraweena : The inhomogeneity of this meteorite as expressed by the CV for both its olivine and pyroxene compositions is also in accord with that reported by Dodd et al showing Carraweena definitely contains unequilibrated silicates. Further comment is made later.

Cockburn Nos.1, 2, and 5 and Silverton : Both the silicate composition and CV results are similar for all of these specimens but they may not be identical meteorites. This also is discussed later.

Hollmayer Nos.5 and 6, Nine Mile, Popilta, Popio and Twin Wells : These are grouped here for convenience. With the possible exception of Twin Wells they all appear to be well equilibrated.

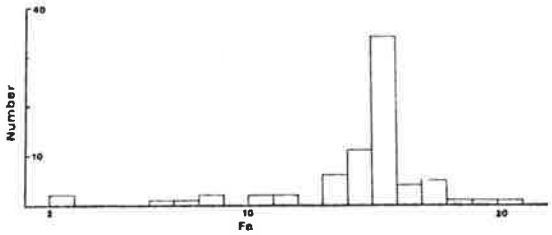
Moorabie : The results of Table 4.5, plus those of Figure 6.5, unambiguously point to a lack of silicate equilibrium and thus they suggest that Moorabie belongs to petrologic type 3 or 4.

Poonarunna : The results suggest that Poonarunna is not completely equilibrated and so it may belong to petrologic type 4 or 5.

Table 6.3 : The classification of the ordinary chondrites on the basis of olivine compositions.

Meteorite Group	*Olivine composition (mole % Fa)*		*Pyroxene composition (mole % Fs)*	
	Wasson (1974)	*Buchwald (1975b)*	*Mason (1962b)*	*Mason and Wiik (1964)*
H	*16-19*	*16-20*	*14-20*	
L	*21-25*	*22-26*	*20-30*	
LL	*27-32*	*27-32*		*23-27*
C3,C4		*32-40*		

Figure 6.5 : Histogram of Moorabie olivine analyses.



6.3.2 Distribution coefficients

a. Olivine-orthopyroxene

The distribution of iron and magnesium between co-existing olivine and pyroxene can be described by the following:

$$Mg_2SiO_4 + 2FeSiO_3 = Fe_2SiO_4 + 2MgSiO_3$$

Assuming both mineral species are ideal solutions then the distribution constant, K_d, can be expressed by the relationship:

$$K_d = \frac{(X_{Fe}^{Ol})\ (X_{Mg}^{Opx})^2}{(X_{Mg}^{Ol})\ (X_{Fe}^{Opx})^2}$$

where the X's are mole fractions of the elements in the appropriate mineral. Using conventional notation this can be rewritten as:

$$K_d = \frac{(Fa)(En)^2}{(Fo)(Fs)^2}$$

Van Schmus and Koffman (1967) among others, evaluated this expression without squaring any of the terms. Ramberg and De Vore (1951) justified this approach by writing the olivine molecules as $MgSi_{1/2}O_2$ etc. Kern and Weisbrod (1967) stated that either method was a priori justified but that only the calculation involving the squared terms was petrologically based.

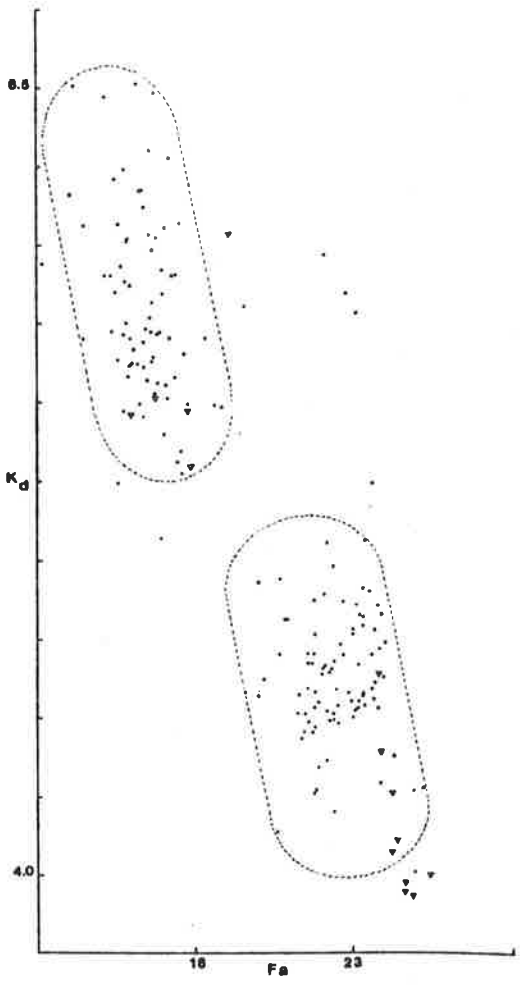
Van Schmus and Koffman showed that the values of their K_d's were a function of the group to which the meteorites belonged and accordingly concluded that these distribution coefficients could not be used to give an accurate indication of the equilibration temperature experienced by the mineral assemblage. The calculation can be used for classification purposes and accordingly the data of Keil and Fredriksson (1964) and Mason (1974) were used to calculate some 170 distribution coefficients by both methods. These were plotted against olivine compositions (Figures 6.6.and 6.7) to define H and L chondrite fields. The expression involving the squared terms produced a better separation. A consistent displacement between the two sets of data was observed with Mason's data plotting to the right of that of Keil and Fredriksson. The distribution coefficients were also calculated by both methods for several meteorites examined in this work and the results are given in Table 6.4. These are also plotted in Figures 6.6 and 6.7 and the resulting classifications listed in Table 6.12.

The distribution coefficient, using the

Table 6.4 : Distribution coefficients.

	$K_d = \frac{Fa.En^2}{Fo.Fs^2}$	$K_d = \frac{Fa.En}{Fo.Fs}$
BARATTA	*10.6*	*1.82*
CARRAWEENA	*4.55*	*1.24*
COCKBURN No.1	*3.91*	*1.18*
COCKBURN No.2	*3.95*	*1.19*
COCKBURN No.5	*3.80*	*1.17*
HOLLMAYER No.5	*5.35*	*1.15*
HOLLMAYER No.6	*5.31*	*1.08*
MOORABIE	*9.1*	*1.30*
MOTPENA	*4.23*	*1.22*
MT. BROWNE	*5.35*	*1.11*
NINE MILE (H03)	*3.80*	*1.18*
POONARUNNA	*5.11*	*1.13*
POPILTA (H04)	*3.81*	*1.15*
POPIO (H01)	*4.10*	*1.21*
SILVERTON	*4.45*	*1.24*
TWIN WELLS (H02)	*5.88*	*1.25*

Figure 6.6 : K_d vs Fa for the ordinary chondrites. ●: literature values, ▽: this work.



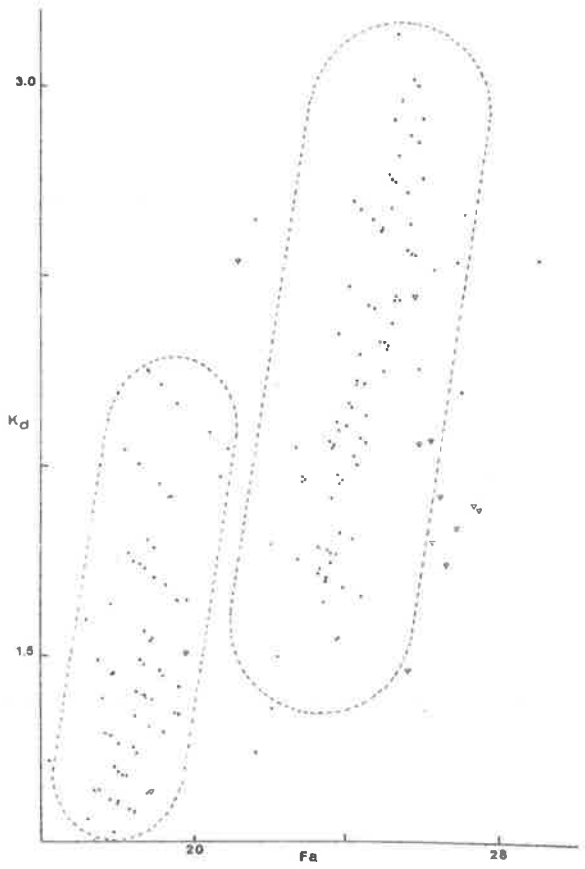


Figure 6.7 : K_d vs Fa for the ordinary chondrites.
●: literature values, ▽ : this work.

"squared method", was high for Barratta as was that for Bishunpur and Krymka using the data of Dodd et al (1967). These values, (10.6, 9.6 and 8.6), are of the same order of magnitude as that of Moorabie (8.3). Conversely, Carraweena, also an unequilibrated L chondrite, showed a more "normal" value of 4.6. It may be that large values of K_d obtained by this calculation are indicative of non-equilibrium whereas both equilibrated and unequilibrated meteorites may have low K_d's.

b. Orthopyroxene-clinopyroxene

Due to the lack of sufficient clinopyroxene data, orthopyroxene-clinopyroxene distribution coefficients could not be calculated.

6.4 PETROGRAPHIC CLASSIFICATION

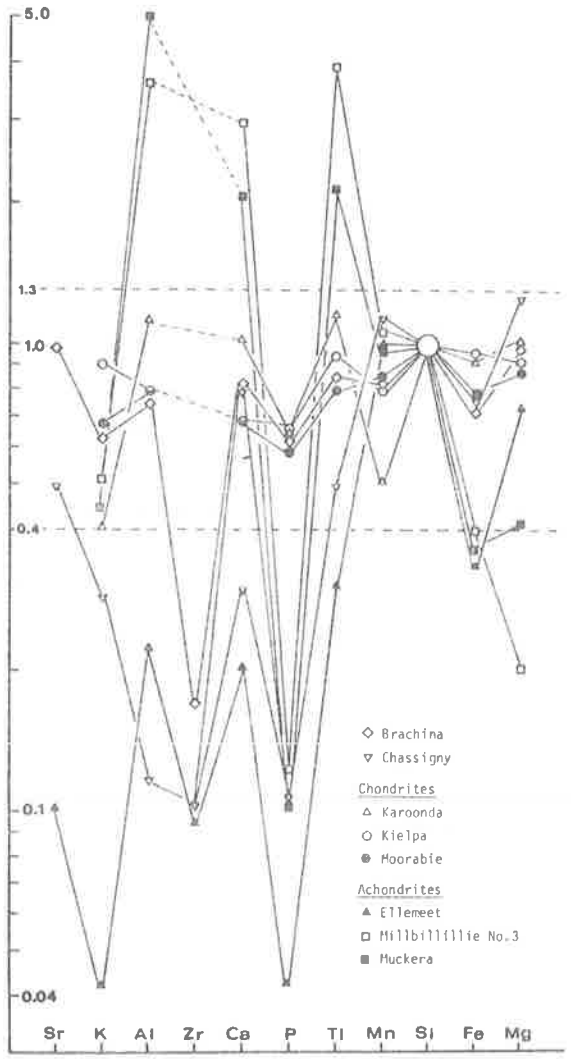
As mentioned in the introduction to this chapter, the only currently used subdivisions of the ordinary chondrites are the petrologic ones of Van Schmus and Wood (1967). Thirteen of the ordinary chondrites examined in this work had not been previously classified according to the criteria proposed by these authors and the petrologic classification for these meteorites is given in Table 6.12. Bulk analyses were not available for three meteorites from the Cockburn area because of their small sizes. Electron microprobe data was obtained for Cockburn Nos. 1 and 2 but only semi-quantitative S.E.M. data could be obtained for Thackinga No. 1. It has been classified on this basis. Petrologic classifications are given for all three in Table 6.12.

6.5 SPECIFIC ORDINARY CHONDRITES

6.5.1 Brachina

The differentiated and undifferentiated meteorites were distinguished in Section 5.2. On the basis of the analytical results of Johnson et al (1977), it appears that Brachina should be classified as undifferentiated. Figure 6.8 shows the close resemblance between the relative elemental composition of Moorabie which is unequilibrated and hence more nearly similar to primary chondritic material (Dodd et al 1967) and Brachina. Brachina is possibly a non chondritic chondrite.

Figure 6.8 : "Differentiation diagram" for selected meteorites.



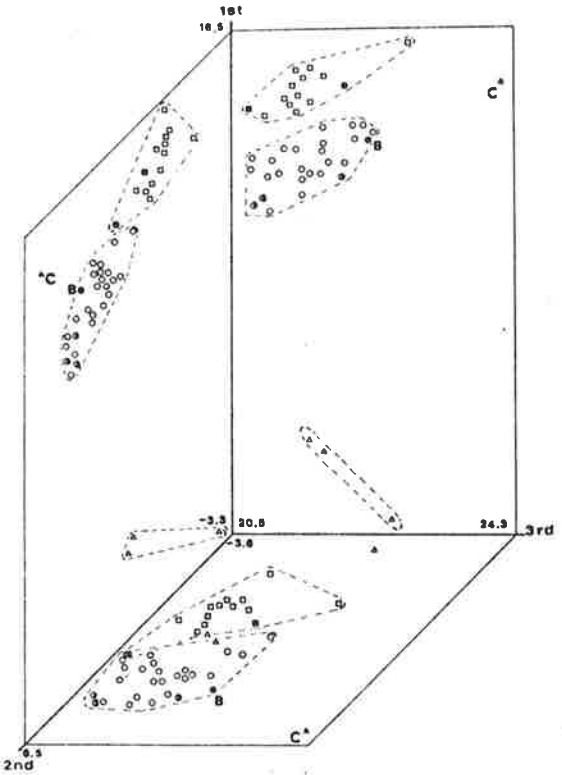


Figure 6.9 : First three principal components for all analysed meteorites, Brachina and Chassigny. ■: C chondrites, □: H chondrites, ○: L chondrites, ◑: LL chondrites, △ : cognate achondrites, B : Brachina, C : Chassigny.

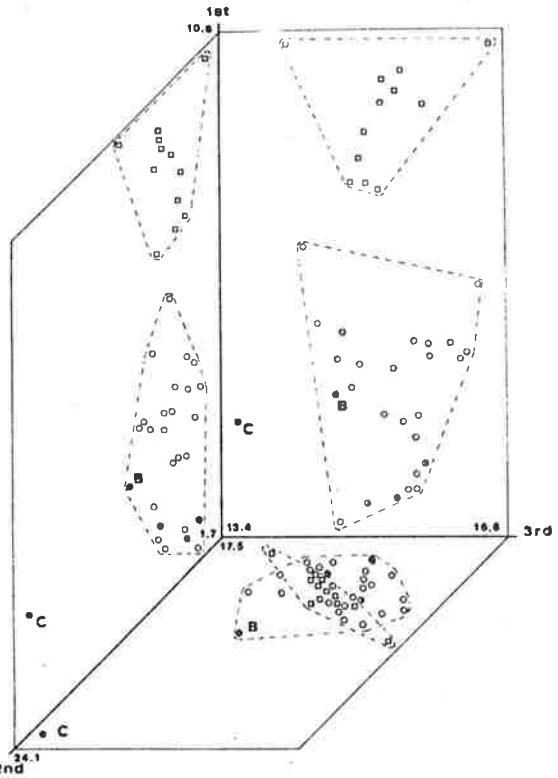
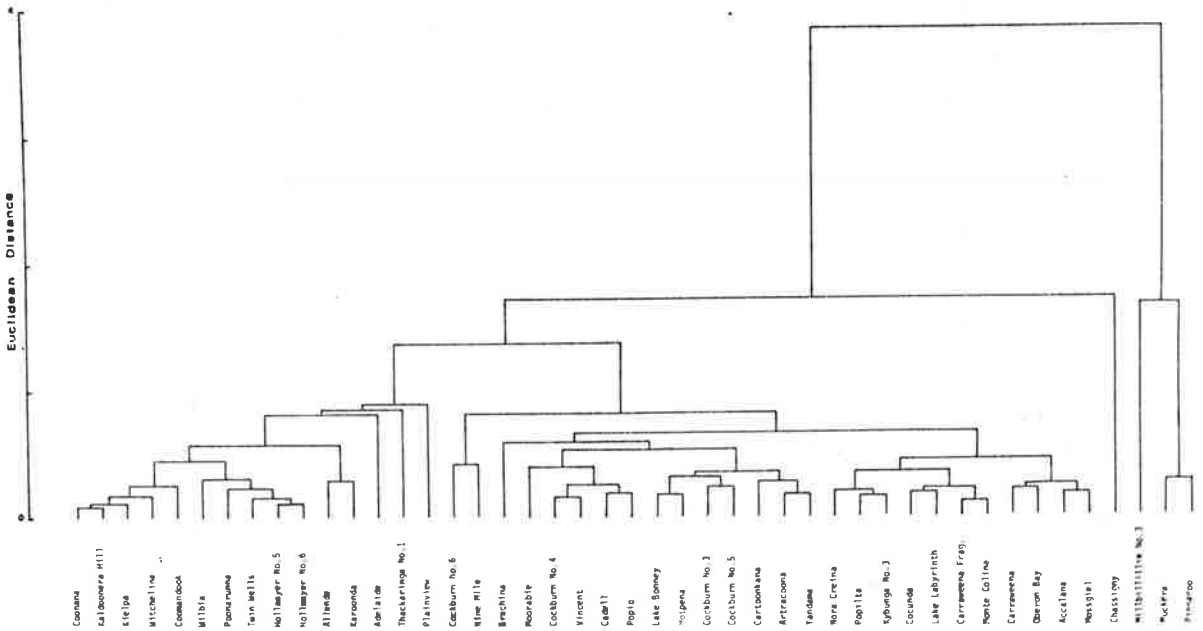


Figure 6.11 : First three principal components for all analysed ordinary chondrites, Brachina and Chassigny. □ : H chondrites, ○ : L chondrites, ◑ : LL chondrites, B : Brachina, C : Chassigny.

On the basis of both its absolute and relative abundances, it fits into either the L or LL chondrite group. Its olivine composition of Fa_{33} suggests an LL classification but this composition is also consistent with a C3 classification. The virtual lack of free metal and the preponderance of olivine in the ferromagnesian silicates is also reminiscent of a carbonaceous chondrite. The REE pattern described by Johnson et al is quite similar to that of Allende figured by Tanaka and Masuda (1973).

A principal component analysis of a data set comprising all the stony meteorites analysed in this work, plus Brachina and Chassigny (Figure 6.9), clearly associated Brachina with the chondritic material while Chassigny was not related to any other

Figure 6.10 : Q-mode cluster analyis of all analysed meteorites, Brachina and Chassigny.



single or group of meteorites. A cluster analysis of the same data set (Figure 6.10), with a cophenetic correlation coefficient of 0.94, gave a similar result and like the principal component analysis it suggested a similarity between Brachina and the low iron chondrites. Principal component analysis of the ordinary chondrites analysed in this work, and Brachina and Chassigny, likewise suggested a fairly close relationship between Brachina and the low-iron chondrites, while Chassigny stood apart from all of them (Figure 6.11). In a similar manner principal component analysis of a data set comprised of Brachina, Chassigny and thirty four carbonaceous chondrites showed that both were distinct from the carbonaceous chondrites.

Thus the multivariate techniques suggested a closer affinity between Brachina and the low iron chondrites than between it and the carbonaceous chondrites. This takes into account, among other things, the low aluminium content of Brachina which precludes it classification as a carbonaceous chondrite on absolute chemical grounds. This, then, is another example of an apparently undifferentiated meteorite which has an atomic Mg/Si ratio greater than 1 but which ought not to be classified as a carbonaceous chondrite.

Mason and Wiik (1964) described the LL chondrites and commented that some of them were almost chondrule-less and some were brecciated. The mineralogical composition of the LL chondrites as described by them is also very similar to Brachina except that it contains even more olivine and less pyroxene than do the LL chondrites. Mason and Wiik commented that "the amphoterites were characterized by olivine around Fa_{29} and frequently the scarcity of chondrules and prominent brecciation". They also commented on structures resulting from a combination of recrystallization, brecciation and crushing. Brachina may represent an extreme example of an LL chondrite in which the recrystallization process reached a maximum so that minimum evidence of crushing or brecciation remains.

Johnson et al (1977) suggested the possiblity of a relationship between the chondrites and Brachina but commented that if this were the case, then some chemical fractionation must have occured to give rise to the observed REE pattern. In the light of the observations on Allende reported by Tanaka and Masuda (1973), this REE pattern may not require this fractionation. On the other hand Schmitt and Smith (1963b) reported a similar distribution pattern for a specimen of Kilauea basalt which is manifestly a specimen of differentiated material.

The only element in Brachina which shows a marked deviation from the undifferentiated pattern in Figure 6.8 is zirconium. This deviation may be real or it may be an artifact of inadequate sampling since the absolute abundance of zirconium in Brachina is so small. If it is real, then it could be explained by very small degrees of partial melting which might also have contributed to the REE distribution pattern. Several authors have invoked the idea of a melting episode in the history of chondrite evolution. Anders (1971b) for example, suggested that some time after accretion the chondrites were heated to a temperature of about 1200°K and that subsequently they took several million years to cool to about 700°K. Rambaldi and Larimer (1976) suggested that the Shaw chondrite, which resembles Brachina in several ways, was heated sufficiently to allow molten metal to drain away. They hypothesized that this meteorite had originated in a marginal region in the parent body somewhere between pure mantle material and core. Several authors (e.g. Wasson et al 1976) have suggested an analogous process for the production of the ureilites from carbonaceous type material by the sinking of a metal-troilite melt and the ascent of a feldspar-rich fraction.

Figure 6.8 also indicates that Chassigny is more differentiated than Brachina. Mason et al (1976) commented that the calcium content of Chassigny as reported by McCarthy et al (1974) "was certainly erroneous" yet Johnson et al (1977) used this analysis to compare Chassigny with Brachina and made no comment concerning the calcium. If the much lower calcium figure quoted for Chassigny by Mason et al (1976) is used, then this element also suggests that Chassigny has undergone significant differentiation.

Thus, even though several aspects of the bulk chemistries of Brachina and Chassigny are similar, their detailed compositions are such that at this stage they should not be grouped together under the name "Chassignite", especially if this name implies that the meteorites so classified are differentiated.

It is also relevant that the ureilites (olivine pigeonite achondrites) also contain some 70% olivine as well as pigeonite and a little nickel-iron and troilite, while the nakhlites (diopside olivine achondrites) contain about 75% diopside and 15% olivine. It has been suggested (e.g. Binz et al 1975 and others) that either or both of these

groups might be related to Chassigny. Boynton et al 1976 showed that a relationship between Chassigny and the nakhlites was not possible, while Wasson et al (1976) showed that Chassigny and the ureilites must have originated in separate bodies. On the basis of REE distribution patterns, Boynton et al (1976) also showed that there is no direct relationship between the nakhlites and the ureilites. Examination of the bulk composition of several ureilites and nakhlites shows that they are undoubtedly differentiated and hence there can be no immediate relationship between them and Brachina.

If Brachina and Chassigny are related, a possibility which cannot at this stage be completely dismissed, then the relationship is probably that Chassigny represents chondritic material that was heated sufficiently to produce significant elemental fractionations with the result that its chemistry resembles that of the differentiated meteorites, whereas in Brachina, either the intensity or duration of the heating was insufficient to produce fractionation on this scale. In this sense, both meteorites could be grouped together under the classification "Chassignite" which would then describe a group of intensely recrystallized chondrites which may or may not possess a chemistry characteristic of the differentiated meteorites. If this were the case, assignment of meteorites to this classification on chemical grounds would become quite difficult.

It seems better if Brachina is given an undifferentiated classification and Chassigny a differentiated one. Accordingly, using the reasoning of Wasson (1974) regarding relatively unique meteorites, Brachina is best classified for the time being as an anomalous chondrite. Chassigny's classification is even more problematical and for the present an anomalous achondrite classification seems appropriate.

Both Mason et al (1976) and Johnson et al (1977) have discussed the possibility of a relationship between Chassigny, Brachina and the chondrites. The former authors reported the presence in Chassigny of circular aggregates of pyroxene which could be relics of former chondrules.

6.5.2 Moorabie

On the basis of its iron content (22.7%) Moorabie ought to be classified as an L or possibly LL chondrite while its olivine composition ($Fa_{15.6}$) suggests an H classification. Accalana, Carraweena and Oberon Bay (see Appendix B), with their iron contents of 18.0%, 18.7% and 18.4% respectively are apparently LL chondrites but they have olivine compositions ($Fa_{24.7, 24.5, 25.5}$) appropriate to the L chondrites. (The compositions of Monte Colina and the Carraweena fragment are similar.) The latter three meteorites may simply represent members of the L chondrite group with quite low iron contents but the deviation in the case of Moorabie was so great that further determinations of both bulk and mineral compositions were carried out and the initial results confirmed. All of these meteorites are characterized by unequilibrated silicates and this probably provides the explanation for the apparent contradictions in their classifications.

Dodd et al (1967) examined 23 unequilibrated ordinary chondrites and found similar trends. They summarized their results by stating that:

a. the average olivine compositions in the most unequilibrated ordinary chondrites do not differ greatly from group to group, and,
b. the average iron content of the olivine in L and LL groups increase during equilibration while that of the H group remains essentially unchanged.

In other words unequilibrated members of the L and LL groups will have olivine compositions similar to the H group and so as Van Schmus and Wood (1769) concluded olivine and pyroxene compositions are of little use in classifying the unequilibrated chondrites, thus underlining the importance of chemical parameters. They also concluded that it may not be possible to distinguish between the unequilibrated L and LL chondrites with low total iron contents.

Mason and Wiik (1966b) and others have classified Carraweena as an L chondrite. On the basis of its free iron content, Moorabie is likewise given an L classification. This differs from that given by Clarke (1975) which was based on preliminary results obtained in this work. The "Clarke classification" was derived from the olivine composition, but since such results are not necessarily reliable in the case of the unequilibrated ordinary chondrites belonging to the L or LL groups this earlier classification ought to be ignored. The highly unequilibrated silicates (P.M.D. of 9) together with major amounts of clinopyroxene and the presence of clear, pale pink, isotropic glass in many chondrules and inclusions, all point to a type 3 classification and so Moorabie is classified as an L3 chondrite.

Table 6.5 : Elemental compositions of the Gill meteorites.

	Fe	Mn	Ti	Ca	K	P	Si	Al	Mg	Ni	S	Cr	Na
Accalana	17.98	0.29	0.081	1.30	0.089	0.079	19.10	1.18	15.22	1.07	1.55	0.31	0.61
Carraweena	18.91	0.28	0.081	1.36	0.109	0.090	19.44	1.21	15.46	1.09	2.05	0.33	0.70
Carraweena Fragment	19.42	0.27	0.087	1.30	0.086	0.065	18.98	1.23	16.23	1.10	2.19	0.32	0.55
Monte Colina	19.07	0.27	0.084	1.29	0.054	0.103	18.99	1.25	16.10	1.10	2.34	0.31	0.60
Artracoona	20.19	0.26	0.074	1.19	0.113	0.105	17.91	1.09	14.04	1.13	1.84	0.31	0.61
Cartoonkana	20.04	0.28	0.093	1.17	0.088	0.120	18.42	1.09	14.43	1.46	1.39	0.43	0.57
Yandama	20.77	0.27	0.078	1.28	0.100	0.099	17.78	1.08	14.01	1.22	1.50	0.31	0.66

6.6 SOME METEORITES POSSIBLY BELONGING TO THE SAME FALL

Although proximity of the location of find does not prove similarity of nature or composition, in several cases there is some evidence of a relationship between certain meteorites which were found adjacent to each other.

6.6.1 The Gill meteorites

The circumstances surrounding the recovery of this group of meteorites (Section A2.2.4) suggest that Monte Colina is a piece of the outer surface of Carraweena and for this reason a fragment of the outer weathered surface of Carraweena (17269) was analysed. This sample is referred to as the Carraweena fragment to distinguish it from the specimen of the central, relatively unweathered material (22588) also analysed in this work.

Since all the Gill meteorites belong to the L group, elemental ratios are of little use in supporting any possible relationship but the absolute values (Table 6.5) can be used.

The results shown in Table 6.5 suggest two groupings as shown, although the figures do not prove any relationships between the meteorites. The first four are fairly similar and Artracoona and Yandama also resemble each other, while Cartoonkana is somewhat divergent. Some of the variations in these analyses no doubt reflect weathering effects. The original recorded weights were : Accalana 2.95kg, Carraweena 28.8kg, Artracoona 20.81kg, Cartoonkana 0.34kg and Yandama 5.68+kg.

The cluster analysis of Section 6.2.2 c divided the L chondrites into two sub groups with the two groups of Gill meteorites separated, thereby emphasising the division proposed in Table 6.5

Table 6.6 : Olivine compositions of the Gill meteorites.

Meteorite	X.R.D.	Probe	Meteorite	X.R.D.
Accalana	24.9		*Artracoona*	25.2
Carraweena	24.9	25.3	*Cartoonkana*	24.0
Carraweena Fragment	25.0		*Yandama*	25.0
Monte Colina	25.2			

The olivine compositions, Table 6.6, are consistent either with the five meteorites belonging to the one fall or to two.

The Carraweena olivine is extremely inhomogeneous on the basis of the microprobe results (CV = 14%) and so the X.R.D. determinations of these olivines are of limited use for classification purposes. Nonetheless, the similarity of the figures in the second column of Table 6.6 shows the similarity of these meteorites. The other three meteorites are well equilibrated and so their olivine compositions are more useful for diagnostic purposes, but the values are somewhat more scattered with Cartoonkana possibly being slightly different from the similar Artracoona and Yandama although, all three values are within the limit of error.

Since Accalana and Carraweena (including Monte Colina) are both members of the relatively rare L3 class of unequilibrated meteorites, it is quite likely that they both belong to the same fall. Such a relationship has already been suggested on textural grounds by Mason (1974) and on the basis of rare gas contents by Heyman (1965a). Artracoona, Cartoonkana and Yandama, on the other hand, are members of the relatively common L6 class and so conclusions are far more tentative. Mason (1974) suggested a possible relationship between Cartoonkana and Yandama and while doing so acknowledged the problems associated with proving the contention. This is probably the first time any suggestion has been made as to the inclusion of Artracoona in this relationship.

6.6.2 Silverton and the Cockburn specimens

To date, nine meteorites have been recovered in an area some 11km east of Cockburn (Section A2.2.6), the first seven of which were very similar. When the eighth was discovered, it was assumed that it was similar to the previous seven but it was noted that its mass was somewhat inconsistent with its location. After the recovery of the ninth, detailed examination of it and the eighth revealed that they were similar to each other but different from the

Table 6.7 : Elemental compositions of the Cockburn finds.

	Fe	Mn	Ti	Ca	K	P	Si	Al	Mg	Ni	S	Cr	Na
Cockburn No.3	20.61	.25	.089	1.18	.071	.062	17.62	1.12	15.01	1.04	1.48	.29	.68
Cockburn No.4	21.74	.27	.092	1.25	.108	.075	18.29	1.17	15.99	1.25	2.29	.34	.80
Cockburn No.5	20.86	.26	.093	1.23	.083	.064	18.24	1.18	15.33	1.04	1.88	.33	.70
Cockburn No.6	22.59	.30	.104	1.24	.133	.124	17.91	1.27	14.15	1.03	.34	.34	.76
Silverton	21.5	.25	.041			.102				1.33		.19	
Thackaringa No.1	24.93	.25	.065	1.11	.101	.153	16.50	1.08	11.49	1.35	.21	.30	.81

first seven. Analyses of available material (Table 6.7) illustrate this, as do Figures 2.1, 2.2 and 2.6 which show sections of the Cockburn and Thackaringa meteorites.

The first seven specimens named after the nearby town of Cockburn are L chondrites, while the last two, which are H chondrites, were distinguished with the name Thackaringa. Table 6.7 indicates compositional variation between the Cockburn specimens. This may simply be the results of the small size of the specimens and weathering effects. The Cockburn specimens also exhibit some textural variations and so they may represent more than one fall or they may be samples of an inhomogeneous body.

The cluster analysis of the ordinary chondrites (Figure 6.4) illustrates the similarity of Cockburn No.3 and No.5, while No.4 and No.6 were placed separately, with No. 6 being grouped with Nine Mile which also has a low sulfur content. The affinities of Thackaringa No.1 for the H chondrite group are clearly shown by this figure.

As is pointed out in Section A2.2.1, the town of Cockburn did not exist when the Silverton meteorite was found and as details of its find are virtually non-existent, it is possible that it may be part of the Cockburn fall and may even have come from the same area. Superficial examination of a very small sample of Silverton revealed a marked resemblance to the Cockburn material. A new chemical analysis was precluded by lack of sample, but Table 6.7 includes results obtained by Greenland and Lovering (1965) showing a general similarity with the Cockburn material.

Mineralogical compositions are detailed in Table 6.8, the Silverton results having been obtained from a thin section from the Australian National University Collection. These results are also consistent with Silverton being related to the Cockburn material but do not prove a relationship.

Table 6.8 : Mineralogical compositions of the Cockburn finds.

	Olivine		Pyroxene	
	Fa		Fs	Wo
Meteorite	X.R.D.	Probe	Probe	
Cockburn No.1	25[1]	26.2	22.8	1.5
Cockburn No.2		26.4	22.8	1.5
Cockburn No.3	24.7			
Cockburn No.4	25.4			
Cockburn No.5	26.1	26.6	23.2	1.7
Cockburn No.6	25.5	25.1[3]	21.4[3]	
Silverton	25[2]	25.8	21.5	1.6
		25.4[3]	21.0[3]	
Thackaringa No. 1	17.2			

References
1. Johnson and McColl 1967.
2. Mason 1963a.
3. Mason 1974.

6.6.3 Mount Browne and the North Eastern meteorites

The possibility that some of the meteorites found in the north eastern part of the State and adjacent regions might be related to the Mount Browne fall of 1903 (Section A2.2.2) was also investigated. Mineral compositions obtained from a thin section lodged in the Australian National University Collection are given in Table 6.9.

A comparison of these results with the data of Table 6.7 shows that Mount Browne cannot be related to any of the Gill meteorites. There is some resemblance between the Mount Browne results and those of Moorabie ($Fa_{15.7}$, $Fs_{12.4}$ $Wo_{0.8}$) but the equilibrated nature of the Mount Browne silicates (CV for olivine and pyroxene equals 0 and 0.2 respectively) precludes any relationship. Likewise, the iron content of Mount Browne (28.3%, Greenland and Lovering 1965; 26.6%, Nakamura 1974) is quite different from that of Moorabie (22.7%). Thus, none of the meteorites from this part of the country which have been examimed to

Table 6.9 : Mineralogical compositions for Mount Browne.

Olivine	Pyroxene		
Fa	Fs	Wo	
18.8	17.0	1.3	This work
18.1	16.5		Mason (1974)

Table 6.10 : Elemental composition of the Hollmayer meteorites.

	Fe	Mn	Ti	Ca	K	P	Si	Al	Mg	Ni	S	Cr	Na
Popio	21.34	.29	.071	1.31	.114	.135	18.64	1.23	15.23	1.33	2.52	.32	.82
Nine Mile	21.28	.30	.068	1.25	.119	.129	18.59	1.22	14.05	.84	.66	.24	.76
Popilta	20.00	.31	.068	1.22	.105	.117	18.68	1.19	15.20	1.29	1.72	.29	.77
Twin Wells	22.98	.25	.067	1.03	.110	.144	16.62	1.09	13.23	1.52	1.49	.24	.66
H05	23.54	.28	.062	1.05	.095	.136	16.71	1.07	13.35	1.62	1.36	.25	.68
H06	23.22	.28	.064	1.17	.104	.130	16.83	1.07	13.62	1.60	1.46	.29	.76

date appear to be related to the Mount Browne fall.

6.6.4 The Hollmayer meteorites

Chemical and mineralogical results obtained in this work for six of the meteorites recovered by Mr. Hollmayer (Section A2.2.10) are given in Tables 6.10 and 6.11.

The cluster analysis of the ordinary chondrites (Figure 6.4) grouped Twin Wells and H05 and H06 together in a single group, while Nine Mile was grouped with Cockburn No.6, both meteorites being low in sulfur, probably because of weathering, being separated from the remainder of the L chondrites. Popio was grouped with Cadell in the "Yandama" group and Popilta and Kybunga No.3 in the "Carraweena" group. Cluster analysis gives a good indication of the similarity of individuals to each other (Section 5.6.6) and so these results suggest the possibility of a close relationship between Twin Well, H05 and H06, and at the same time suggest some differences among the other three.

Popio, Nine Mile and Popilta belong to the L6 group while the others have been classified as H5. Their mineralogical compositions (Table 6.11) are consistent with the relationships suggested by their bulk chemistry but again do not prove such a relationship.

Differences between the specimens are not great enough to prove that they are not individuals from the same fall while distances between the finds might provide some indirect evidence, but this data was not available to the author. The only overall conclusion that can be made is that at least two "falls" are represented.

Table 6.11 : Mineralogical compositions of the Hollmayer meteorites.

	Olivine		Pyroxene	
	Fa		Fs	Wo
	X.R.D.	Probe	Probe	Probe
Nine Mile	23.5	26.9	23.4	1.4
Popilta	25.0	25.6	22.8	1.3
Popio	23.9	26.2	22.4	1.5
H05	18.9	19.8	17.5	1.0
H06	15.1	18.0	16.7	1.2
Twin Wells	18.9	21.1	17.4	1.0

6.7 RESULTS AND CONCLUSION

Table 6.12 summarizes the classifications arrived at for the ordinary chondrites in this and the previous chapter. For comparative purposes, the results of Mason (1974) are listed for those meteorites studied by him. Meteorites marked with an asterisk were either previously unclassified or the previous classification has been altered.

Section	5.3	5.4	6.2.2 a	6.2.2 b	6.2.2 c	6.2.2 d	6.3.1	6.3.1	6.3.1	6.3.2 a	6.7	6.4	6.7	
Technique	Absolute abundances	Relative abundances	Discriminant analysis	Principal component analysis	Canonical correlation analysis #	Cluster analysis #	Olivine - X.R.D.	Olivine - Probe	Pyroxene - Probe	K_d	Consensus	Petrographic Group	Final Classification	Mason 1974
ACCALANA	LL	LL	LL	L	L	"L"	"L"				L			L3
ARTRACOONA	L,LL	L	L	L	L	"L"	L				L			L6
BARATTA								"L"	"H"	?	L			L3
CADELL	L,LL	L	L	L	L	"L"	L				L			L6
CARRAWEENA	LL	LL	LL	L	L	L	"L"	"L"	"L"	L	L			L3
CARTOOONKANA	L,LL	L	LL	L	L	L	L				L			L6
COCKBURN No.1								L	L	L	L	6	L6	
*COCKBURN No.2								L	L	L	L	6	L6	
*COCKBURN No.3	L,LL	L	LL	L	L	L	L				L	6	L6	
*COCKBURN No.4	L,LL	L	L	L	L	L	L				L	6	L6	
*COCKBURN No.5	L,LL	L	LL	L	L	L	L	L	L	L	L	6	L6	
COCKBURN No.6	L,LL	L	L	L	L	L	L				L	6	L6	L6
COCUNDA	L,LL	L	LL	L	L	L	L				L			L6
COOMANDOOK No.1	H	H	H	H	H	H	H				H			H6
COONANA	H	H	H	H	H	H	H				H			H4
*HOLLMAYER No.5	H	H	H	H	H	H	H	H	H	H	H	5	H5	
*HOLLMAYER No.6	H	H	H	H	H	H	H	H	H	H	H	5	H5	
KALDOONERA HILL	H	H	H	H	H	H	H				H			H6
KIELPA	H	H	H	H	H	H	H				H			H5
KYBUNGA No.3	L,LL	L	L	L	L	L	L				L	5	L5	L5
LAKE BONNEY	L,LL	L	L	L	L	L	L				L			L6
LAKE LABYRINTH	LL	LL		"LL"	L	L	LL				LL			LL6
MONTE COLINA	LL	LL	LL	L	L	L	"L"				L			L3
*MOORABIE	L	L	L	L	L	L	"H"	"H"	"H"	?	L	3	L3	
MOTPENA	L,LL	L	L	L	L	L	L	L,LL	L	L	L			L6
MOUNT BROWNE							H			H	H			H6
*NINE MILE (HO3)	L,LL	L	L	L	L	L	L	L,LL	L	L	L	6	L6	
NORA CREINA	LL	L	L	L	L	L	L				L			L4
*POONARUNNA	H	H	L	H	H	H	H	H	H	H	H	5	H5	
*POPILTA (HO4)	L,LL	L	L	L	L	L	L	L	L	L	L	6	L6	
*POPIO (HO1)	L,LL	L	L	L	L	L	L	L	L	L	L	6	L6	
SILVERTON								L	L	L	L			L6
*THACKARINGA No.1	H	H	H	H	H	H	H				H	5	H5	
*THACKARINGA No.2								H**			H	5	H5	
*TWIN WELLS (HO2)	H	H	H	H	H	H	H	L?	H	H	H	5	H5	
VINCENT	L,LL	L	LL	L	L	L	L				L			L5
WILBIA	E	H	H	H	H	H	H				H			H5
WITCHELLINA	H	H	H	H	H	H	H				H			H4
YANDAMA	L,LL	L	L	L	L	L	L				L			L6

#These techniques could not distinguish between L and LL-chondrites

**Semiquantitative S.E.M. Data

Chapter 7

THE CARBONACEOUS CHONDRITES

7.1 INTRODUCTION

The aim of this chapter is to review the classification of the carbonaceous chondrites and then to examine previously classified carbonaceous chondrites with the techniques described in earlier chapters. After establishing the relevance of these techniques to the characterization of the carbonaceous chondrites, they are applied to two South Australian meteorites with unusual characteristics - namely Adelaide and Karoonda.

7.2 SUBDIVISIONS OF THE CARBONACEOUS CHONDRITES

The carbonaceous chondrites were defined in Section 5.5 in terms of Al, Ca, Mg and Fe abundances. This definition avoids problems such as the absence of chondrules in certain meteorites normally regarded as carbonaceous chondrites and the high carbon content of some "non-carbonaceous" chondrites.

Development in knowledge and understanding of the carbonaceous chondrites has been paralleled by improvements in classificationary schemes. One of the early modern schemes based on compositional parameters was that of Wiik (1956), which was later modified by others (e.g. Mason 1962b). Wiik's three groups were distinguished from each other by major chemical differences which reflected their diverse mineralogies. There is little apparent relationship between the three groups. Van Schmus and Wood (1967) incorporated the carbonaceous chondrites into their chemico-petrologic classification with Wiik's three groups generally corresponding to C1, C2 and (C3, C4) chondrites. They commented that they did not envisage the same metamorphic relationship in these as that in the other chondrite groups.

Wood (1967a) and Van Schmus (1969a) recognized textural and mineralogical variations in the C2, C3 and C4 chondrites and Van Schmus divided the C3 and C4 meteorites into Ornans (C3O) and Vigarano (C3V) subgroups while Van Schmus and Hayes (1971,1974) introduced the Ivuna (C1I) and Mighei (C2M) subgroups. They commented that while most of the C2 meteorites resembled the Ornans subgroup, a few were similar to the Vigarano type. They showed on the basis of selected atomic ratios that all of the carbonaceous chondrites they examined could be divided into two chemical subgroups which they called A and B, the A group being comprised of the Vigarano-type meteorites and the B group the remainder.

The author noticed the resemblance between Adelaide and Bench Crater, two recently described carbonaceous chondrites, and this led Fitzgerald and Jones (1977) to introduce another subtype of the carbonaceous chondrites. They called this the K (Kakangari) subgroup and placed in in a new chemical subgroup, AB, as it resembled both the A and B subgroups of Van Schmus and Hayes but was distinct from them. Table 7.1 shows the present classification scheme for the carbonaceous chondrites with the categories for known carbonaceous chondrites indicated.

Yavnel (1976) suggested that the C1, C2 and C3V meteorites formed a sequence separate from the C3O meteorites. It would appear however, that if the C1 and C2 meteorites are related to type 3, then a relationship with the C3O is likely. This probably parallels a possible relationship of Vigarano type meteorites extending from petrologic group 2 to 6 although evidence will be presented below that many of the properties of the Ornans and Vigarano subgroups tend to merge at high petrologic grade.

Table 7.1 : Classification grid for the carbonaceous chondrites.

PETROLOGICAL GROUP	*CHEMICAL GROUP*		
	A	*B*	*AB*
1		*C1I*	
2	*C2V*	*C2M*	*C2K*
3	*C3V*	*C3O*	*C3K*
4	*C4V*	*?C4O*	
5	*C5V*		
6	*C6V*		

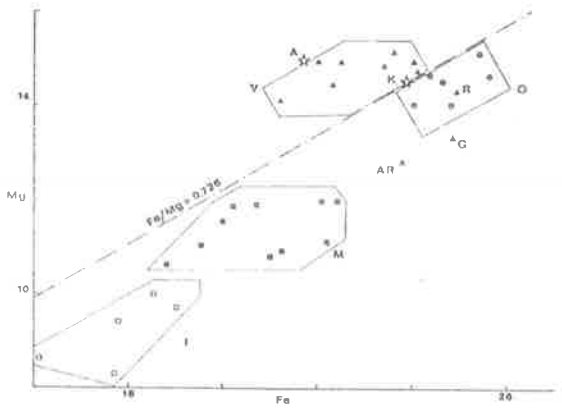
7.3 SUBDIVISIONS BASED ON BULK CHEMISTRY

7.3.1 Absolute

Figures 7.1 and 7.2 show that the C1, C2 and (C3+C4+C5) groups can be readily distinguished on the basis of bulk chemistry. The diagrams also show that the A and B chemical subgroups can generally likewise be distinguished and hence the C3V and C3O can be separated whereas the C2V meteorites Al Rais and Renazzo cannot be easily separated from the B subgroup on either plot. Mason (1971a) stated that the C3V-C3O distinction could be made simply on the basis of iron content (the boundary being 25% Fe) but Figure 7.1 shows that this is not always an adequate distinction. The gradient of the line dividing the A and B subgroups on this plot is 10/17. This is equivalent to an atomic Fe/Mg ratio of 0.726. This result is used in Section 7.3.2 to define values of 7.7 and 10.6 for the Fe/Si and Mg/Si ratios to distinguish these two groups.

As with other elements, the abundance of the rare earth elements (REE) is a result of various fractionation processes experienced by pristine material. The chemical similarity of these elements renders them less susceptible to mutual fractionation than any other group of elements. Accordingly, the abundance patterns of the REE in the carbonaceous chondrites can be used as classificationary tools. These abundance patterns are usually calculated by normalizing measured abundances against a standard. The average abundances in ten chondrites examined by Nakamura (1974) have often been used for this normalization. Evensen et al (1978) examined fifteen chondrites and combined their results with those of others to produce a new set of absolute abundances of the REE in C1 chondrites to be used for normalization purposes. All values in this work have been compared to these values.

Figure 7.1 : Mg vs Fe for analysed and literature carbonaceous chondrites. □: CI, ■: CM, ●: CO, ▲ : CV, A : Adelaide, AR : Al Rais, G : Grosnaja, K : Karoonda, R : Renazzo.



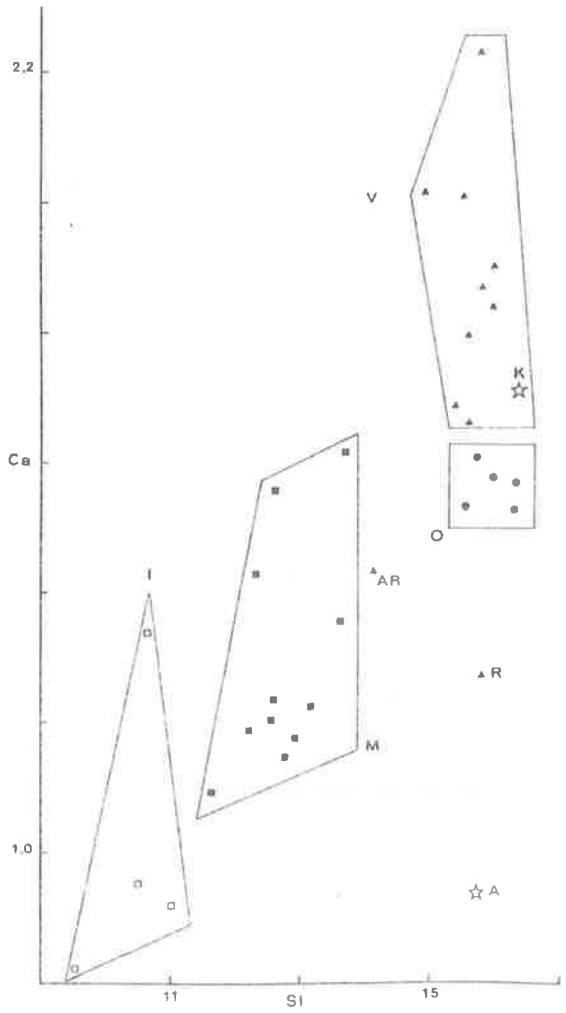


Figure 7.2 : Ca vs Si for analysed and literature carbonaceous chondrites. □ : CI, ■ : CM, ● : CO, ▲ : CV, A : Adelaide, AR : Al Rais, K : Karoonda, R : Renazzo.

Limited data is available for the carbonaceous chondrites and Figure 7.3 shows the REE distribution patterns for several representative samples. The diagram shows a clear distinction between typical members of the C1I, C2M and C3V meteorites.

7.3.2 Relative

Van Schmus and Hayes (1974) used five ratios to distinguish their A and B chemical subgroups. The author examined both the data available to Van Schmus and Hayes and later results and found that in nearly every case the range in values shown by the B subgroup was very much smaller than that of the A subgroup. Iron and magnesium values appeared to be almost continuous from one group to the other while there was a marked hiatus between the two groups for the other ratios. The author redefined the ranges slightly, a lead followed by Fitzgerald and Jones

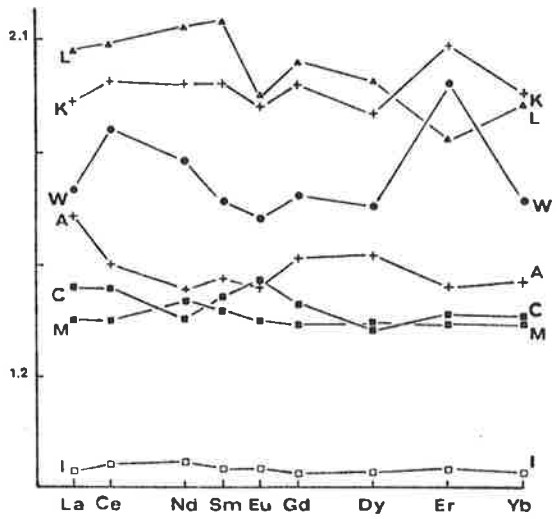


Figure 7.3 : REE abundance patterns. AA : Adelaide, CC : Cold Bokkeveld, II : Ivuna, KK : Karoonda, LL : Allende, MM : Murray, WW : Warrenton. Adelaide - this work, Allende - Nakamura (1974), all others - Evensen et al (1978).

(1977), and in each instance set the boundary between the two groups in close proximity to the B group because of the smaller range of values in that group. Table 7.2 shows these new ranges as well as those for the AB subgroup which were defined at the same time. This group overlaps with either the A or B subgroups in some instances or is independent.

The ratio Mg/Si has been used despite the conclusion of Van Schmus and Hayes that its use was inappropriate. It may, however, not be as precise a discriminator as the others. Figures 7.4 and 7.5 illustrate some of these points.

This compositional differentiation effectively separates the Vigarano-type carbonaceous chondrites from the others thereby also effecting a segregation of petrologic characteristics

7.3.3 Multivariate techniques

Of the four multivariate techniques described in Section 5.3, only discriminant analysis differentiated the carbonaceous chondrites from the H category. The

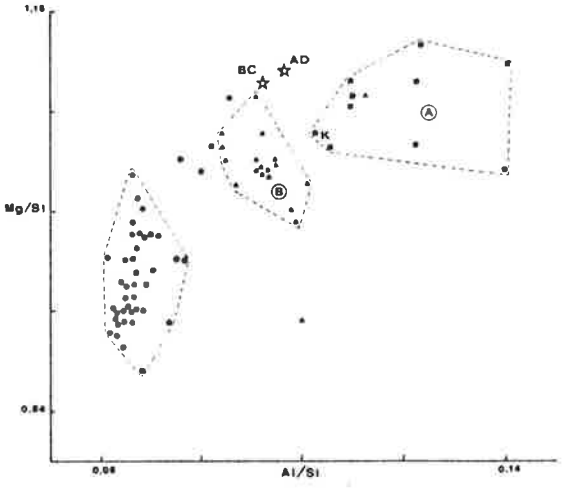


Figure 7.4 : Mg/Si vs Al/Si. ● : ordinary chondrites, this work, ■ : A subgroup carbonaceous chondrites, ▲ : B subgroup carbonaceous chondrites, AD : Adelaide, BC : Bench Crater.

situation changed when it was a matter of distinguishing the different types of carbonaceous chondrites. In this instance, the three inductive methods clearly separated the Ivuna and Mighei subgroups from each other and the Ornans and Vigarano groups but the latter were found to be quite similar.

Figure 7.5 : Ca/Si vs Al/Si. ● : ordinary chondrites, this work, ■ : A subgroup carbonaceous chondrites, ▲ : B subgroup carbonaceous chondrites, AD : Adelaide, BC : Bench Crater.

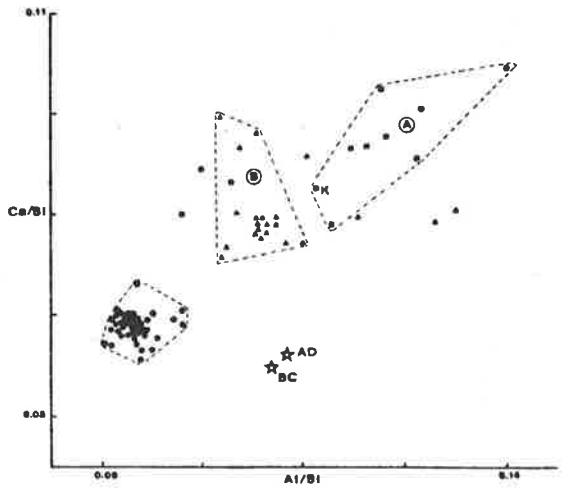


Table 7.2 : Ranges in atomic ratios for the A and B subgroups of the carbonaceous chondrites.

Group	*Fe/Si x10*	*Mg/Si x10*	*Ca/Si $x10^2$*	*Al/Si $x10^2$*	*Ti/Si $x10^3$*	*Cu/Si $x10^4$*	*Reference*
A	*7.1 - 7.1*	*10.6 - 12.0*	*7.5 - 9.0*	*9.6 - 15.0*	*3.0 - 4.0*	*2.0 - 3.4*	
B	*7.7 - 9.0*	*10.0 - 10.6*	*5.8 - 7.0*	*8.0 - 9.6*	*2.4 - 3.0*	*3.4 - 6.0*	*This work*
AB	*4.0 - 7.1*	*10.6 - 12.0*	*4.0 - 5.5*	*8.0 - 9.6*	*2.4 - 3.0*	*2.0 - 3.4*	
	(Below A)	*(As for A)*	*(Below B)*	*(As for B)*	*(As for B)*	*(As for A)*	
A	*<7.7*	-	*>7.6*	*>10.8*	*>3.5*	*<3.2*	*Van Schmus and*
B	*>7.9*	-	*<7.0*	*< 9.5*	*<3.1*	*>3.4*	*Hayes (1974)*

Table 7.3 : Sources of carbonaceous chondrite analyses.

*Adelaide**	1	*Karoonda**	1	*References:*
Alais	17	*Lance**	3	1. *This work*
*Allende**	1	*Leoville**	9	2. *Ahrens et al (1969)*
Al Rais	17	*Mighei**	16	3. *Ahrens et al (1973)*
Bali	10, 11, 13	*Mokoia**	16	4. *Christie (1914)*
Boriskino	17	*Murchison**	6	5. *Folinsbee et al (1967)*
*Cold Bokkeveld**	16	*Murray**	16	6. *Fuchs et al (1973)*
*Coolidge**	7, 9	*Nawapali*	17	7. *Jarosewich (1966)*
*Efremovka**	8	*Nogoya**	2	8. *Jarosewich and Mason (1969)*
Erakot	17	*Ornans**	2	9. *McCarthy and Ahrens (1972)*
Essebi	17	*Orgueil**	2	10. *McSween (1977b)*
*Felix**	3	*Renazzo*	17	11. *McSween and Richardson (1977)*
Grosnaja	17	*Revelstoke**	5	12. *Mason (1963c)*
Haripura	17	*Santa Cruz*	17	13. *Mason (1971a)*
*Isna**	14	*Tonk*	4	14. *Methot et al (1975)*
Ivuna	17	*Vigarano**	16	15. *Sztrokay et al (1961)*
*Kaba**	15	*Warrenton**	9	16. *Von Michaelis et al (1969)*
*Kainsaz**	3			17. *Wiik (1969)*

a. Discriminant analysis

This technique proved to be the best method for characterizing both the carbonaceous chondrites and their subgroups. It distinguished the four major subgroups but the adequacy of this distinction is a function of the accuracy with which the groups are defined. Table 7.3 gives the sources of the analyses used to effect these definitions. The complete analytical results for Bali were not available until late in this work, and so this data was not used for several of the multivariate analyses. The distribution was as follows - Ivuna 4, Mighei 11, Ornans 6, Vigarano 10. This analysis is discussed further in the section devoted to Karoonda and Adelaide. (Perhaps it ought to be pointed out at this stage that, even though a meteorite is used to define a group, its affinities for the other groups being defined was examined, and in no instance did any of these 31 meteorites show any significant resemblance to any of the other three groups.)

b. Principal component analysis

Table 7.4 shows the variance distribution obtained by the principal component analysis of 34 carbonaceous chondrites - 3 analysed in this work and the 31 literature values described above. The plotted output from this analysis (Figure 7.6) shows that the analyses of three meteorites, Al Rais, Grosnaja and Renazzo, extend the Vigarano group considerably. Van Schmus and Hayes (1974) have expressed some concern regarding the apparent conflict between chemical and textural evidence in these three meteorites. As a consequence, a more restricted data set of 22 analyses based on the work of Ahrens and others was selected and Table 7.4 shows the variance distribution obtained in this analysis. (These analyses are marked with an * in Table 7.3.)

In both cases, the first three eigenvectors account for almost the same amount of variance but in the second case more is contained in the first eigenvector. The plot of this analysis (Figure 7.7) shows the distinction between the I and M subgroups even more distinctly than in the first while the V and O meteorites are also more readily resolved into two groups.

Table 7.4 shows that in each data set

Figure 7.6 : First three principal components for the full carbonaceous chondrite data set. □ : CI, ■ : CM, ● : CO, ▲ : CV, ▽ : Adelaide and Karoonda.



Table 7.4 : Eigenvalues and eigenvectors for the carbonaceous chondrites.

Eigenvalues

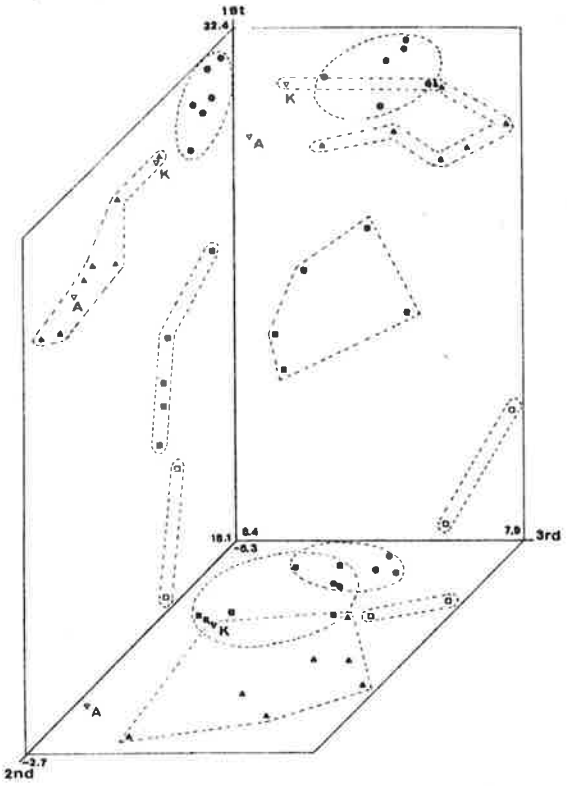
	Extended data set		*Restricted data set*	
Eigenvector	*%age variance*	*Cumulative %age*	*%age variance*	*Cumulative %age*
1st	*89.3*	*89.3*	*91.0*	*91.0*
2nd	*6.9*	*96.2*	*7.0*	*98.0*
3rd	*2.5*	*98.7*	*0.9*	*98.8*

Eigenvector elements both as absolute values and as percentages of the total variance

	Extended data set						*Restricted data set*					
	1st		*2nd*		*3rd*		*1st*		*2nd*		*3rd*	
Fe	*0.59*	*30.8*	*-0.80*	*4.4*	*0.03*		*0.64*	*36.8*	*-0.76*	*4.0*	*0.12*	
Mn			*-0.01*						*-0.01*		*-0.01*	
Ti			*0.01*						*0.01*		*0.01*	
Ca	*0.06*	*0.3*	*0.06*		*0.14*		*0.07*	*0.4*	*0.12*	*0.1*	*0.38*	*0.1*
K	*-0.01*		*-0.01*						*-0.01*		*0.01*	
P					*0.01*							
Si	*0.52*	*24.4*	*0.29*	*0.6*	*0.06*		*0.52*	*24.8*	*0.35*	*0.9*	*-0.11*	
Al	*0.05*	*0.2*	*0.17*	*0.2*	*0.12*		*0.05*	*0.2*	*0.18*	*0.2*	*0.43*	*0.2*
Mg	*0.52*	*24.1*	*0.43*	*1.3*	*0.43*	*0.5*	*0.51*	*23.7*	*0.49*	*1.7*	*0.23*	*0.1*
Ni	*0.03*	*0.1*	*0.01*				*0.03*	*0.1*			*-0.08*	
S	*-0.33*	*9.4*	*-0.24*	*0.4*	*0.88*	*1.9*	*-0.23*	*5.0*	*-0.13*	*0.1*	*0.76*	*0.5*
Cr	*0.01*				*-0.01*		*0.01*				*0.04*	
Na	*-0.01*		*-0.06*		*0.01*		*-0.01*		*-0.06*		*0.10*	

virtually all of the variance arises from variations in iron, silicon and magnesium, plus a smaller, but significant, sulfur variation. The importance of Fe, Mg and Si reflects their presence in both the low temperature layer silicates and the high temperature minerals olivine and pyroxene. It is the relative abundance of these low and high temperature groups which characterizes the three main groups of the carbonaceous chondrites. Likewise, the significant variations in sulfide content is reflected in these eigenvectors. The low significance of nickel in these unnormalized data sets reflects its low absolute abundance and small variation from group to group.

Figure 7.7 : First three principal components for the reduced carbonaceous chondrite data set. □ : CI, ■ : CM, ● : CO, ▲ : CV, ▽ : Adelaide and Karoonda.



c. Canonical correlation analysis

Both data sets were examined with the technique of canonical correlation analysis. The two groups of variables used for the analysis being indicated by an R-mode cluster analysis, namely:

Set 1 : Fe, Ti, Ca, Si, Al, Mg, Ni and Cr

Set 2 : Mn, K, P, S and Na

The significance of these elemental groupings will be discussed in the next section. Figure 7.8, the plot for the larger data set, shows a clear distinction between the I and M meteorites, except for Haripura, which on mineralogical and textural evidence belongs to the Mighei subgroup but plots in the Ivuna field. These results suggest the possibility that the Haripura analysis is in error. A similar suggestion was made by Van Schmus and Hayes (1974). The I and M groups

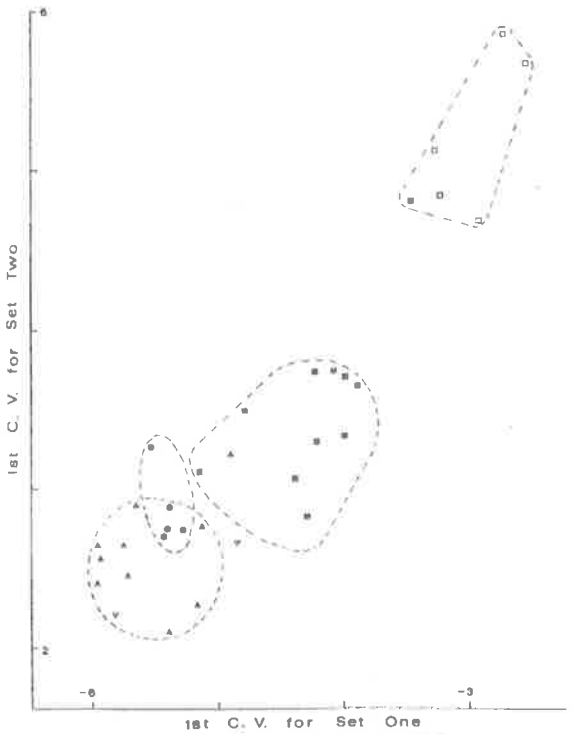


Figure 7.8 : First two canonical variables for the full carbonaceous chondrite data set. □ : CI, ■ : CM, ● : CO, ▲ : CV, ▽ : Adelaide and Karoonda.

are distinct from the O and V groups except for the C2V meteorite Al Rais which plots in the M field. Van Schmus and Hayes likewise suggested that the analysis of this meteorite might be in error. The V subgroup otherwise plots in an approximately circular field intersecting the O group field.

Using the smaller data set (Figure 7.9), the technique still clearly separates the V and O subgroups into two non-linear groups

Figure 7.9 : First two canonical variables for the reduced carbonaceous chondrite data set. □ : CI, ■ : CM, ● : CO, ▲ : CV, △ : Adelaide and Karoonda.

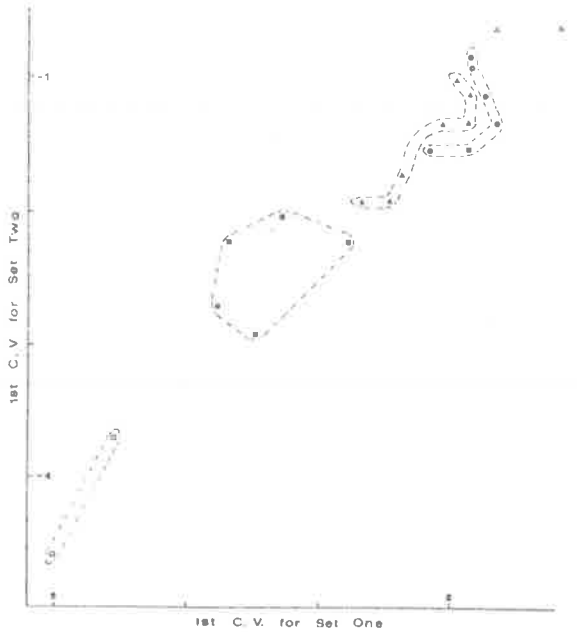


Table 7.5 : Cophenetic correlation coefficients.

Analysis Mode	*Large data set*	*Restricted data set*
R	*0.92*	*0.92*
Q	*0.76*	*0.81*

which are subparallel to each other, but not as clearly separated as before. The greater cohesiveness of the restricted data set is also demonstrated. The correlation coefficient for the first two canonical variables was 0.91 for the full data set and 0.95 when the restricted set was used.

d. Cluster analysis

Cluster analysis was carried out on both data sets. In each case, raw data was used as preliminary investigations had shown that normalization gave rise to somewhat greater distortion. Furthermore, the dendograms produced from the raw data clustered similar meteorites more effectively. Both R- and Q-mode analyses were performed and the cophenetic correlation coefficients are given in Table 7.5.

The value of 0.76 for the Q-mode analysis of the large set indicates that the dendogram (Figure 7.10) may be somewhat misleading due to distortions at lower linkages, whereas the value of 0.81 for the restricted set (Figure 7.11) suggests that this dendogram more accurately portrays the inter-meteorite relationships. The Q-mode analysis divided the larger set into four main clusters (Figure 7.10) and the smaller set into three (Figure 7.11). In both cases, the I and M groups are clearly distinguished from the V and O with the I and M further separated from each other in the larger set. In both cases, the V and O groups are divided such that one cluster contains Vigarano meteorites only while the other consists mainly of Örnans type but with some Vigarano.

The value of 0.92 for both the R-mode analyses indicates little distortion has been introduced. The apparent correlation between the two groups of about -0.4 does not preclude their use for canonical

Figure 7.12 : R-mode cluster analysis of the two carbonaceous chondrite data sets.

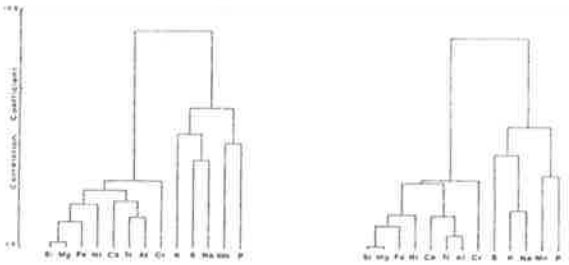
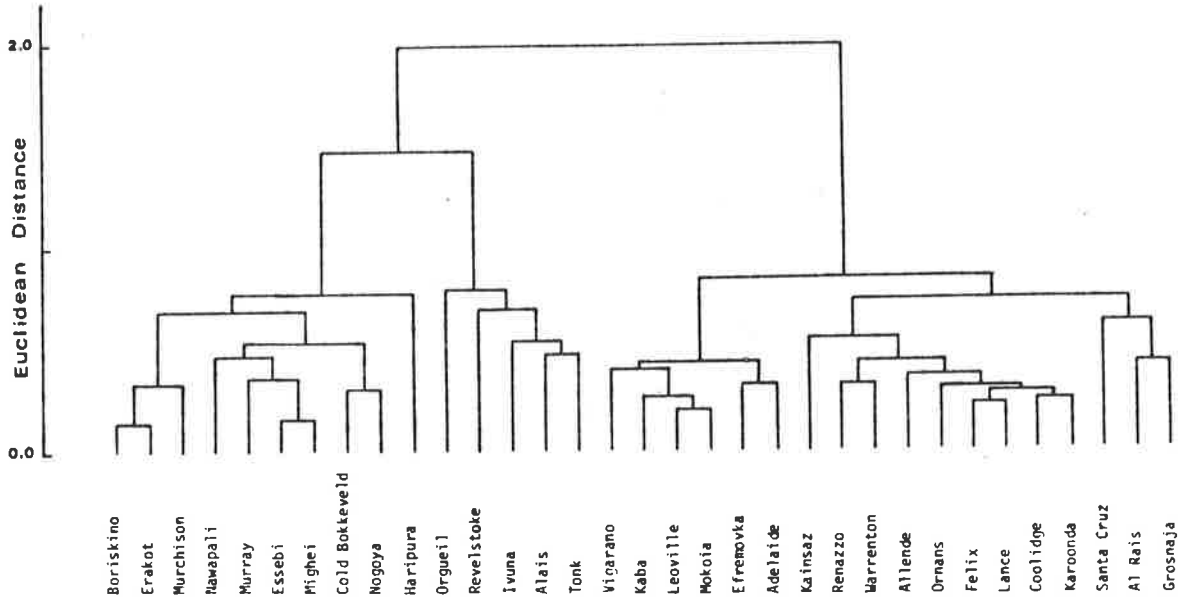


Figure 7.10 : Q-mode cluster analysis of the full carbonaceous chondrite data set.



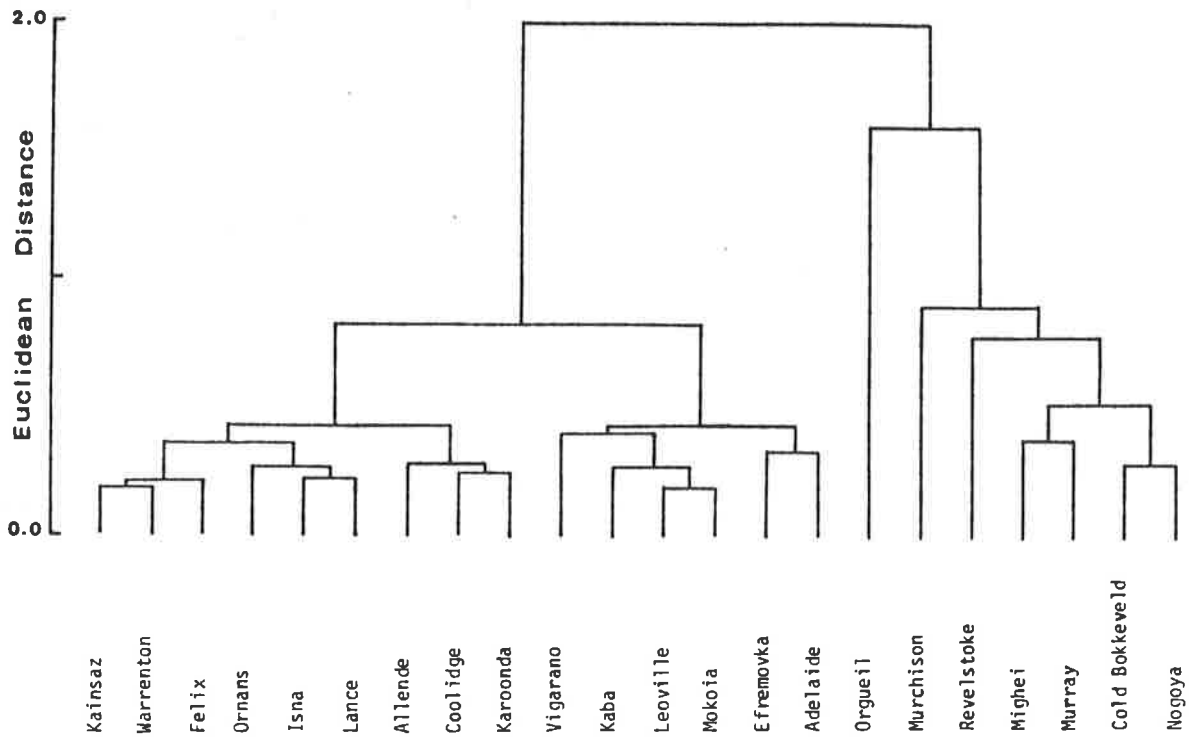
correlation analysis. Figure 7.12 shows the R-mode dendograms are almost identical and so the same groups of elements were used for canonical correlation analysis for both data sets.

Figures 7.12 shows in each case the separation of the elements into the two groups:
Fe, Ti, Ca, Si, Al, Mg, Ni and Cr, and,
Mn, K, P, S and Na.
The distribution of the elements into these groups is significant.

In terms of their geochemical affinities, the second group of elements contains the lithophilic elements K, Na and Mn plus the siderophilic element phosphorus, which according to Buchwald (1975b), also exhibits lithophilic tendencies. As pointed out above, however, phosphorus generally occurs in most stony meteorites as phosphate minerals. Sulfur is chalcophilic and potassium also has similar tendencies being readily incorporated into an Fe-FeS melt to give such minerals as djerfisherite ($K_3CuFe_{12}S_{14}$) (Goettel 1976). Of the first group, all the elements except Fe and Ni are litholphilic, while these two exhibit lithophilic, chalcophilic and siderophilic tendencies.

In terms of their thermal properties, the

Figure 7.11 : Q-mode cluster analysis of the restricted carbonaceous chondrite data set.



first group contains all those elements characterized by Anders (1972) as being refractory (viz. Ti, Ca, Si, Al, Mg and Cr) while the volatile ones (Mn, K, S and Na) are in the second group. Anders also pointed out that in the carbonaceous chondrites the other member of this second group, phosphorus, has some volatile characteristics. Thus the first group contains the siderophile and refractory lithophile elements and the second group the chalcophile and volatile lithophile ones.

The Ca-Al-Ti association correlates with the occurence in the carbonaceous chondrites of these three elements in various refractory phases such as spinel, melilite, anorthite, perovskite, diopside etc. These Ca-Al-Ti rich inclusions represent early high temperature condensates from the solar nebula. The (Si-Mg)-Fe-Ni relationship arises from the association of iron and nickel in opaque minerals along with the sympathetic relationship between iron and magnesium, together with silicon, in olivine, pyroxene and layer silicates. The presence of Cr in this group correlates with its occurence in stony meteorites mainly as the spinel, chromite, $FeCr_2O_4$. The other major group of elements does not correlate so well with mineral phases. Except for sulfur, the members of the group are generally not major elements. Sodium and potassium are commonly associated in feldspars which are not unusual in carbonaceous chondrites (Van Schmus 1969a).

It is generally agreed that most of the carbonaceous chondrites are two component mixtures (Anders 1972, Wasson and Chou 1974), the matrix being a volatile-rich low-temperature component and the chondrule plus metal grain fraction a volatile-free high-temperature component. The two groups of elements delineated by the R-mode analysis may correspond to these two components. The apparent correlation coefficient of -0.4, although not statistically significant, may be indicative of the inverse relationship between these two components.

Yavnel (1976) studied 15 of Wiik's type III carbonaceous chondrites and suggested that the elements of which they were composed fell into four groups, viz.

a. O
b. Fe, Ni and P
c. Si, Mg, Cr, Ca, Al and Ti
d. Na, K, Mn, S and C

Except for phosphorus, his second and third group correspond to the first group delineated by the R-mode analysis and the fourth group with the second group.

The realistic subdivisions of the elements by the R-mode analysis highlights the point made earlier that multivariate techniques are useful for displaying complex relationships but if the groupings do not appear to have a chemical and/or mineralogical basis then they may be suspect.

7.4 SUBDIVISIONS BASED ON MINERALOGICAL PARAMETERS

Carbonaceous and ordinary chondrites are similar in possessing olivine and pyroxene as major phases but minerals such as serpentine and other layer structure minerals and the calcium-aluminium minerals such as melilite and fassaite are commonly found only in the carbonaceous chondrites. The presence of these minerals is usually diagnostic of the carbonaceous chondrites but their presence is by no means mandatory for this classification.

The C1, C2 and C3 meteorites can be distinguished on a mineralogical basis as can the C3O and C3V chondrites. Table 7.6 lists some of the critera advocated by different authors to effect these distinctions. No mineralogical boundaries have been suggested to delineate types 4, 5 and 6.

The unequilibrated nature of the C2 and C3 chondrites is evidenced by the compositional variability of the olivines and/or pyroxenes in these meteorites.

7.5 SUBDIVISIONS BASED ON MAGNETIC PROPERTIES

Brecher (1972,1973) and Brecher and Arrhenius (1974) measured the chemical and low-temperature partial remanence carried by magnetite grains in several carbonaceous chondrites. They drew some conclusions concerning the similarites of several meteorites but did not set up a formal classification scheme on this basis.

Wasilewski (1973) stated that the three groups of carbonaceous chondrites could be distinguished on the basis of magnetic properties which reflected redox conditions during condensation and accretion of the meteorites.

Larson and co-workers (Larson *et al* 1974, Watson *et al* 1975, Herndon *et al* 1976) studied the thermomagnetic properties of 38 carbonaceous chondrites. They found three groups of meteorites - the first initially contained little magnetite but it was produced by the thermal breakup of some other phase - presumably troilite. In the second, the magnetic changes were perfectly reversible suggesting that only magnetite was present, troilite being rare or absent

Table 7.6 : Mineralogical distinctions between the carbonaceous chondrite groups.

Property	*C1*	*C2*	*C3*	
Matrix Mineralogy	*Serpentine and other layer silicates*[3,4,6,7]	*Layer silicates*[3,4,7]	*Fine grained olivine*[3,4,7]	
Olivine Composition	*Absent*[3,4]	*A peak at low fayalite content*[3,6,7,9]	*Wider compositional range*[6,7]	
			CV	*CO*
			Uniform and iron poor[5,6]	*Uniform and more iron rich or less uniform in composition*[2,5,6]
Pyroxene Composition	*Absent*[3,4]		*More magnesium rich than olivine*[6]	
Sulfide assemblages	*Free sulfur and troilite*[3]	*"disequilibrium" kamacite-troilite-pentlandite*[6,8,10]	*"equilibrium" kamacite-troilite-pentlandite or kamacite-taenite-troilite*[6,8,10]	
			CV	*CO*
			nickel in pentlandite[1,10]	*nickel in nickel-iron*[1,10]

References:

1. *Anders et al 1976*
2. *McSween 1977e*
3. *Mason 1963c*
4. *Mason 1971a*
5. *Method et al 1975*
6. *Van Schmus 1969a*
7. *Van Schmus and Hayes 1974*
8. *Van Schmus and Wood 1967*
9. *Wood 1967a*
10. *Wood 1967b*

while the results for the third suggested that in addition to magnetite some metallic iron and possibly troilite were present.

Table 7.7 shows that groupings of the carbonaceous chondrites on the basis of magnetic minerals cut across chemical and petrographic subdivisions.

The constancy of composition within the different established groups of the carbonaceous chondrites is possibly suggestive of separate locations of formation. The variations in opaque mineral contents revealed by these magnetic studies possibly reflect fluctuations in redox

Table 7.7 : Magnetic groups withing the carbonaceous chondrites.

Group	*Minor magnetite plus a significant amount of troilite which produces magnetite*	*Significant percentage of magnetite plus minor troilite and/or nickel-iron which produces magnetite*	*Predominantly magnetite with negligible further thermal breakdown*
C1		*C1I*	*C1I*
		Revelstoke	*Alais*
			Ivuna
			Orgueil
			Tonk
C2	*C2M*	*C2M*	*C2M*
	Boriskino *Murray*	*Haripura*	*Bells*
	Cold Bokkeveld *Nawapali*		
	Crescent *Nogoya*	*C2V*	*C2V*
	Erakot *Pollen*		
	Mighei *Santa Cruz*	*Al Rais*	*Al Rais*
	Murchison	*Renazzo*	
C3	*C3V*	*C30*	*C30*
	Allende	*Isna*	*Ornans*
	Arch	*Felix*	*C3V*
	Efremovka	*Kainsaz*	*Bali*
	Leoville	*Lance*	*Grosnaja*
	Vigarano	*Warrenton*	*Kaba*
C4		*C4V*	*C?*
		Coolidge	*Karoonda*

conditions which affected the mineralogy but not the bulk composition (McSween and Richardson 1977). Hence, the basic classification of a carbonaceous chondrite cannot be unambiguously deduced from its magnetic properties, but subdivisions of the main groups could possibly be established on such a basis. In these cases, there would be some correlation between these subgroups and the oxidised and reduced ones of McSween (1977b).

7.6 KAROONDA

7.6.1 Introduction

Since the spectacular fall and subsequent recovery of this meteorite in 1930 many aspects of its chemistry, mineralogy and other properties have been studied (cf. Chapter A3). Mawson (1934), in the initial description and analysis of the meteorite, recognized problems associated with its classification and such problems have beset the characterization of the meteorite ever since. Few analyses of its bulk composition have been published and several authors (e.g. McCarthy and Ahrens 1972, Nichiporuk and Moore 1974, and McSween 1977a) have suggested that a new analysis might remove several points of contention concerning its classification and genesis.

It is without doubt a carbonaceous chondrite. The problem is to which of the petrologic and petrographic subgroups does it belong, does it fit into the A and B chemical subgroups of Van Schmus and Hayes (1974), the AB group of Fitzgerald and Jones (1977) or ought a further group be defined to accomodate it? Table 7.8, containing a selection of comments from various authors illustrates the enigmatic nature of this meteorite.

A new analysis (Fitzgerald 1979) has resulted in a clarification of this situation and Karoonda is classified as C5V, although, as shown later, the distinction between the V and O groups becomes blurred at high petrologic grades.

Table 7.8 : Previous classsifications of Karoonda.

Classification	*Reference*
Unique - highly oxidised and equilibrated	*Schmitt et al (1972)* *Van Schmus and Wood (1967)*
Uncertain classification	*Van Schmus and Hayes (1974)*
Ornans subgroup	*Brecher and Arrhenius (1974)* *Evensen et al (1978)* *McSween and Richardson (1977)* *Mason (1971a)* *Van Schmus (1969a)* *Wasson (1974)*
Vigarano subgroup	*McSween (1977a)* *Takahashi et al (1978a,b)*
C4	*Evensen et al (1978)* *Salisbury et al (1978)* *Van Schmus and Wood (1967)* *Wasson (1974)*
C4 or C5	*Higuchi et al (1976)* *McSween (1977a)* *Srinivasan et al (1976, 1977)* *Van Schmus (1969a)* *Wood (1968)*

7.6.2 Classification based on bulk chemistry

a. Absolute and relative values

Figures 7.1 a and b indicate that Karoonda belongs with the C3-C6 chondrites and furthermore both figures are suggestive of a Vigarano classification.

Evensen et al (1978) measured the REE abundances in Karonda and their results are reproduced in Figure 7.3. Resemblances between the distribution pattern for Karoonda and Warrenton led these authors to concur with Wasson's (1974) classification of Karoonda as an Ornans type chondrite. Warrenton however, has, like Karoonda, undergone significant thermal metamorphism (McSween and Richardson 1977) and as discussed below it would appear that the distinction between the CO and CV meteorites tends to become blurred at high petrologic grades. Accordingly, the similarity between the REE distribution patterns of Karoonda and Warrenton does not necessarily imply an Ornans classification for Karoonda. Furthermore, the diagram indicates several resemblances between the Allende and Karoonda distribution patterns.

Ranges in atomic ratios were set out in Table 7.2 to distinguish between the A, B and AB chemical subgroups. Table 7.9 lists the values of these ratios for Karoonda. All values are from this work except for copper which is from Schmitt et al (1972).

The values of these ratios are indicative of an A group classification for Karoonda. Some of the values are near the A-B boundary. This positioning has at least two possible explanations. Karoonda may not belong to any of the A, B or AB subgroups as now defined, or, it may have experienced compositional alteration during the intense recrystallization it has experienced. Bearing these possibilities in mind,

Table 7.9 : Atomic ratios for Karoonda.

Fe/Si x10	*Mg/Si x10*	*Ca/Si x10^2*	*Al/Si x10^2*	*Ti/Si x10^3*	*Cu/Si x10^4*
7.6	*10.6*	*7.5*	*10.3*	*3.8*	*2.5*

Karoonda is assigned an A classification.

The transitional properties of Karoonda, which were also commented on by McSween (1977a), were also revealed by the multivariate techniques.

b. Multivariate techniques

i. Discriminant analysis

Karoonda was examined to investigate its relationship to the four subgroups defined in Section 7.3.3 a. The programme's output indicates the affinites of each individual by giving its distance from the mean of each of the defined groups and a probability of membership of each group.

The meteorites used to define the groups all lay within 4.5 units of the mean of their own groups. Karoonda was located 3.7 units from the mean of the Vigarano group with an associated probability of 0.95. This probability is only relative, i.e. given that Karoonda belongs to one of the defined groups then there is a probability of 0.95 that it belongs to the Vigarano subgroup. The possibility remains that it may belong to an undefined subgroup.

In a second analysis, omitting calcium from the data, Karoonda was still located 3.7 units from the centre of the Vigarano subgroup but its probability of membership had dropped to 0.83 and that of belonging to the Ornans subgroup had risen to 0.17. Within the limitation of the technique, this result still suggests a Vigarano classification.

ii. Principal component analysis

Figures 7.3 and 7.4 indicate that both Coolidge (C4V) and Karoonda occupy possitions suggestive of affinities with either the Ornans of Vigarano subgroups. In both cases, Karoonda is slightly more similar to the bulk of the Vigarano group than Coolidge and hence principal component analysis is also suggestive of a Vigarano classification for Karoonda.

iii. Canonical correlation analysis

Figure 7.5, a plot of the first two canonical variables for the large data set suggests a definite Vigarano classification for Karoonda while Figure 7.6, the plot for the smaller data set is inconclusive.

iv. Cluster analysis

Figures 7.8 and 7.9 show the Ornans and Vigarano meteorites clustered into two groups. In each case Karoonda is placed in the cluster containing both V and O meteorites. In both instances it can be seen that Karoonda resembles Coolidge more than any other, and it should be recalled that this is where the strength of cluster analysis lies, thus suggesting a Vigarano classification for Karoonda and at the same time highlighting the similarity of these two V-type meteorites to the O-group.

7.6.3 Classification based on mineralogical parameters

Although several criteria were listed in Table 7.6 which enabled the distinction to be made between the C1, C2 and C3 chondrites, the Coefficient of Variation of 0.4 for 50 olivine grain analyses for Karoonda indicates a high degree of equilibration and these are consequently not applicable. On the other hand, some of the mineralogical parameters used by Van Schmus and Wood (1967) to distinguish between type 4, 5 and 6 ordinary chondrites may be applicable.

The equilibrated nature of its olivine led Salisbury et al (1975) to classify Karoonda as a C4 chondrite but they pointed out that it did not display other type 4 characteristics. The absence of polysynthetically twinned clinopyroxene on the one hand and well developed feldspar on the other are indicative of a type 5 classification as is both the 0.1% carbon content (Mason and Wiik 1962b) and the high Na-Al correlation in Karoonda chondrules (Osborn et al 1974).

If the distinctions made between the Ornans and Vigarano subgroups in Table 7.6 are applicable to higher grades, then the absence of metal and the presence of nickel in the form of pentlandite (Mawson 1934, Mason and Wiik 1962b, Wood 1967b and McSween 1977a) are indicative of a Vigarano classification for Karoonda as is its texture of isolated grains and occasional "spongy" chondrules set in an abundant matrix (Van Schmus and Hayes 1974). On the other hand, the occurence of uniform, iron-rich olivine is apparently contradictory. This point is developed in Section 7.6.5.

7.6.4 Classification based on magnetic properties

Little unambiguous evidence bearing on the classification of Karoonda is available from a study of its magnetic properties.

The results of Brecher and Arrhenius (1974) indicate that if Karoonda belongs to the Vigarano subgroup then it is of high petrologic grade while those of Herndon et al (1976) which placed Karoonda in column 3 of Table 7.7 were even less conclusive.

7.6.5 Karoonda and the other metamorphosed carbonaceous chondrites

The major subdivisions of the carbonaceous chondrites which are based on substantial variations have a genetic significance and reflect varying conditions prior to, during, and after accretion.

Major, minor and trace element fractionations are all present in the carbonaceous chondrites. The author (Fitzgerald 1979a) compared selected properties of eight C3V chondrites with those of Coolidge, Karoonda and the recently described Western Australian meteorite Mulga West. Table 7.10 enlarges both the scope and extent of this comparison to include seven C3V chondrites and nine C2M and C3O as well as Isna and Warrenton which have both experienced significant thermal metamorphism (McSween and Richardson 1977). This table shows that in the case of these more strongly metamorphosed carbonaceous chondrites the values of the relative elemental abundances generally lie near the boundaries between the A and B subgroups. Furthermore, there is even a tendency for a progression paralleling the metamorphic grade to exist. In the case of calcium, for example, the values for Coolidge, Karoonda and Mulga West decrease from the average C3V value while those for Isna and Warrenton increase from the C3O average towards the A-B boundary. These trends may be due to little more than experimental error. However, their general consistency and the fact that the mineralogical data of Table 7.10 and the REE data of Figure 7.3 show a similar variation suggests that the trends are real and that these differences between the A and B subgroups disappear at high petrologic grades.

Minor and trace element data can be conveniently recorded in terms of depletion factors which are defined as the ratio of the abundance of an element relative to silicon (on an atomic basis) in the meteorite, to that in the C1 chondrites. Table 7.11 lists depletion factors for Cd,

Table 7.10 : Comparisons between the type 3 carbonaceous chondrites and more metamorphosed representatives.

	Chemical composition					Mineralogical composition		
	Fe/Si x10	Mg/Si x10	Ca/Si x10^2	Al/Si x10^2	Ti/Si x10^3	Olivine Fa	Principal opaque phase	
Arbitrary Limits[1]	7.1-7.7	10.6-11.1	7.5-9.0	9.6-13.5	3.0-4.0			
Seven C3V*								A SUBGROUP
Range	6.7-7.5	10.7-11.2	8.3-9.9	11.0-14.1	3.4-4.0			
Average	7.2	11.0	8.8	12.1	3.7	7.6[5]	sulfide and metal or magnetite[5]	
Coolidge	7.6[3,4]	10.9[3,4]	7.9[3,4]	11.2[3,4]	3.5[3,4]	14.2[5]	sulfide, metal and magnetite[5]	
Karoonda	7.6[1]	10.6[1]	7.5[1]	10.3[1]	3.8[1]	34.2[1]	(chromian) magnetite and sulfide[6]	
Mulga West		10.5[2]	7.7[2]	12.3[2]		32[2]	chromian magnetite	
A - B BOUNDARY								
Warrenton	7.7[4]	10.9[4]	6.9[4]	9.1[4]	2.9[4]	33.9[8]	metal and sulfide[5]	
Isna	7.9[7]	10.4[7]	6.8[7]	9.5[7]	2.9[7]	32.2[7]	metal and sulfide[5]	
Nine C2M+C3O**								B SUBGROUP
Range	7.7-8.2	10.2-10.5	6.5-7.0	8.7-9.5	2.6-3.3			
Average	7.9	10.4	6.7	9.3	2.7	17.6[3]	metal and sulfide[5]	
Arbitrary Limits[1]	7.7-9.0	10.3-10.6	5.8-7.0	8.4-9.6	2.4-3.0			

References:

1. This work
2. Binns et al (1976)
3. Jarosewich (1966)
4. McCarthy and Ahrens (1972)
5. McSween (1977b)
6. Mason and Wiik (1962b)
7. Methot et al (1975)
8. Van Schmus (1969b)

*Allende, Bali, Efremovka, Kaba, Leoville, Mokoia and Vigarano

**Cold Bokkeveld, Felix, Kainsaz, Lance, Mighei, Murchison, Murray, Nogoya and Ornans.

See Table 7.3 for the sources of these data.

Table 7.11 : Depletion factors for Cd, Cu and Mn.

Meteorite	Mn	Cu	Cd
Allende	0.53[1]	0.52[1,8]	0.49[10]
Kaba	0.58[8,9]	0.55[8,9]	0.54[4]
Mokoia	0.56[6]	0.52[6,8]	0.34[4]
Vigarano	0.53[6]	0.54[6,8]	0.014[4]
Coolidge	0.44[6]	0.40[6,8]	0.092[11]
Karoonda	0.53[1]	0.46[1,8]	0.16[1,7,10,11]
Warrenton	0.61[6]	0.68[6,8]	0.006[4]
Felix	0.59[6]	0.69[6,8]	0.006[4]
Kainsaz	0.58[3]		0.009[4]
Lance	0.60[6]	0.66[6,8]	0.004[4]
Ornans	0.54[2]	0.65[2,8]	0.008[10]

References:

1. This work
2. Ahrens et al (1969)
3. Ahrens et al (1973)
4. Anders et al (1976)
5. Clarke et al (1970)
6. McCarthy and Ahrens (1972)
7. Matza and Lipschutz(1977)
8. Schmitt et al (1972)
9. Sztrokay et al (1962)
10. Takahashi et al (1978a)
11. Takahashi et al (1978b)

Cu and Mn for several type 3 and higher carbonaceous chondrites. This table shows little systematic variation in the case of manganese but for the other two elements the values for Coolidge, Karoonda and Warrenton appear to diverge from the boundaries between the A and B chemical subgroups in contrast to the trends shown by the major elements in Table 7.10, suggesting that both major element compositions and mineralogical parameters are of limited use for the classification of carbonaceous chondrites of high petrologic grade. By contrast, the trends shown by the copper and cadmium data suggest that differences betwen the Ornans and Vigarano groups become more marked at high petrologic grades and so may provide the best means of classifying such carbonaceous chondrites. Van Schmus and Hayes (1974) also commented on the usefulness of copper data.

It is generally accepted (Wasson and Chou 1974) that the C1, C2 and C3 chondrites are mixtures of volatile-rich (matrix) and volatile-poor (chondrule plus metal) fractions. It has been suggested that the ordinary chondrites formed in a similar way but this suggestion, at least in the case of the ordinary chondrites of petrologic type 4, 5 and 6, is presently the subject of considerable controversy. As the number of carbonaceous chondrites belonging to high petrologic grades is limited, the controversy has not formally included them but the implications of it cannot be neglected. In essence, the controversy revolves around the chondrites of highest petrologic grade and whether they accreted in the central or outer portions of the parent body with their lack of volatiles arising from incomplete condensation prior to accretion or from outgassing after accretion. Both theories do, however, allow for post-accretionary metamorphic events.

The condensation temperatures of the refractory elements examined in Table 7.11 are so high that it is most unlikely that the fractionations exhibited by these elements were brought about during a metamorphic heating event and so they are more than likely the results of pre-accretionary events. Thus, it is possible that the A and B chemical subgroups are samples of two separate parent bodies, which in turn, have sampled slightly different portions of the solar nebula. Larimer and Anders (1967) suggested that the carbonaceous chondrites accreted towards the outer fringe of the asteroid belt while the ordinary and enstatite chondrites which are successively more depleted in refractory elements accreted at the centre and inner fringe respectively. If the A and B subgroups of the carbonaceous chondrites correspond to material from different parent bodies, it is possible that the A group (Vigarano type) parent body was further from the sun than the B group parent.

Regardless of the exact order of accretion of the C4-C6 chondrites, it appears that it was prior to the C1-C3 and so it is possible that the regions sampled by the earlier accreted members of the A and B subgroups were very similar and thus high-petrologic grade members of either group show little variation from each other in refractory element content. By the time the C3 meteorites accreted, the regions of the nebula being sampled bore less resemblance to each other thereby producing more marked differences between the C3O and C3V chondrites but in such a manner that minor variations observed in the C4-C6 chondrites became more pronounced in their C2 and C3 counterparts.

Variations in the distribution of the minor elements may also be functions of their geochemical natures. Manganese, one of the least volatile elements, condenses as a silicate (Mn_2SiO_4 - Wai and Wasson 1977, or $MnSiO_3$ - Larimer 1967) which is readily incorporated into pre-existing silicate structures. The small variations in manganese content seen in Table 7.11 sugest

that the parent bodies formed before any significant fractionation of this element had taken place. Its stability and volatility are such that subsequent events had little effect on its abundance even though as shown by McSween (1977a) it was remobilized, along with iron, during a subsequent metamorphic event. Copper, another of the less volatile elements, condenses as the element but is subsequently readily incorporated into sulfide phases while the highly volatile cadmium condenses directly as the sulfide (Larimer 1967).

Such trace element fluctuations are variously interpreted as occuring during accretion or subsequent metamorphic events. The exact cause however, does not affect the suggestion made above that they are of great value in characterizing the high petrologic grade members of the A and B subgroups as the trends appear to be too marked to be random. The chemical differences between the recrystallized meteorites are thus minimal but this does not necessarily minimize their significance, particularly if the meteorites represent samples of different regions of the solar nebula. Even though metamorphism would not appear to be responsible for the variations in refractory element chemistry, it cannot be ignored as the equilibrium seen in the Coolidge, Karoonda and Mulga West olivine was no doubt effected during this process. Simultaneous iron and magnesium mobilization which resulted in an increase in the Fe/Mg ratio in the chondrules and other inclusions was sometimes accompanied by a complementary decrease in this ratio in the matrix (McSween 1977a,b). The present volatile trace element depletion pattern in Karoonda has been seen as evidence both for open system (Matza and Lipschutz 1977) and closed system (Takahashi et al 1978b) metamorphism.

The present properties of the recrystallized carbonaceous chondrites (as also the ordinary chondrites) thus reflect both variations inherent in the materials from which they formed and subsequent metamorphic events. There are only small, but nonetheless significant, differences between the recrystallized members of the A and B subgroups and accordingly care must be exercised in choosing parameters to distinguish between these groups.

The trends in major element chemistry discussed in this section are no doubt the reason for the intermediate nature of Karoonda suggested by several of the multivariate techniques and explain the apparent conflict between different classifications based on various parameters.

7.6.6 Conclusion

Chemical and mineralogical evidence suggest a Vigarano classification for Karoonda. The proximity of Karoonda, on the basis of major element chemistry, to the dividing line between the A and B subgroups has been explained by suggesting that the distinction, on these grounds, between the two groups, becomes blurred at high petrologic grades. There are other possible explanations for this behaviour. Karoonda may, for example, belong to some, as yet undefined, group. However, despite this, it is here classified as a C5V meteorite - a classification which is supported by the trace element data given above and is in line with some of the suggestions of Table 7.8.

7.7 ADELAIDE

7.7.1 Introduction

Adelaide, a recently discovered meteorite, was initially described by Davy and Whitehead (1972) who classified it as a carbonaceous chondrite on the basis of the ratio SiO_2/MgO and the presence of carbon. As pointed out above, neither of these parameters is necessarily diagnostic of a carbonaceous chondrite. The attention of the author was drawn to this meteorite by, among other things, some unusual features of the reported bulk composition.

7.7.2 Classification based on bulk chemistry

a. Absolute and relative values

The calcium content of Adelaide, as reported by Davy and Whitehead was very low, as was the Ca/Al ratio. Davy and Whitehead did not comment on this but they did mention a supposed low silica content. The meteorite was re-analysed by the author and Table 7.12 compares the results obtained in this work

Table 7.12 : Elemental composition of Adelaide.

	This work	*Davy and Whitehead (1972)*	*Range in carbonaceous chondrites-Mason (1971b)*
Fe	*21.69*	*21.64*	*17.76 - 25.94*
Mn	*0.187*	*0.14*	*0.137- 0.220*
Ti	*0.081*	*0.09*	*0.040- 0.140*
Ca	*0.941*	*0.92*	*0.87 - 1.87*
K	*0.027*	*0.01*	*0.031- 0.119*
P	*0.143*	*0.10*	*0.05 - 0.18*
Si	*15.68*	*15.24*	*9.71 - 16.29*
Al	*1.46*	*1.25*	*0.80 - 1.64*
Mg	*14.99*	*13.57*	*9.44 - 14.66*
Ni	*1.50*	*1.31*	*0.75 - 1.51*
S	*1.77*	*1.90*	*1.31 - 6.70*
Cr	*0.234*	*0.23*	*0.21 - 0.39*
Na	*0.292*	*0.04*	*0.30 - 0.55*

Table 7.13 : Atomic ratios for Adelaide.

	Ordinary Chondrites	Carbonaceous Chondrites	Adelaide
Ca/Mg	3 - 10	3 - 10	3.8
Fe/(Fe+Mg) ($x10^2$)	15 - 60	15 - 60	39
Al/Si ($x10^2$)	4.5 - 8	8 - 15	9.7
Mg/Si ($x10^2$)	87 - 100	100 - 120	111

with those of Davy and Whitehead. With the exception of sodium the agreement is good to excellent.

The combination of low calcium and sulfur contents is unusual in the carbonaceous chondrites as can be seen from the compilations of Mason (1971b) with the calcium results suggesting a C1 carbonaceous chondrite and the sulfur a C3 classification. The high magnesium and silicon results are consistent with the C3 grouping. There are at least two possible solutions to this apparent anomaly - either the analyses are in error, perhaps due to sampling problems, or Adelaide is not a carbonaceous chondrite. The general agreement between the results obtained in this work and those of Davy and Whitehead using different techniques suggest that the analyses are not grossly inaccurate. (The analytical results of Davy and Whitehead are given by Davy et al (1978).) The carbonaceous chondrites were defined in Section 5.2.4 in terms of four elemental ratios and evaluation of these ratios (Table 7.13) shows that in each case they lie within the carbonaceous chondrite range and hence a carbonaceous chondrite classification for Adelaide seems inescapable.

The plot of Figure 7.1 a indicates a Group A classification for Adelaide while that of Figure 7.1 b suggests it resembles the B group in a rather uncertain fashion.

Figure 7.2 shows that Adelaide's REE distribution pattern is similar to that of the C2 chondrites Cold Bokkeveld and Murray (Evensen et al 1978) and different from those of the C1 and C3 chondrites. The figure shows that Adelaide fits in with several trends visible in the progression from Ivuna to Allende, such as the change in the abundance of Eu relative to Sm and Gd and that of Er relative to Dy and Yb. These results, though few in number, are consistent with, if not suggestive of, a C2 classification for Adelaide.

The A and B chemical subgroups of the carbonaceous chondrites were defined in Section 7.3.2 on the basis of several elemental ratios. Evaluation of these ratios for Adelaide (Table 7.14) indicates that it belongs to neither of these subgroups.

b. Multivariate techniques

i. Discriminant analysis

When compared to the other carbonaceous chondrites, Adelaide was found to be most similar to the Ornans group, being located about 7.7 units from the mean of this group with an associated probability of 0.95. Due to its low calcium content and the output from the programme which indicated that calcium was playing a significant role in distinguishing between the O and V groups, calcium was eliminated from the data and the analysis repeated. Adelaide was then located 6.4 units from the mean of the Vigarano group with a membership probability of 0.89. This allocation must be viewed with caution since the meteorites defining the group were all within 4.3 units of its mean. The results underline the importance of Adelaide's calcium content and its similarity in other respects to the Vigarano subgroup.

ii. Principal component analysis

Since calcium did not contribute significantly to any of the first three eigenvectors of either of the data sets used, a comparison of Adelaide with the other carbonaceous chondrites was not affected by its low calcium content. Analysis of either data set (Figures 7.3 and 7.4) clearly associated Adelaide with the C3V chondrites.

Table 7.14 : Atomic ratios for Adelaide.

	Fe/Si x10	Mg/Si x10	Ca/Si $x10^2$	Al/Si $x10^2$	Ti/Si $x10^3$	Cu/Si $x10^4$
A	7.1 - 7.7	10.6 - 12.0	7.5 - 9.0	9.6 - 15.0	3.0 - 4.0	2.0 - 3.4
B	7.7 - 9.0	10.0 - 10.6	5.8 - 7.0	8.0 - 9.6	2.4 - 3.0	3.4 - 6.0
Adelaide	7.0[1]	11.1[1]	4.2[1]	9.7[1]	3.0[1]	2.3[1,2]
	7.1[2]	10.3[2]	4.1[2]	8.7[2]	3.5[2]	2.3[2]

References: 1. This work.
2. Davy et al (1978).

iii. Canonical correlation analysis

The results of the canonical correlation analyses of both the large and small data sets (Figures 7.5 and 7.6) suggested slightly different classifications for Adelaide. In the case of the large data set it was clearly associated with the Vigarano group but when the reduced data set was examined both Adelaide and Karoonda plotted in such a manner that no unambiguous conclusion could be drawn.

iv. Cluster analysis

Figures 7.8 and 7.9 each have a group of meteorites containing C3V chondrites only and in each instance Adelaide is included in that group and is most similar to Efremovka. Ahrens et al (1973) commented that this meteorite and two other C3V chondrites - Coolidge and Leoville - (all members of McSween's (1977b) reduced group) appeared to be characterized by a significantly low Ca/Al ratio. Both diagrams show that Leoville is quite similar to Adelaide and Efremovka while the more metamorphosed Coolidge shows a greater resemblance to Karoonda.

7.7.3 Classification based on mineralogical parameters

Preliminary S.E.M. investigations of the matrix of Adelaide shows that it is neither olivine nor pyroxene and it seems likely that it is composed of layer structure silicates. Magnetite grains are also present in the matrix. The olivine exhibits a wide range in composition with an X.R.D. trace showing marked peaks corresponding to compositions of Fa_1 and Fa_{42}. Most of the pyroxene grains analysed by Davy et al (1978) had compositions of Fs_1. Davy et al also recorded the presence of troilite, pentlandite and kamacite in Adelaide. Table 7.6 showed the classification of carbonaceous chondrites on mineralogical grounds, Table 7.15 applies these criteria to Adelaide to arrive at its classification.

Davy et al (1978) also argued for a C2 classification but some of their criteria are ambiguous. They cited the presence of well defined chondrules but in the section examined in this work, many of the larger grains appeared to be sub- to anhedral grains of olivine. Likewise, it is not the presence of a nickel-bearing sulfide phase which is indicative of a C2 chondrite, but rather the disequilibrium assemblage pentlandite-troilite-kamacite which is found in Adelaide.

Table 7.15 : Classification of Adelaide based on its mineralogy.

Nature of matrix	C2[1]
Olivine composition	C2[1]
Pyroxene composition	C2[2]
Sulphide composition	C2[2]
Consensus	C2

References:

1. *This work*
2. *Davy et al 1978.*

7.7.4 Conclusion

Textural resemblances between Adelaide and Murchison suggest that Adelaide has an affinity for the C2M subgroup, while many facets of its chemistry suggest it has many features in common with the Vigarano subgroup but deviations from the average properties of this subgroup are such as to sugest that it does not readily fit into it. Thus, the classification of Adelaide as a C2 meteorite is definite but its petrographic affinities are enigmatic and a final classsification will be deferred until after the next section .

7.8 THE K-GROUP CARBONACEOUS CHONDRITES

7.8.1 Chemical considerations

McSween (1976b) described a meteorite fragment which had been recovered in the lunar soil sample 12037 obtained during a traverse of Bench Crater, the stratigraphically youngest crater at the Apollo 12 landing site. This sample was first decribed and classified as a meteorite by Wood et al (1972) and the first bulk analysis given by McSween. Both of these authors pointed out several resemblances between Bench Crater and the C2 meteorites. Table 7.16 confirms its classification as a carbonaceous chondrite. The bulk composition of Bench Crater is very similar to that of Adelaide as shown by Table 7.17 and Figures 7.2, 7.4 and 7.5. These figures illustrate both the similarity of Adelaide and Bench Crater and their diversity from the other carbonaceous chondrites.

On an absolute basis, both Adelaide and Bench Crater are slightly enriched in aluminium relative to the other C2

Table 7.16 : Atomic ratios for Bench Crater.

	Ordinary Chondrites	*Carbonaceous Chondrites*	*Bench Crater*
Ca/Mg	*3 - 10*	*3 - 10*	*3.6*
Fe/(Fe+Mg) ($x10^2$)	*15 - 60*	*15 - 60*	*29*
Al/Si ($x10^2$)	*4.5 - 8*	*8 - 15*	*9.3*
Mg/Si ($x10^2$)	*87 - 100*	*100 - 120*	*110*

Table 7.17 : Elemental composition of Adelaide and Bench Crater.

	Absolute abundances			*Atoms relative to 100 silicon atoms*		
	ADELAIDE[1]	*BENCH CRATER*[2]	*AVERAGE C2*[3] *CHONDRITE*	*Adelaide*[1]	*Bench Crater*[2]	*Average C2*[3] *Chondrite*
Fe	*21.69*	*15.31*	*20.85 - 23.78*	*70.0*	*44.0*	*84.0*
Mn	*0.19*	*0.08*	*0.16 - 0.17*	*0.52*	*0.22*	*0.62*
Ti	*0.08*	*0.06*	*0.05 - 0.07*	*0.30*	*0.25*	*0.29*
Ca	*0.94*	*1.00*	*1.11 - 1.63*	*4.2*	*4.0*	*7.2*
K	*0.03*	*0.08*	*0.03 - 0.05*	*0.12*	*0.34*	*0.22*
P	*0.14*	*0.44*	*0.07 - 0.14*	*0.83*	*2.2*	*0.74*
Si	*15.68*	*17.67*	*12.2 - 14.3*			
Al	*1.46*	*1.59*	*0.98 - 1.21*	*9.7*	*9.3*	*8.4*
Mg	*14.99*	*16.77*	*10.8 - 14.2*	*110.5*	*110.0*	*104.0*
Ni	*1.50*	*1.34*	*1.17 - 1.34*	*4.6*	*3.6*	*4.6*
S	*1.77*	*5.3*	*2.8 - 5.4*	*9.9*	*26.3*	*23.0*
Cr	*0.23*	*0.41*	*0.30 - 0.31*	*0.81*	*1.3*	*1.2*
Na	*0.29*	*0.67*	*0.25 - 0.51*	*2.3*	*4.6*	*3.5*

References:

1. *This work*
2. *McSween (1976b)*
3. *Mason (1971b) - appropriate chapters except for K and Na - Nichiporuk and Moore (1974)*

chondrites, while Bench Crater is also depleted in iron and enriched in phosphorus and sulfur. Table 7.17 shows that Bench Crater is not significantly deficient in either calcium or aluminium relative to Adelaide. The small size of Bench Crater (3x1.5mm) raises the possibility that it is non-representative of the body from which it was broken and is simply a piece of matrix from a larger carbonaceous chondrite. The much larger Adelaide (ca. 2kg) must, however, be more representative. Table 7.18 shows that Bench Crater is not simply a specimen of "Murchison type" matrix. This table also shows that Bench Crater, like Adelaide, has a very low Ca/Al ratio compared to the "average" carbonaceous chondrite value of about 0.75.

The apparent iron deficiency in Bench Crater could have arisen from non-representative sampling of metal particles. Kamacite is the only nickel-iron phase present in type 2 carbonaceous chondrites (Wood 1967b) and the average composition of this mineral is fairly constant at around 5.5% nickel. Table 7.19 shows a recalculated analysis for Bench Crater with its iron content adjusted to that of Adelaide. This change could be brought about by the addition of 3 volume percent of kamacite to the Bench Crater fragment - this would be equivalent to a sphere of approximately 0.3mm radius. Mason and Wiik (1962a) reported metal grains with radius greater than 0.5mm in Renazzo. Addition of one such grain to Bench Crater would bring about significant changes in its bulk chemistry. On the other hand, this iron deficiency cannot be brought about by "oversampling" of pyroxene grains which are moderately

Table 7.18 : Comparison of Adelaide, Bench Crater and Murchison matrix.

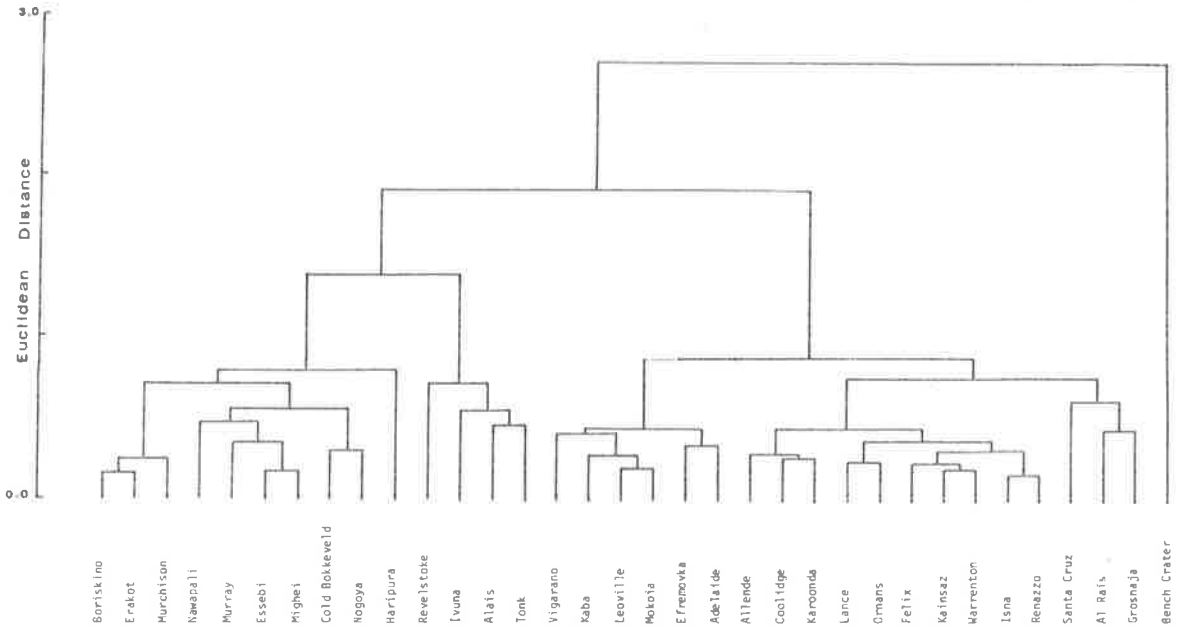
	Adelaide[1]	*Bench Crater*[3]		*Murchison*[2]	
	Bulk	*Matrix*	*Bulk*	*Matrix*	*Bulk*
Al/Si (x10^2)	*9.7*	*9.5*	*9.3*	*15.6*	*8.9*
Ca/Si (x10^2)	*4.2*	*2.6*	*4.0*	*3.8*	*6.9*
Ca/Al	*0.43*	*0.26*	*0.43*	*0.27*	*0.78*
Fe/Si	*0.70*	*0.46*	*0.44*	*1.22*	*0.81*
Mg/Si	*1.11*	*1.09*	*1.10*	*0.96*	*1.04*

1. *This work*
2. *Fuchs et al (1973)*
3. *McSween (1976b)*

Table 7.19 : Recalculated Bench Crater Analysis.

	Absolute abundances		*Atoms relative to 100 silicon atoms*		
	ADELAIDE	*BENCH CRATER*	*ADELAIDE*	*BENCH CRATER*	*AVERAGE C2*
Fe	*21.69*	*21.69*	*70.0*	*67.0*	*84.0*
Mn	*0.19*	*0.07*	*0.6*	*0.22*	*0.62*
Ti	*0.08*	*0.06*	*0.30*	*0.25*	*0.29*
Ca	*0.94*	*0.92*	*4.2*	*4.0*	*7.2*
K	*0.03*	*0.08*	*0.12*	*0.34*	*0.22*
P	*0.14*	*0.40*	*0.83*	*2.2*	*0.74*
Si	*15.68*	*16.25*			
Al	*1.46*	*1.46*	*9.7*	*9.3*	*8.4*
Mg	*14.99*	*15.42*	*110.5*	*110.0*	*104.0*
Ni	*1.50*	*1.68*	*4.6*	*4.9*	*4.6*
S	*1.77*	*4.87*	*9.9*	*26.3*	*23.0*
Cr	*0.23*	*0.38*	*0.81*	*1.3*	*1.2*
Na	*0.29*	*0.61*	*2.3*	*4.6*	*3.5*

Figure 7.13 : Q-mode cluster analyis of the full carbonaceous chondrite data set and Bench Crater.



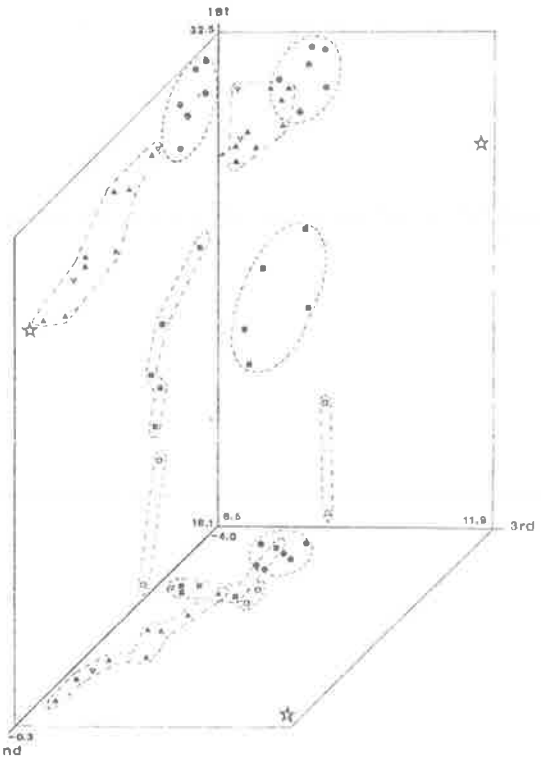
abundant in Bench Crater.

Terrestrial weathering effects ought also to be considered in this connection. Thus, for example, any epsomite originally present in Adelaide would most likely have been leached out, thereby affecting the magnesium content. Most of the sulfur in type 2 carbonaceous chondrites is present in the elemental form (Mason 1963c) which would likewise tend to be removed by terrestrial weathering. Hence, the apparent excess of sulfur in Bench Crater may be the result of the weathering of Adelaide rather than a reflection of original compositional differences.

Even though it has been suggested that the very low iron content of Bench Crater might be due to an undersampling of nickel-iron alloy grains and an analysis recalulated on this basis, discretion must be exercised in using this recalculated analysis in multivariate techniques.

Use of the original analysis resulted on each occasion in it being placed well away from all the other carbonaceous chondrites. Figure 7.13, for example, shows the result of a cluster analysis of a data set comprised of Bench Crater and the complete carbonaceous chondrite data. Even the adjusted analysis differed sufficiently in several respects from the other carbonaceous chondrites for Bench Crater to stand alone. Figures 7.14 and 7.15, illustrating the results of principal component and cluster analysis for the reduced data set plus Bench Crater, illustrate this. The cophenetic correlation coefficient of 0.82 in the latter instance shows that the addition of Bench Crater has not added to the distortion. Figure 7.16 shows that even when the full data set is used, the adjusted Bench Crater analysis stands aside from the other carbonaceous chondrites. In this instance, the cophenetic correlation coefficient of 0.77 shows that the addition of Bench Crater has again not adversely affected the analysis. Data normalization had no significant effect on the results of either the principal component or cluster analysis.

Figure 7.14 : First three principal components for the restricted carbonaceous chondrite data set and the recalculated Bench Crater analysis. □ : CI, ■ : CM, ● : CO, ▲ : CV, ▽ : Adelaide and Karoonda, ☆ : Bench Crater.



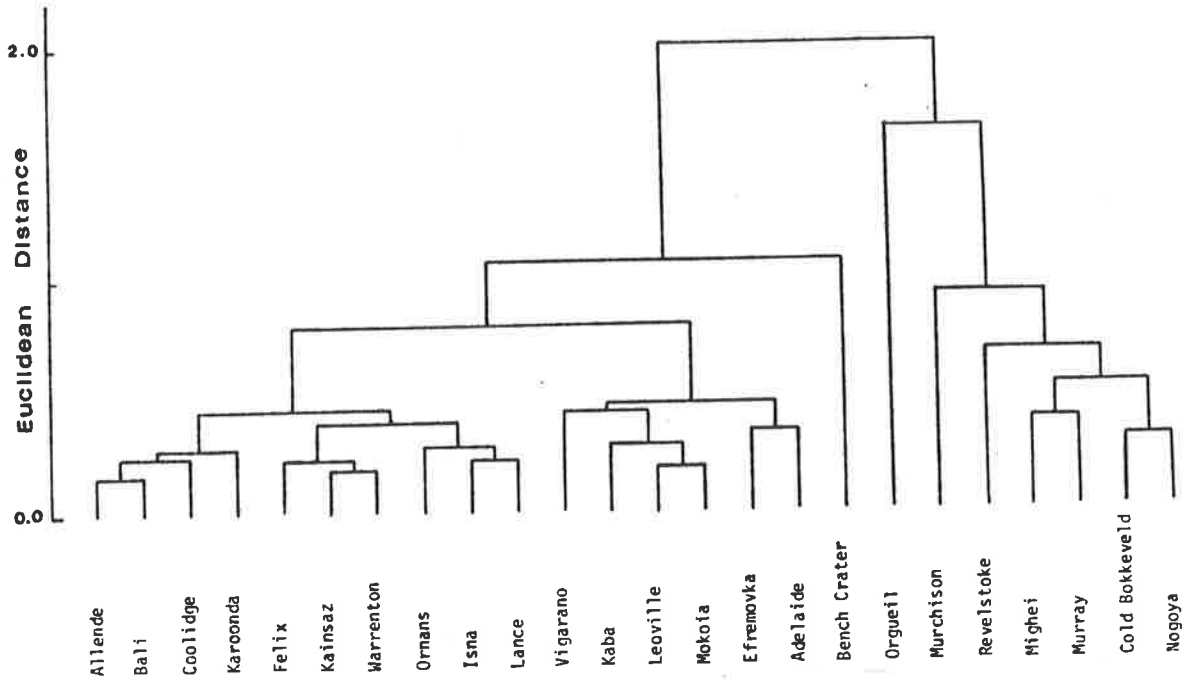


Figure 7.15 : Q-mode cluster analysis of the restricted carbonaceous chondrite data set and the recalculated Bench Crater analysis.

7.8.2 Mineralogical considerations

The mineralogies of Adelaide and Bench Crater are also quite similar. Magnetite is a common constituent of C1 and C2 chondrites, spherules of this mineral having been reported in several C1 chondrites. Rounded grains of magnetite occur in the matrix of Bench Crater (McSween 1967b) and similar grains, about 1 micron in diameter, are present in Adelaide. The size of these grains is intermediate between the two groups reported by McSween and unlike the framboidal aggregates of Bench Crater, the magnetite in Adelaide tends to occur as isolated grains. Troilite occurs in Bench Crater in euhedral grains (McSween) whereas

Figure 7.16 : Q-mode cluster analysis of the full carbonaceous chondrite data set and the adjusted Bench Crater analysis.

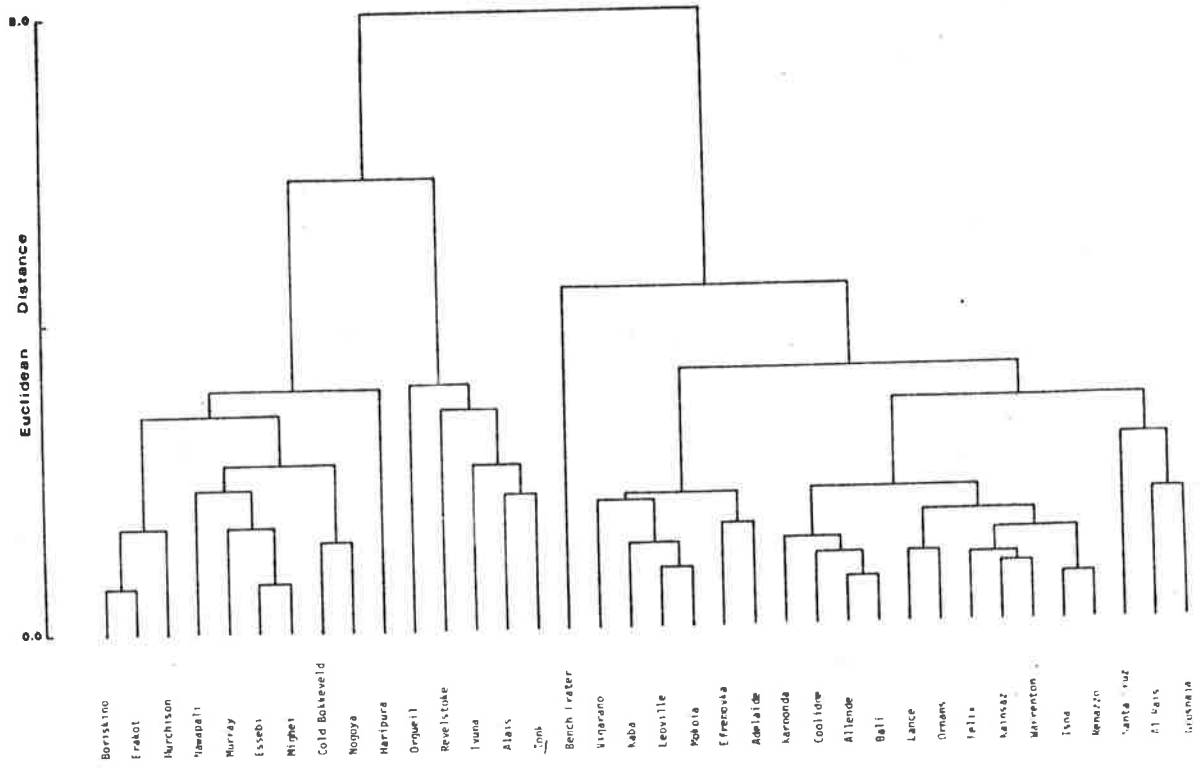


Table 7.20 : Atomic ratios for Adelaide and Bench Crater.

Group/ Meteorite	Fe/Si x10	Mg/Si x10	Ca/Si $x10^2$	Al/Si $x10^2$	Ti/Si $x10^3$	Cu/Si $x10^4$	Classification
A	7.1 - 7.7	10.6 - 12.0	7.5 - 9.0	9.6 - 15.0	3.0 - 4.0	2.0 - 3.4	
B	7.7 - 9.0	10.0 - 10.6	5.8 - 7.0	8.0 - 9.6	2.4 - 3.0	3.4 - 6.0	
AB	4.0 - 7.1	10.6 - 12.0	4.0 - 5.5	8.0 - 9.6	2.4 - 3.0	2.0 - 3.4	
Adelaide	7.0[1]	11.1[1]	4.2[1]	9.7[1]	3.0[1]	2.3[1,2]	AB
Bench Crater	4.4[3]	11.0[3]	4.0[3]	9.3[3]	2.5[3]		AB

References: 1. This work.
2. Davy et al (1978).
3. McSween (1976b).

in Adelaide it commonly occurs as rounded droplets, although there is a significant number of rectangular grains present. The margins have, in Adelaide, generally been corroded. Both Adelaide and Bench Crater contain far more troilite than pentlandite, a situation which is unusual for the C2 chondrites.

Thus, there are marked similarities between Adelaide and Bench Crater and the differences between them are probably explicable in terms of sampling and different environments subsequent fo fall.

7.8.3 Definition of the K-group

These resemblances between Adelaide and Bench Crater, first noticed by the author, led Fitzgerald and Jones (1977) to investigate them and several other similar meteorites. Evaluation of the ratios of Section 7.3.2 (Table 7.20) shows that Bench Crater deviates from the A and B subgroups in the same way as Adelaide. Since neither Adelaide nor Bench Crater can be accomodated in either of these two groups simply by extending their ranges, a new group must be defined for them. Since this new group overlaps with both the A and B subgroups it is proposed that it be called the AB subgroup and this is the terminology that was used by Fitzgerald and Jones to classify Adelaide and Bench Crater. Except for magnesium, the AB subgroup corresponds in each instance to smaller relative values of each of the elements. The compositional ranges for this new group are given in both Tables 7.2 and 7.20.

Several other meteorites having conspicuously low values of the Ca/Al ratio are known. These include Mount Morris (Wis.), Pontlyfni, Winona and possibly Kakangari, as well as chondritic inclusions in Cumberland Falls and Plainview (1917). On the basis of the analyses of these meteorites (Table 7.21) and other results such as oxygen isotope measurements, Fitzgerald and Jones concluded that Kakangari was a carbonaceous chondrite with marked similarities to Adelaide and Bench Crater. (Mason and Wiik (1966a) also concluded that Kakangari was a carbonaceous chondrite, but of uncertain affinities.)

Because of this apparent similarity, Fitzgerald and Jones placed the three meteorites together in the AB chemical subgroup and as their petrographic features were different from the other defined groups, they defined a new subgroup of the carbonceous chondrites which they called the K or Kakangari group. They used this nomenclature since Graham and Hutchison (1974) had already suggested the establishment of a group of chondrites to be known as the K-group chondrites. Table 7.21, containing new data for Kakangari (Graham et al 1977), suggests that it is not a carbonaceous chondrite. This does not affect the resemblances between Adelaide and Bench Crater and so ironically Kakangari apparently does not belong in the group named after it. Graham et al (1977) grouped Kakangari together with Mount Morris (Wis.).

Table 7.21 : Atomic ratios for selected meteorites.

Meteorite	Ca/Al	Fe/Fe+Mg $x10^2$	Ca/Mg	Mg/Si x10	Al/Si $x10^2$
Adelaide[1]	0.43	39	3.8	11.1	9.7
Bench Crater[5]	0.43	29	3.6	11.0	9.3
Mount Morris[4]	0.47	35	3.4	10.0	7.3
Winona[7]	0.50	31	3.5	9.7	6.7
Pontlyfni[4]	0.51	55	5.1	9.5	9.4
Cumberland F[2]	0.49	35	4.4	9.4	8.4
Plainview PV7a[3]	0.55	43	4.6	9.3	7.8
Kakangari[4]	0.67	41	5.1	9.8	7.1
Av. C2[6]	0.76	44	6.8	10.4	9.4
Av. C3[6]	0.75	42	7.4	10.7	10.5

References:
1. This work
2. Binns (1969)
3. Fodor and Keil (1976)
4. Graham et al (1977)
5. McSween (1976b)
6. McSween and Richardson (1977)
7. Mason and Jarosewich (1967)

Pontlyfni and Winona as forsterite chondrites but results of oxygen isotope analyses (Clayton and Mayeda 1978) preclude this grouping also, emphasising the unusual nature of Kakangari.

7.8.4 Origins of the K-group

Comparison of the average composition of C2 and C3 chondrites with those of the K-group chondrites (Table 7.21) shows that the origin of the low Ca/Al ratio is a marked calcium depletion coupled with an aluminium enrichment. This is relevant to considerations concerning the origins of these meteorites.

Anders (1964,1972) and Larimer and Anders (1967) suggested that the carbonaceous chondrites are mixtures of two components - a high and a low temperature fraction. The low temperature fraction consisted of the dark matrix, magnetite, epsomite, gypsum, sulfur and possibly limonite, while the high temperature fraction was comprised of olivine, pyroxene, several Ca-Al-(Ti-) rich silicates and metal and sulfides. Table 7.18 confirms the assignment of the Ca-rich phases to the high temperature fraction in Bench Crater and Murchison and also indicates the relative deficiency of these phases in Adelaide and Bench Crater. In the view of Fuchs et al (1973) the Ca-rich phases acted as crystallization nuclei for the olivine and pyroxene in the case of Murchison.

The calcium deficiency in Adelaide and Bench Crater can be explained by assuming a separate parent body for the CK meteorites which formed in a calcium-deficient region such that the earliest condensates were dominated by minerals such as spinel and lacked the calcium-rich ones such as melilite. Alternatively, the CK meteorites could be samples of the outer regions of a Murchison-like body which was deficient in the Ca-rich minerals on account of their early condensation and subsequent deep burial. The second alternative appears the more attractive as it lessens the number of parent bodies which must be predicated. It also explains the small number of CK chondrites currently represented in meteorite collections, since the outer layers of such a parent body would suffer much greater disruptive forces during any subsequent break-up of the planetesimal.

7.9 Final classification of Adelaide

The similarities between Adelaide and Bench Crater have now been detailed as well as their differences from the other known carbonaceous chondrites. They are both described here as C2K chondrites, the same classification which was given to them by Fitzgerald and Jones (1977). At present they stand as the sole definite members of this new subgroup.

Chapter 8

THE STONY AND STONY-IRON ACHONDRITES

8.1 INTRODUCTION

Consistent with the chondrite definition of Section 5.2, an achondrite is defined as a meteorite whose chemistry is unlike that of the sun. Although the term has been restricted to meteorites containing little or no free metal, in the light of the above definition, a departure will be made from this practice in this study. In virtually every case, chondrules are absent the textures of these differentiated meteorites having commonly been produced by the magmatic events responsible for their formation.

The achondrites have in the past been subdivided into calcium-rich and calcium-poor subgroups. Prior (1920) and Mason (1962b) proposed that each of these groups be further divided into four, viz. angrites, eucrites, howardites and nakhlites; and aubrites, chassignites, diogenites and ureilites. Due to the small number of known angrites, chassignites and nakhlites, Wasson (1974) suggested the elimination of these groups with their members being reclassified as anomalous achondrites.

The other differentiated meteorites are the irons, the irons with silicate inclusions, and the stony irons, which are often subdivided into mesosiderite and pallasite classes. The irons are discussed in Chapter 9, while little reference will be made to the pallasites which, with olivine and nickel-iron as their major minerals, are well documented elsewhere. This chapter includes a discussion of some of the irons with silicate inclusions and the mesosiderites. The latter class has been described as a convenient "rubbish bin" for meteorites, containing approximately equal proportions of metal and silicates, which wouldn't fit elsewhere (Wood 1963), but recent work has modified this situation and the mesosiderites are now a fairly well defined group containing some twenty members. Their relationship to other meteorites is still not fully known but some suggestions are made in this chapter.

As pointed out by Wasson (1974), some of the traditional meteorite subdivisions have concealed important genetic relationships. For example, there is a growing body of evidence which suggests that the calcium-poor diogenite and the calcium-rich eucrite and howardite achondrite groups are all related to the mesosiderites. It is proposed that the meteorites belonging to these groups be classed together under the name "cognate achondrite". In general, this group can then be subdivided into four.

The non-chondritic South Australian meteorites, Muckera and Pinnaroo, are discussed in this chapter and, in addition, reference is made to the Western Australian specimen, Millbillillie No.3. Their classification is confirmed in the section devoted to chemical considerations and their mineralogy is shown to be consistent with such classifications. The discussion in the mineralogy section extends to other South Australian and foreign meteorites in an attempt to explain this mineralogy, while, in the last section, a synthesis of this and other material is made in an attempt to explain some facets of the origins of these meteorites.

8.2 CLASSIFICATION BASED ON BULK CHEMISTRY

8.2.1 Absolute

The traditional calcium-rich and calcium-poor achondrite groups are readily distinguished, in most cases, on the basis of their calcium contents. Table 5.3, which ignores this distinction, shows that the achondrites can still be readily distinguished on the basis of absolute composition. (If the composition of the silicate phase only is considered, the mesosiderites, will, however, be grouped with the howardites.) Table 5.8, based on the criteria of Table 5.3, listed Muckera as a howardite and Pinnaroo as a mesosiderite. Application of the same criteria produces a eucrite classification for Millbillillie No.3.

8.2.2 Relative

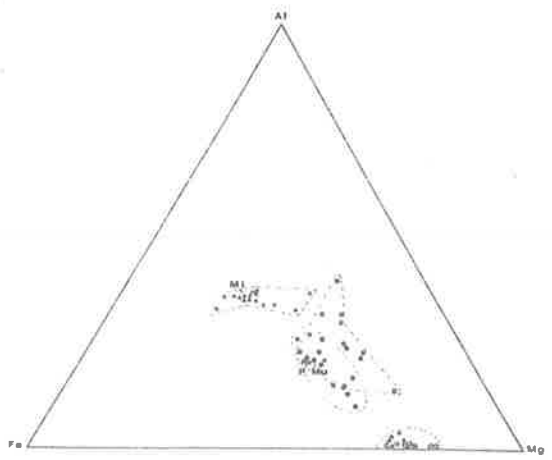
Application of the relative criteria proposed in Table 5.4 results in the same classification for these meteorites (Table

Table 8.1 : Sources of achondrite analyses.

Barea	10	*Hainholz*	11	*Mount Padbury*	4	1.	*This work*
Bereba	7	*Haraiya*	7	*Muckera*	1	2.	*Duke and Silver (1967)*
Binda	7	*Havero*	18	*North Haig*	5	3.	*Lovering (1975)*
Bondoc	11	*Ibitara*	16	*Norton County*	14	4.	*McCall (1966)*
Bununu	9	*Johnstown*	6	*Novo-Urei*	17	5.	*McCall and Cleverly (1968)*
Cachari	7	*Juvinas*	7	*Nuevo Laredo*	2	6.	*McCarthy et al (1972)*
Chaves	6	*Kapoeta*	15	*Pasamonte*	7	7.	*McCarthy et al (1973)*
Clover Springs	17	*Lakangaon*	8	*Patwar*	11	8.	*McCarthy et al (1974)*
Crab Orchard	11	*Lowicz*	11	*Pinnaroo*	1	9.	*Mason (1967e)*
Dingo Pup Donga	5	*Luotolax*	17	*Serra de Mage*	7	10.	*Mason and Jarosewich (1973)*
Dyalpur	17	*Macibini*	7	*Shalka*	6	11.	*Powell (1971)*
Dyarrl Island	10	*Malvern*	6	*Sioux County*	7	12.	*Shima (1974)*
Ellemeet	6	*Manegaon*	8	*Stannern*	7	13.	*Symes and Hutchison (1970)*
Emery	10	*Medanitos*	13	*Tatahouine*	6	14.	*Von Michaelis et al (1970)*
Estherville	11	*Millbillillie No.3*	1	*Vaca Muerta*	11	15.	*Wanke et al (1972)*
Frankfort F	6	*Moama*	3	*Veramin*	11	16.	*Wanke et al (1974)*
Frankfort T	6	*Moore County*	7	*Yamato 6902*	12	17.	*Wiik (1969)*
Goalpara	17	*Morristown*	11	*Zmenj*	6	18.	*Wiik (1972)*

5.8). Deuser (1968) distinguished between four achondrite groups by calculating the ratios Fe/Mg and Fe/Al and plotting his results on a triangular diagram. Figure 8.1 shows a similar diagram constructed using results obtained in this work and literature values as shown in Table 8.1. The calcium-rich and calcium-poor groups are clearly distinguished from each other and the distinction between the eucrites and howardites is likewise fairly clear cut. However, there is little separation between the calcium-poor groups. The mesosiderites, plotting in a less cohesive field than any of the other achondrite groups overlap the howardites. Muckera plots in the howardite field and Pinnaroo in the mesosiderite one. The elongated nature of the eucrite field is significant and is discussed below.

Figure 8.1 : Fe-Al-Mg for a group of achondrites, (See Table 8.1). ○ : aubrites, △ : diogenites, ▲ : eucrites, ● : howardites, ■ : mesosiderites, □ : ureilites, Mi : Millbillillie No.3, Mu : Muckera, P : Pinnaroo.



8.2.3 Multivariate techniques

a. Preamble

Representative analyses of the various achondrite groups and the mesosiderites were used as input for the multivariate techniques to establish a. whether the techniques could distinguish these groups, and, b. to classify, if possible, the meteorites analysed in this work. Most of this work was done using the data of Table 8.1, but some was repeated when the compilation of eucrite and howardite analyses (Mason et al 1978) became available.

b. Discriminant analysis

Initially four groups (ureilite, diogenite, eucrite and howardite) were defined and the analysed meteorites tested against them. The distinctions between each of the four groups was clear cut, Millbillillie No.3 being grouped with the eucrites and Muckera and Pinnaroo with the howardites. When the number of groups was increased to five by adding literature values for the mesosiderites, the distinctions between each of the five groups were equally clear, Pinnaroo now being classified with the mesosiderites. These results illustrated on one hand, the power of discriminant analysis to separate the howardites and the mesosiderites, and on the other the relative nature of the technique.

c. Principal component analysis

Principal component analysis effectively separated the calcium-rich achondrites from the calcium-poor, and in addition, separated the individual groups within these two classes (Figure 8.2). Muckera falls in the

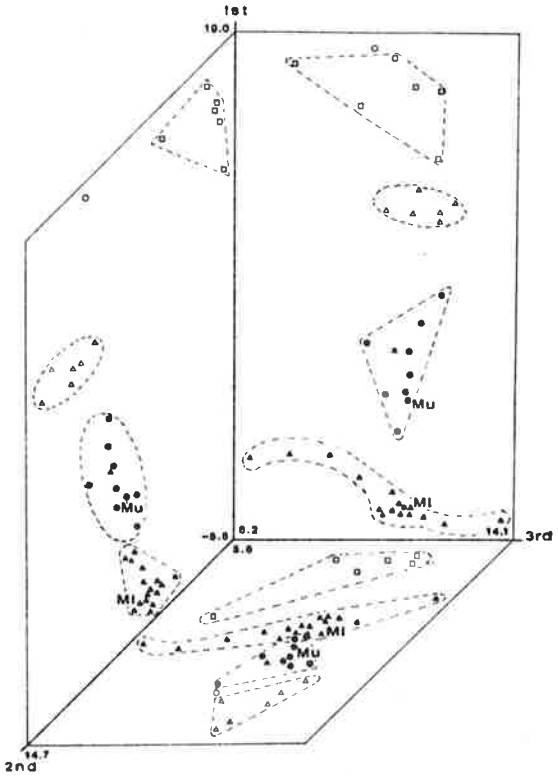
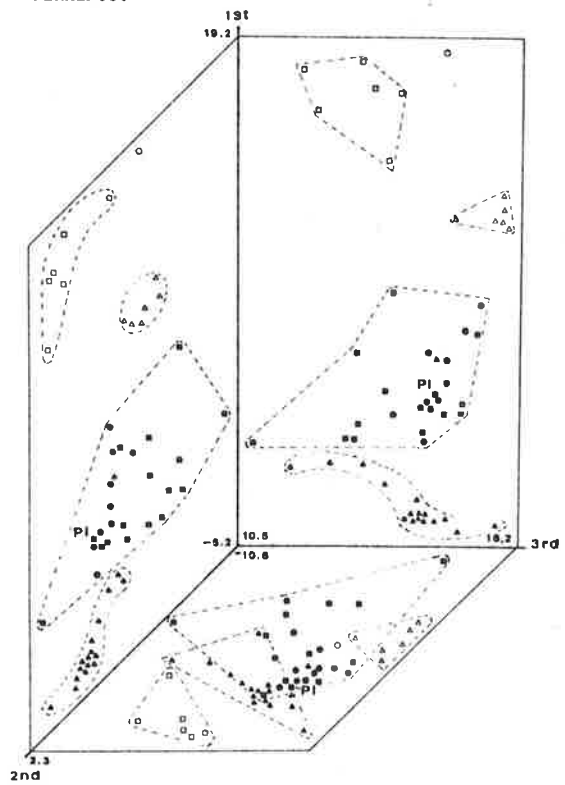


Figure 8.2 : First three principal components for a group of achondrites. ○ : aubrites, △ : diogenites, ▲ : eucrites, ● : howardites, □ : ureilites, Mi : Millbillillie No.3, Mu : Muckera.

howardite field and Millbillillie No.3 in the eucrite field. Addition of mesosiderite

Figure 8.3 : First three principal components for a group of achondrites, and mesosiderites. ○ : aubrites, △ : diogenites, ▲ : eucrites, ● : howardites ■ : mesosiderites, □ : ureilites, Pi : Pinnaroo.



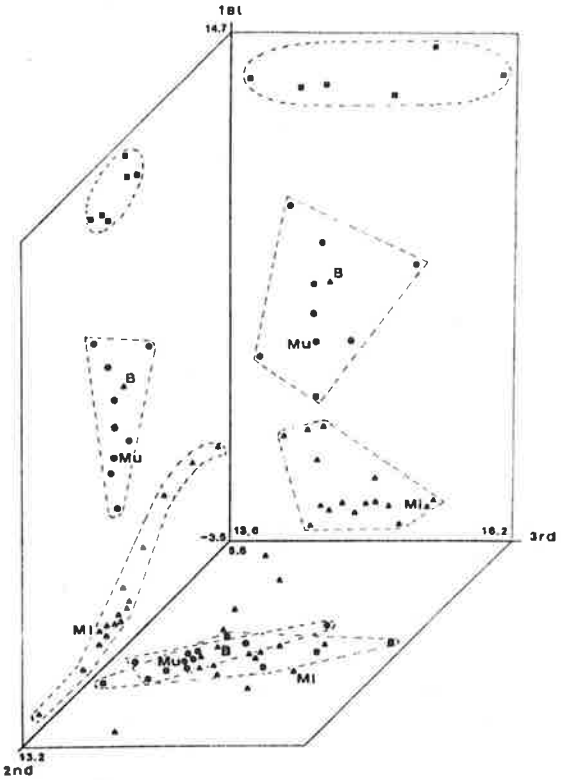


Figure 8.4 : First three principal components for a set of diogenites, eucrites and howardites. ■ : diogenites, ▲ : eucrites, ● : howardites, B : Binda, Mi : Millbillillie No.3, Mu : Muckera.

data has little effect other than spreading out the howardite field in which it plots. Pinnaroo falls in the combined howardite-mesosiderite field (Figure 8.3). Reduction of the data set so that it contained only diogenite, eucrite and howardite analyses (see also Section 8.7) produced an even more marked distinction between the eucrites and howardites (Figure 8.4).

Tables 8.2, 8.3 and 8.4 show the importance of magnesium in distinguishing the various groups. This reflects the mineralogy of the various groups as the calcium-poor meteorites are essentially "pyroxenites" and the calcium-rich ones, "basalts". The feldspar of the latter is reflected in the lowered magnesium content and also explains the calcium and aluminium contribution to the first eigenvector. The second eigenvector reflects iron and silicon variations when all the meteorites are examined, or iron and aluminium ones when only the calcium-rich specimens are analysed. These variations also closely correlate with the mineralogy, reflecting in the first instance the presence or absence of feldspar and in the second the relative amounts of this mineral. Normalization does not significantly alter the elements contributing to the variance represented by the eigenvectors.

Table 8.2 : Eigenvalues and eigenvectors for the achondrites.

Eigenvalues

Eigenvector	*%age Variance*	*Cumulative %age*
1st	*89.4*	*89.4*
2nd	*7.0*	*96.4*
3rd	*2.5*	*98.9*

Eigenvector elements both as absolute values and as percentages of the total variance.

	1st		*2nd*		*3rd*	
Fe	*-0.05*	*0.2*	*-0.48*	*1.6*	*0.76*	*1.4*
Mn	*-0.01*		*0.01*		*0.01*	
Ti	*-0.02*		*-0.01*		*0.02*	
Ca	*-0.36*	*11.4*	*-0.19*	*0.3*	*-0.30*	*0.2*
P			*-0.01*			
Si	*-0.09*	*0.7*	*0.84*	*4.8*	*0.26*	*0.2*
Al	*-0.35*	*10.8*	*-0.15*	*0.2*	*-0.45*	*0.5*
Mg	*0.86*	*66.3*	*-0.08*		*-0.24*	*0.1*

Table 8.3 : Eigenvalues and eigenvectors for the achondrites and the mesosiderites.

Eigenvalues

Eigenvector	*%age Variance*	*Cumulative %age*
1st	*81.8*	*81.8*
2nd	*12.6*	*94.4*
3rd	*4.2*	*98.6*

Eigenvector elements both as absolute values and as percentages of the total variance.

	1st		*2nd*		*3rd*	
Fe	*-0.01*		*0.79*	*7.9*	*0.51*	*1.1*
Mn	*-0.01*				*0.02*	
Ti	*-0.02*					
Ca	*-0.35*	*10.0*	*0.16*	*0.3*	*-0.26*	*0.3*
P			*-0.03*		*-0.04*	
Si	*-0.10*	*0.8*	*-0.59*	*4.4*	*0.62*	*1.6*
Al	*-0.35*	*10.2*			*-0.49*	*1.0*
Mg	*0.86*	*60.6*	*0.01*		*-0.23*	*0.2*

Table 8.4 : Eigenvalues and eigenvectors for the diogenites, eucrites and howardites.

Eigenvalues

Eigenvector	*%age variance*	*Cumulative %age*
1st	*94.3*	*94.3*
2nd	*4.7*	*98.9*
3rd	*0.7*	*99.6*

Eigenvector elements both as absolute values and as percentages of the total variance

	1st		*2nd*		*3rd*	
Fe	*-0.16*	*2.4*	*0.86*	*3.5*	*-0.25*	
Mn			*0.01*		*-0.03*	
Ti	*-0.02*		*0.03*		*0.13*	
Ca	*-0.44*	*17.9*	*-0.18*	*0.1*	*0.14*	
K					*-0.01*	
P					*-0.01*	
Si	*0.12*	*1.5*	*0.10*		*0.88*	*0.5*
Al	*-0.41*	*15.9*	*-0.43*	*0.9*	*-0.25*	
Mg	*0.77*	*56.7*	*-0.17*	*0.1*	*-0.24*	

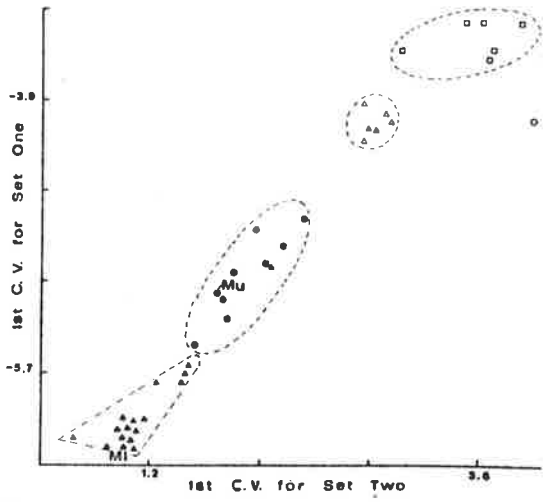
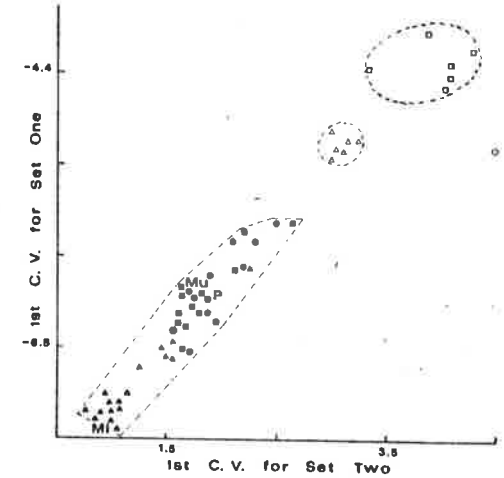


Figure 8.5 : First two canonical variables for a set of achondrites. ○ : aubrites, △ : diogenites, ▲ : eucrites, ● : howardites, □ : ureilites, Mi : Millbillillie No.3, Mu : Muckera.

d. Canonical correlation analysis

The R-mode cluster analysis described below suggests that one of the first two canonical variables ought to contain only magnesium. As this is not possible, manganese was added to this variable because of its low absolute abundance and overall low correlation with other elements in the whole data set (cf. Figure 8.16 for example). Analysis of a data set excluding the mesosiderites, with a correlation between the first two variables of 0.97, effectively distinguished five achondrite groups and placed Millbillillie No.3 with the eucrites and Muckera with the howardites (Figure 8.5). Addition of mesosiderite data effectively removed the eucrite-howardite distinction (Figure 8.6), but left the correlation between the first two canonical variables unchanged. Thus, like principal component analysis, this technique cannot distinguish between the howardites and the mesosiderites. Pinnaroo plotted in the combined field.

Figure 8.6 : First two canonical variables for a set of achondrites, and mesosiderites. ○ : aubrites, △ : diogenites, ▲ : eucrites, ● : howardites, ■ : mesosiderites, □ : ureilites, Mi : Millbillillie No.3, Mu : Muckera, P : Pinnaroo.



e. Cluster analysis

R-mode analysis of the achondrite data, both without and with the mesosiderites, divided the elements into two groups with cophenetic correlation coefficients of 0.86 and 0.84 (Figure 8.7 a and b).

i. Mg

ii. Ca, Al, Ti, Mn, Si, K, P and Fe

(Only nine elements are listed here as many of the analyses in the literature did not have data for nickel, sulfur, chromium or sodium.)

The major role of magnesium in distinguishing between the different achondrite groups is thus shown by both principal component analysis and R-mode cluster analysis. Since the differentiated meteorites have experienced substantial fractionations after accretion, the elemental associations revealed by this cluster analysis cannot be explained in terms of geochemical properties of the elements as they affect the accretionary process. However, the comments made in c. above concerning mineralogical correlations are relevant here also.

Q-mode analysis separated the calcium-rich and calcium-poor groups (Figure 8.8), and these groups in turn were separated into eucrite, howardite, diogenite and ureilite groups with a cophenetic correlation coefficient of 0.86. The sole aubrite, Norton County, was grouped with the ureilites. Millbillillie No.3 fell in the eucrite group and Muckera in the howardite one. Addition of mesosiderite data results in an increase in higher level distortions as revealed by the cophenetic correlation

Figure 8.7 : R-mode cluster analysis of the achondrites,

a. including the mesosiderites,

b. excluding the mesosiderites.

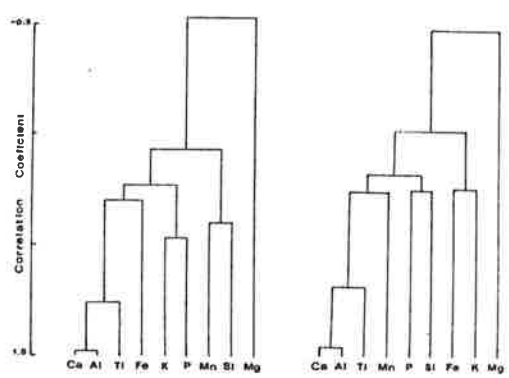
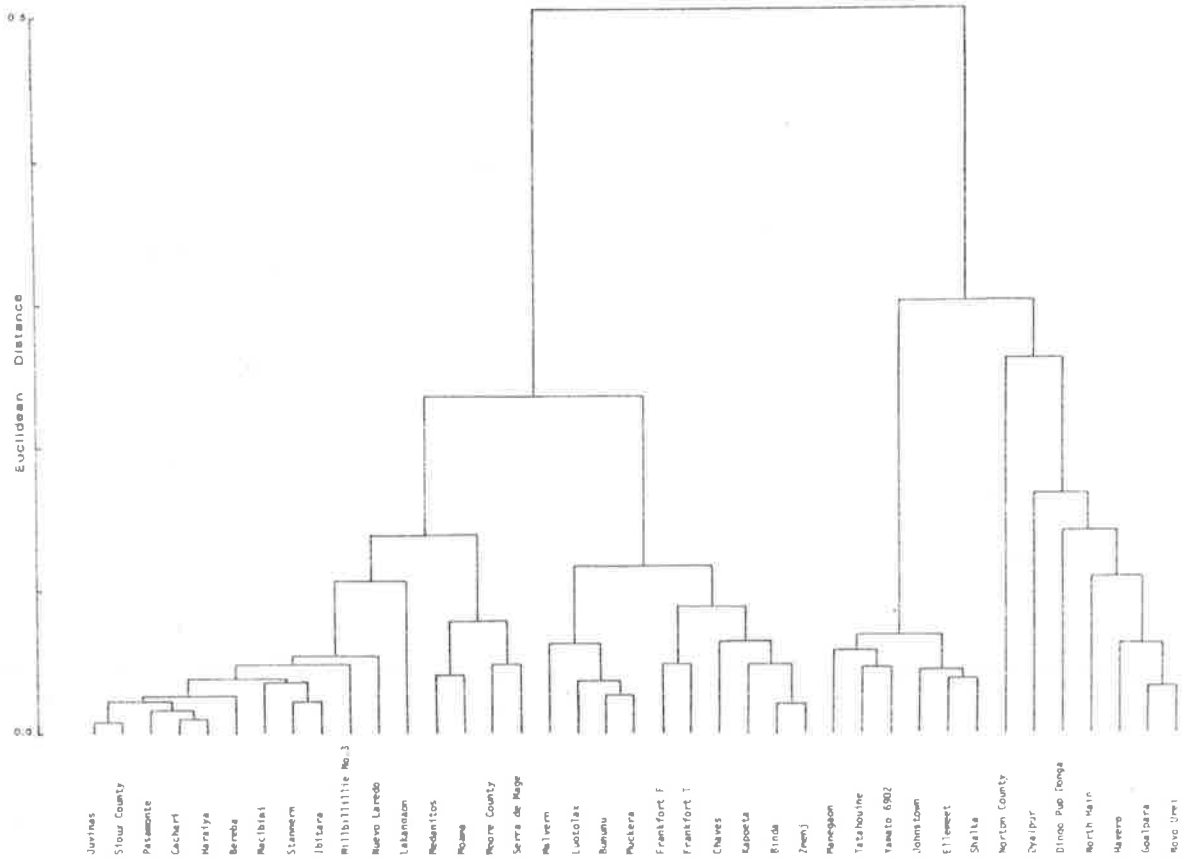


Figure 8.8 : Q-mode cluster analysis of the achondrites excluding the mesosiderites.



coefficient of 0.83. In this instance, the non-eucrite, calcium-rich meteorites are subdivided into three smaller groups, one containing only mesosiderites and the other two howardites and mesosiderites. Millbillillie No.3 was again placed with the eucrites while Pinnaroo fell along with Muckera in the group containing both howardites and mesosiderites (Figure 8.9).

Thus, of the multivariate techniques examined, only discriminant analysis was able to differentiate between the howardites and the mesosiderites. This distinction is trivial if the whole meteorite is considered but when only the silicate fraction of the mesosiderites is examined the resemblance to the howardites is very marked.

Figure 8.9 : Q-mode analysis of a set of achondrites including mesosiderites.

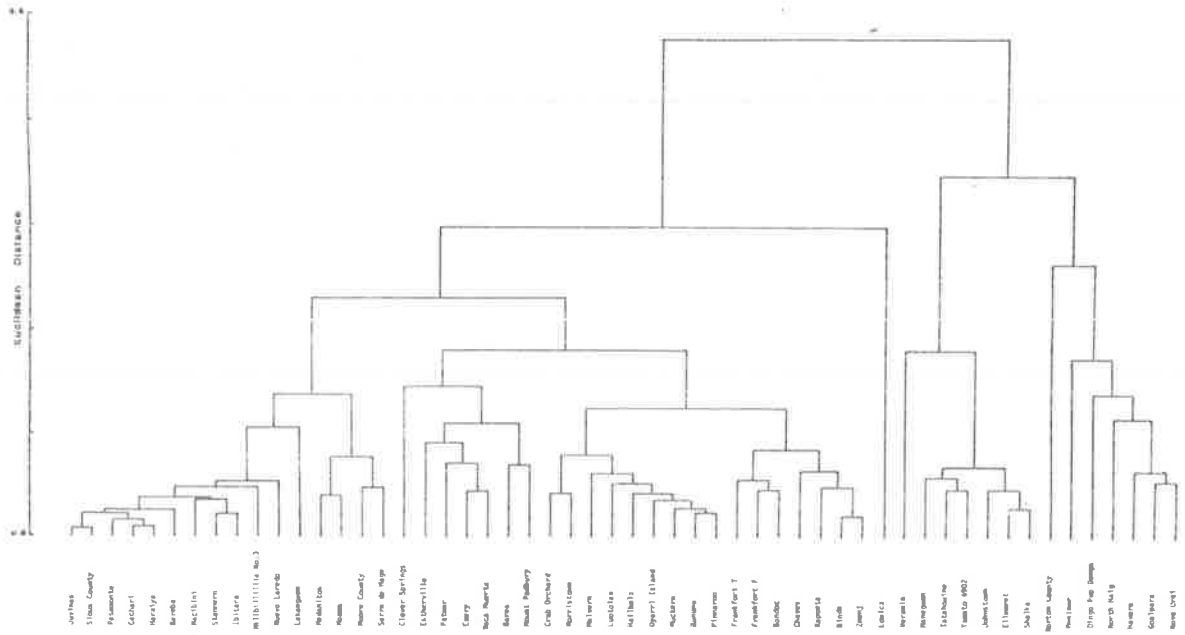


Table 8.5 : Achondrite mineralogy.

Achondrite Group	*Major minerals present*
aubrite	*enstatite*
diogenite	*hypersthene*
howardite	*hypersthene ± pigeonite, anorthite*
mesosiderite	*hypersthene ± pigeonite, anorthite*
eucrite	*pigeonite ± hypersthene, anorthite*
ureilite	*pigeonite, olivine*
pallasite	*olivine*

8.3 CLASSIFICATION BASED ON MINERALOGICAL PARAMETERS

8.3.1 Preamble

The chemical distinctions of Section 8.2 correspond to basic mineralogical differences among the achondrites. Table 8.5 summarizes the major mineralogy of these meteorites (Mason 1962b, McCall 1973).

The distinction between the eucrites and the howardites has also been made on a textural basis with the former being defined as monomict breccias and the latter as polymict (Wahl 1952). Generally, both this and the mineralogical definition lead to the same classification. The mesosiderites and pallasites are readily distinguished from the others by their metal content. The distinction between the mesosiderites and the irons with silicate inclusions is sometimes contentious. The mesosiderite silicates are generally polymict breccias which are very similar to the howardites.

The following sections involve the comparison of mineral compositions measured in this work with those recorded elsewhere.

8.3.2 Feldspar

Eucrite, howardite and mesosiderite feldspars fall in the compositional range An_{80-95}, the most common eucrite and howardite composition being in the range An_{85-90} (Duke and Silver 1967). Feldspar compositions measured in this work (Table 8.6) lie within these limits and are accordingly consistent with the proposed classification of these meteorites.

The table shows the Pinnaroo feldspar to be very uniform while that of the other two is more variable.

8.3.3 Olivine

There is an almost perfect balance between silica and the basic oxides in the eucrites and howardites and accordingly there is sometimes a slight excess of silica in the form of quartz or tridymite, or more rarely, a deficit which appears as olivine (Mason 1962b). The silica excess normally appears in the eucrites and the olivine in the howardites. This latter is rare but has been reported in several specimens (Duke and Silver 1967, Desnoyers and Jerome 1973). Its composition is not constant and variations of 15 or more Fa units, for example, have been reported by Desnoyers and Jerome for eight howardites, mean compositions lying in the range Fa_{10-80}.

Modal olivine was not observed in Millbillillie No.3 and minor amounts only in Muckera. In the latter cases it was confined almost exclusively to the dark ground mass with only a few grains being found in lighter clasts. The compositional range, as measured by the microprobe - Fa_{24-35} - is consistent with the results of Desnoyers and Jerome. The low absolute abundance precluded any X.R.D. determinations of its composition. Table 8.7 lists the content of normative olivine and quartz in Millbillillie No.3 and Muckera which are in accord with the observations of Mason et al (1978) and are consistent with Millbillillie No.3 being classified as a eucrite and Muckera as a howardite.

Olivine is invariably present in minor amounts in the mesosiderites, frequently occuring as megacrysts disseminated among the other silicates. The irregular nature of this distribution is illustrated by Pinnaroo. In spite of the presence of megacrysts with diameters up to 2cm (Alderman 1940), the overall abundance is such that attempts to utilize the material, used for bulk analytical work, for olivine composition determinations employing the standard X.R.D. method failed as the olivine peak was too small to permit accurate measurements. Samples of relatively pure olivine were therefore obtained with a dental drill from several megacrysts in a large slab. X.R.D. results obtained for this material differed from those obtained by the microprobe. The X.R.D. method gave a composition of $Fa_{10.8}$ while the microprobe result was $Fa_{18.2}$. Comparison of these values with reported mesosiderite ranges -

Table 8.6 : Feldspar compositions for Millbillillie No.3, Muckera and Pinnaroo.

Meteorite	*Range*	*Mean*	*Mode*
Millbillillie No.3	*78-92*	*84*	*82*
Muckera	*74-94*	*88*	*89*
Pinnaroo	*88-93*	*91*	*90*

Table 8.7 : Normative quartz and olivine contents of Millbillillie No.3, Muckera and Pinnaroo.

	Olivine[1]	*Quartz*[1]	*Olivine*[2]	*Quartz*[2]
Millbillillie No.3	*0.0*	*9.0*	*0.0*	*2.5*
Muckera	*0.5*	*0.0*	*2.9*	*0.0*

1. Results calculated using MINORM programme.

2. Results calculated using CIPW programme.

Figure 8.10 : Muckera pyroxenes.

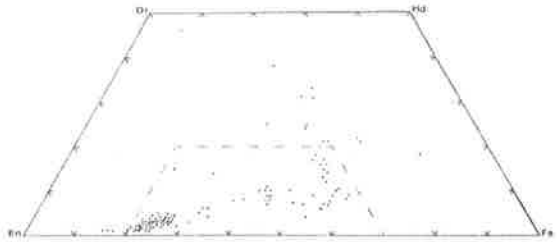
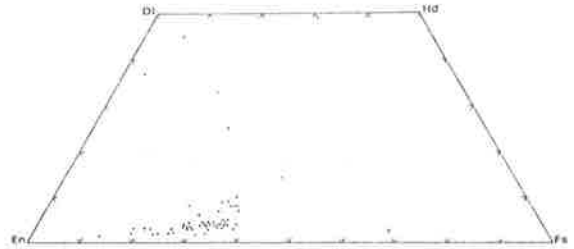


Figure 8.12 : Pinnaroo pyroxenes.



Fa_{9-25} (McCall 1965c), Fa_{20-40} (Powell 1971) and Fa_{16-51} (Wasson 1974) - suggests they are consistent with the mesosiderite classification.

The origin of mesosideritic olivine is the subject of some debate. The discussion centres around whether the olivine crystallized along with the other silicates or whether it was introduced subsequently. The olivine megacrysts in Pinnaroo generally have corroded and altered edges with trains of opaque minerals sub-paralllel to what appear to have been the original grain margins. Such textures are suggestive of post-crystallization alteration. The divergence of the olivine composition from what would be expected on the basis of the pyroxene composition is suggestive of separate origins for the olivine and the other silicates. But, as pointed out by McCall (1965c), there appears to be a consistent difference between olivine and pyroxene compositions and so it is unlikely that the olivines and pyroxenes originated completely independently of each other. This matter is referred to again below.

8.3.4 Pyroxenes

The pyroxene variation in Muckera (Figure 8.10) is very similar to that of Kapoeta or Malvern (Desnoyers and Jerome 1977, Duke and Silver 1967, Dymek et al 1976, Simpson 1975). The majority of the analyses fall within the field $En_{80}Fs_{20}$ - $En_{30}Fs_{70}$ - $En_{30}Fs_{20}Wo_{20}$ - $En_{60}Fs_{20}Wo_{20}$, with the remainder trending along the line En_{30} to a maximum Wo value of approximately 40.

This distribution is quite different from that shown by the eucrites (e.g. Millbillillie No.3, Figure 8.11) or the diogenites. In the latter case, most analyses are remarkably constant at about Fs_{26} (Mason 1963d). Further reference is made to this point later. The aparent continuity of composition in eucritic and lunar pyroxenes arises from the presence of exsolved phases (e.g. Carter et al 1971, Wilkening and Anders 1975).

The range in composition found in the Pinnaroo orthopyroxenes - Fs_{19-37} (Figure 8.12) - is similar to that reported for other mesosiderites (Powell 1971, Weigand 1975) as is the mean value of $Fs_{31.2}En_{64.3}Wo_{4.5}$.

8.3.5 The iron-manganese relationship

The iron-manganese correlation in lunar, meteoritic and terrestrial olivines and pyroxenes is well documented with the three groups being fairly readily distinguished on this basis (Desnoyers and Jerome 1973, Dymek et al 1976, Simpkin and Smith 1970). The correlation arises as a result of the ability of Mn^{2+} to replace Fe^{2+} in olivine or pyroxene lattices due to the similarity of their ionic radii (Wanke et al 1973). Intergrain constancy of this ratio has been suggested as indicating the derivation of all grains from related source materials (Dymek et al 1976).

The Muckera pyroxenes show a wide range in iron and manganese contents. That the data is somewhat non-cohesive is shown by the correlation coefficient of 0.91 for 118 determinations. The average Fe/Mn ratio for the pyroxenes is 28.8 while the value for the bulk analysis is 33.9. A relatively narrow range in iron composition in the

Figure 8.11 : Millbillillie No.3 pyroxenes.

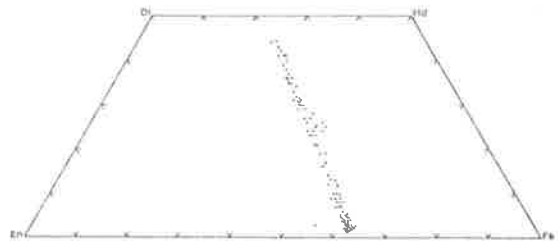


Figure 8.13 : MnO vs FeO for Muckera olivines and pyroxenes. x : bulk composition.

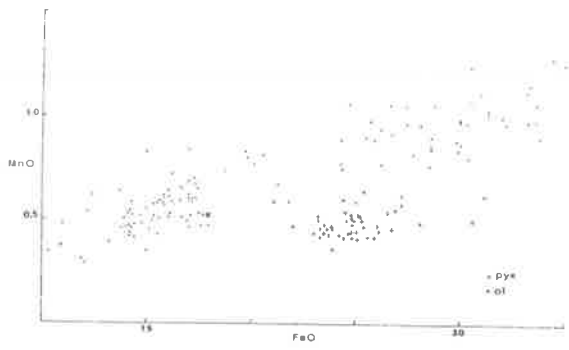
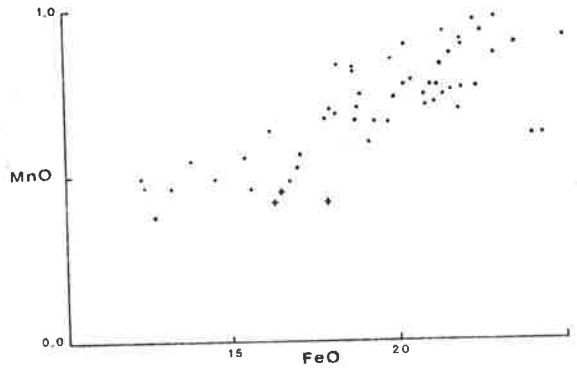


Figure 8.14 : MnO vs FeO for Pinnaroo olivines and pyroxenes.



olivines, coupled with a considerable spread in manganese values, results in the relationship between these elements in the olivine grains being less obvious (Figure 8.13), the spread being indicated by the low correlation coefficient of 0.34 for the 50 analyses. The average value of the ratio for the olivine is 50.3, thereby explaining the difference between the bulk ratio and that for the pyroxenes.

The Pinnaroo pyroxenes (Figure 8.14) exhibit a smaller range in iron composition and a larger manganese range than Muckera, as is evidenced by the correlation coefficient of 0.78 for 53 analyses. The average value is 27.7, which compares well with the value of 29.6 for the Patwar orthopyroxenes (Weigand 1975). From the few olivine analyses obtained it can be seen that, as was the case with Muckera, the Fe/Mn ratio is greater in the olivine, having an approximate value of 39.5 for the few analyses performed.

These results can be compared with eucrites such as Millbillillie No.3 (Figure 8.15) in which the pyroxenes also exhibit a wide range in Fe and Mn values but the data is more cohesive as shown by the correlation coefficient of 0.97 for 103 analyses. The value of the ratio for the bulk analysis is 33.1 while the average value for the pyroxene analyses is 32.9. The agreement

Figure 8.15 : MnO vs FeO for Millbillillie No.3 pyroxenes. x : bulk composition.

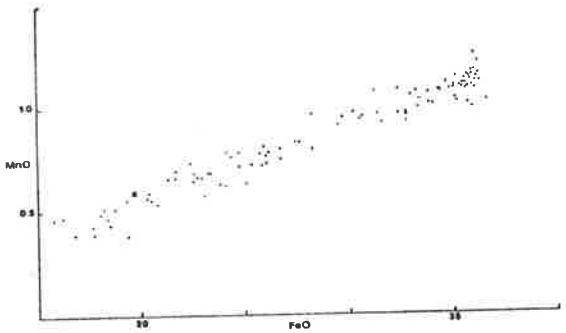
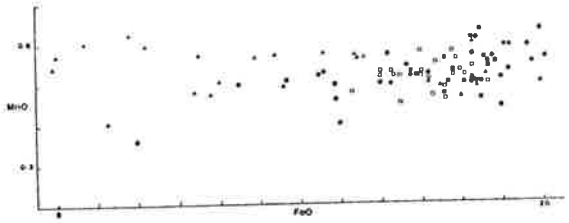


Figure 8.16 : MnO vs FeO for achondrite bulk analyses. ● : diogenites, ■ : eucrites, □ : howardites, △ : mesosiderites.



between these two values indicates that essentially all of the iron and manganese are contained in the pyroxenes in spite of trace amounts of iron found in the feldspar analyses. Similar agreement of pyroxene and bulk chemistry is shown by other eucrites such as Moama (Lovering 1975) which has a bulk ratio of 29.3 and one of 27.5 for the host hypersthene.

Wanke et al (1973) and other authors have claimed that this correlation and distinction extends to the bulk analyses for the chondrites, mesosiderites, pallasites, diogenites, eucrites and howardites. Figure 8.16, a plot of Mn vs Fe for a group of diogenites, eucrites, howardites and mesosiderites, shows that this is not the case. A similar scatter was found by Schmitt and Laul (1973).

In lunar and terrestrial basalts, the value of the Fe/Mn ratio for coexisting olivines and pyroxenes is consistently higher for the olivine. In the suite of terrestrial basalts examined by Dale and Henderson (1972) for example, the ratio $(Fe/Mn)_{ol}/(Fe/Mn)_{pyx}$ has a value of 1.9. A similar trend was observed in the non-chondritic meteorites studied in this work. Table 8.8 lists the values of the Fe/Mn ratio obtained for various phases as well as values reported by others. The $(Fe/Mn)_{ol}/(Fe/Mn)_{pyx}$ ratio for Muckera is 1.7 and that for Pinnaroo is 1.4.

It can be seen from Figure 8.16 that the values recorded in this table are averages only and so care must be taken in interpreting them. The resemblance between the two listed values for the eucrites reflects the fact that pyroxene is essentially the only iron and manganese bearing phase in these meteorites, whereas, in the howardites, these two elements are also present in olivine. In the latter case, the entries in this table cannot be used to calculate the relative abundances of the two phases because of the spread in values as shown by Figure 8.16.

8.4 MUCKERA

Muckera has been shown to be howardite on

Table 8.8 : Fe/Mn ratios for various meteorites.

Meteorite	*Pyroxene*	*Olivine*	*Bulk*
Muckera	29^{1}	50^{1}	34^{1}
Pinnaroo	28^{1}	40^{1}	
Eucrites			
Millbillillie No.3	33^{1}		33^{1}
Moama	28^{3}		30^{3}
Several eucrites, howardites and diogenites	$35^{2,4,6}$		$35^{2,4,6}$
Mesosiderites			
Patwar	30^{7}		26^{5}
Three mesosiderites			24^{6}
Seven mesosiderites			19^{5}

References

1. *This work*
2. *Dymek et al 1976*
3. *Lovering 1975*
4. *Schmitt and Laul 1973*
5. *Simpson and Ahrens 1977*
6. *Wanke et al 1973*
7. *Weigand 1975*

both chemical and mineralogical grounds. This section highlights textural features which support this classification.

The meteorite consists of sub-rounded to angular fragments, varying in size from about 1mm to 3+cm, set in a dark grey to black ground mass. The clasts vary in nature from single mineral fragments to polymineralic aggregates. Minor amounts of olivine are present, almost invariably as small grains in the matrix. Other monomineralic grains include pyroxene and large grains and aggregates of feldspar. Most of the latter appear to have been produced by shock events which brecciated the grains. Many of the larger clasts appear to have had a similar origin. Numerous clasts of glassy microbreccias containing even sized, angular to sub-rounded, grains, mainly of orthopyroxene, are also present.

The polymineralic fragments include eucrite-like material with ophitic to sub-ophitic textures. These are fine grained, the feldspar laths being about 0.1mm in length and the pyroxene grains, some exhibiting exsolution lamellae, up to 0.5mm in size.

Many of the largest clasts are pyroxene-plagioclase assemblages consisting of large grains of these minerals.

These textural features parallel those of the Malvern howardite described by Simpson (1975). He identified mineral clasts, glassy microbreccias and coarse grained fragments. Among the mineral clasts he found that the frequency of occurence was in the order orthopyroxene, plagioclase, pigeonite with minor olivine. He noted the presence of orthopyroxene aggregates and subophitic basaltic clasts, while he found that the coarse grained fragments were pyroxene-plagioclase assemblages with constant intra-clast compositions.

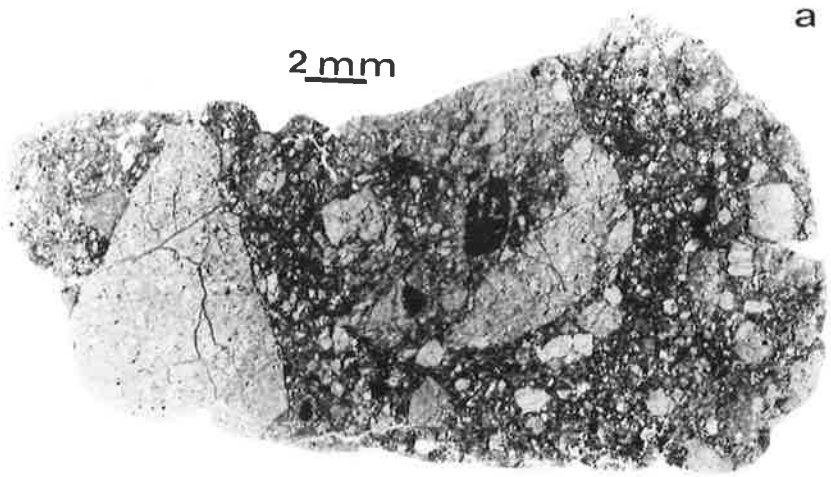
The brecciated nature of the howardites and other achondrites has long been recognized. Bunch (1975), for example, pointed out the great similarity between the howardites and the lunar breccias. He examined several howardites and lunar breccias and placed similar clasts found in both into six groups. Clasts found in Muckera can be related to these groups.

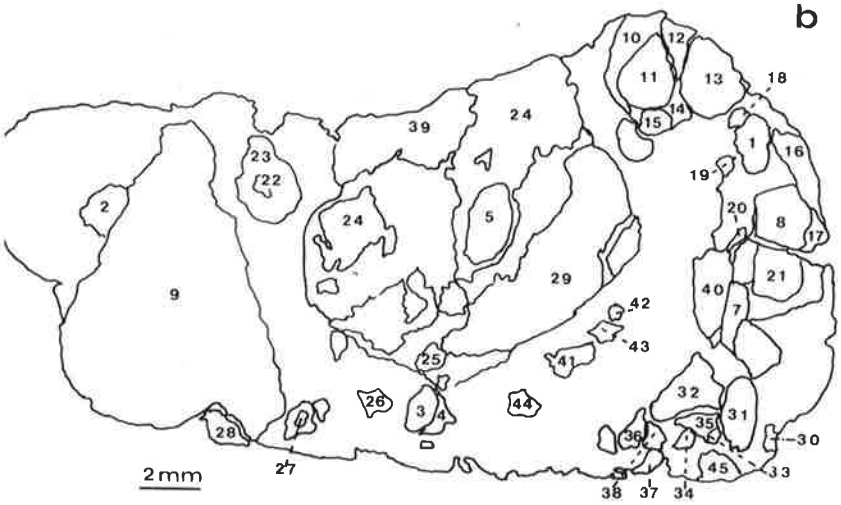
Bunch's first group comprised igneous and metaigneous clasts, the description of which is somewhat difficult. The term "basalt" and "microgabbro" have been used below with the distinction being based on textural rather than size considerations. Thus, fine grained clasts of pyroxene and plagioclase with a granular allotriomorphic texture have been called microgabbros, while fine grained clasts of a similar mineralogy but possessing an ophitic, subophitic, intergranular or insertal texture have been called basalts. Floran et al (1972) used the term "micronorite" in their description of lunar breccia 14313 basing their terminology on texture and grainsize. They pointed out that other writers had used terms such as "orthopyróxene plagioclase fragments", "norite" and "basalt" for the same material. Bunch, however, commented that he was loath to use the more specific term "norite" in preference to "gabbro" because of the limited sample size and subsequent recrystallization events. Thus, following Bunch's lead, all igneous material composed of feldspar and pyroxene is described as a gabbro regardless of the present pyroxene composition. Three sections of Muckera are shown in Figure 8.17 and various clasts labelled. and identified in Table 8.9. Some

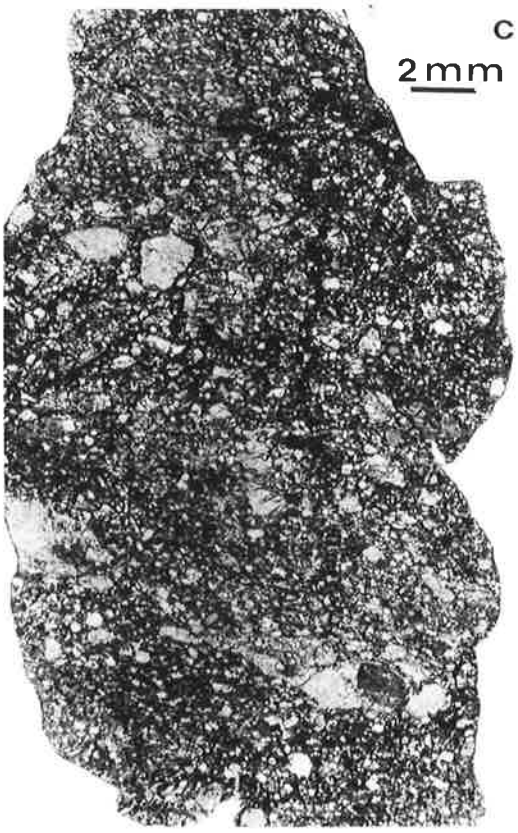
Table 8.9 : Muckera clasts (Figure 8.17).

Basalt	*5, 19, 20*
Gabbro	*2, 3, 22*
Crush breccia	*8, 9, 10, 11, 12, 13, 14, 15, 24, 28, 29, 33, 43, 45*
Mineral fragment	*7, 18, 24, 25, 38, 41, 42, 44*
Pre-existing breccia	*1, 4, 21, 23, 31, 32, 34, 35, 39, 40*
Melt rock fragments	*26, 27, 30, 36, 37*

Figure 8.17 : Thin sections of the Muckera howardite.


a
2 mm


b
10
12
11
13
18
15
14
1
16
19
20
8
17
21
40
7
42
43
41
32
31
35
30
36
45
33
38
37
34
39
24
23
22
2
24
5
29
9
25
26
3
4
44
28
27
2mm


c
2 mm


d
2 mm

of them have been identified as basalts, some as microgabbros, some as mineral grains or aggregates and still others as microbreccias. These three sections which were originally only a few centimetres apart in the meteorite illustrate its great variability also.

Several of the clasts can best be described as "crush breccias", i.e. they have been fractured and pulverized but not disaggregated. Mason (1963d) commented on similar intense mechanical deformation in his description of the diogenites. Pyroxene compositions within some of these clasts are constant as shown by the following results obtained for three large and two small "matrix" grains in one clast.

	Large grains			"Matrix grains"	
Fs	26.9	25.5	26.7	27.0	27.2
Wo	3.2	3.6	3.8	3.0	3.2

These figures are significant not only because they illustrate the constancy of composition but also for their resemblance to the constant compositional ranges observed in most of the diogenites (Mason 1963d, Takeda et al 1976, Fukuoka et al 1977). Many of the Muckera pyroxene grains, like those of the diogenites, show undulose extinction indicative of shock. Similar features are observed in feldspar grains. The intensity of the shock was such that many of these grains have mosaic textures.

Kurat et al (1974) noted a "breccia within breccia" relationship in the lunar sample 14318, similar to that in Muckera, and concluded that it had been produced by two impact episodes, the first producing the polymict fragments and the second mixing together the various lithologies now present in the lunar sample.

The howardites are now generally recognized as surface breccias although discussion is continuing as to the nature of the parent materials. Both the texture and nature of the fragments in Muckera, along with its chemistry, are consistent with its classification as a polymict meteoritic breccia, or howardite, and as such it is the first recorded Australian representative of this class.

8.5 PINNAROO

The analytical results reported in Section 4.2.3 a were for the non-magnetic portion of the meteorite, i.e. the material analysed was a mixture of silicates, troilite and weathered nickel-iron. Due to extensive weathering, the latter component is not negligible. To calculate the amount of this present, a sample was treated with a mixture of sodium dithionate etc. as described in Section 3.3.4 c and the optical density of the final solution measured in a spectophotometer. The results indicated the presence of 1.01% iron as limonite. (The material used in this work was actually that

Table 8.10 : Elemental composition of Pinnaroo.

	Non-magnetic portion		*Recalculated silicate fraction*		*Average Mesosiderite*	
Elemental Composition	*Alderman (1940)*	*This work*	*I*	*II*	*Powell (1971)*	*Simpson and Ahrens (1977)*
Fe	25.49	24.81	14.27	9.75	10.50	8.27
Mn		0.29	0.38	0.41	0.39	0.43
Ti	nil	0.14	0.18	0.25	0.28	0.19
Ca	3.58	3.54	4.62	4.95	4.05	5.31
K	0.033	0.043	0.056	0.061		0.001
P		0.43	0.56	0.60	0.36	0.58
Si	17.30	17.55	22.90	24.53	24.71	24.56
Al	4.02	3.38	4.41	4.72	4.63	5.06
Mg	6.67	6.78	8.85	9.48	8.96	9.84
Ni	0.80	0.95				
S	7.87	7.39				
Cr		0.34	0.44	0.47		0.70
Na	0.30	0.22	0.29	0.31		0.21
Partial norm						
Quartz			-	5.7	5.8	
Feldspar			24.5	26.2	27.0	
Pyroxene			70.3	63.3	63.1	
Olivine			0.8	-	-	
Mole%						
FeO/(FeO+MgO)			41.3	30.9	34.0	

analysed by Alderman (1940) and the results of Table 8.10 show the excellent agreement between the two analyses.)

On the assumption that all of the sulfur in the material was present as troilite, an assumption which may not be completely justified, as Alderman recorded the presence of oldhamite, an equivalent amount of iron as well as the sulfur and nickel, was subtracted from the analysis along with the weathered iron. The results were then recalculated to 100% to approximate to the composition of the silicate fraction as shown in column 4 of Table 8.10.

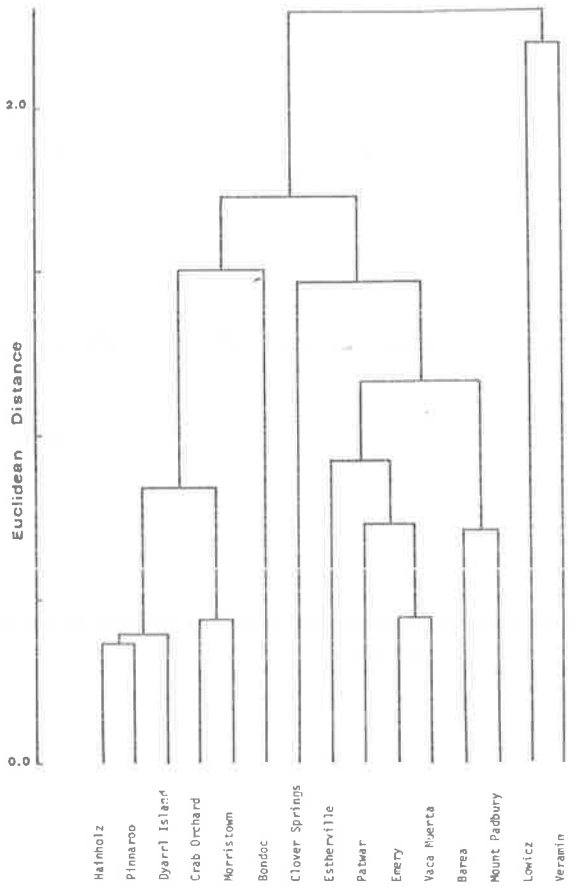
Table 8.10 shows that, except for iron, the recalculated analysis (I) is in good agreement with the average composition of the mesosiderites. On the basis of metal phase compositions (Alderman 1940, Wasson et al 1974b) the 0.95% nickel recorded in the analysis ought to be associated with some 9% iron. Removal of this amount of iron makes the final iron content unacceptably low. Recent work on the Holbrook chondrite (Gibson and Bogard 1978) suggests that in the case of that meteorite, iron and nickel were stable during weathering, apparently increasing due to the leaching of magnesium and possibly silicon. In the case of the pallasites, there is possibly preferential removal of nickel (Nininger 1938, Buchwald 1977) which would imply even more iron ought to be associated with the nickel. On the other hand, some of the nickel might be present as schriebersite, a common accessory in mesosiderites, although the unweathered mineral is magnetic and perhaps ought to be absent from the material analysed. The nickel could also be present in solid solution in the troilite.

The second recalculation (II) was performed on the basis of an FeO/MnO ratio of 24 (Laul et al 1972), sufficient iron being removed to achieve this value. Comparison of this result with the average values quoted in Table 8.10 shows very good overall agreement. However, since the results of Section 8.3 d show considerable variation in individual values for the FeO/MnO ratio, only the first recalculated analysis was used for subsequent calculations. The normative mineral composition for the second recalculated analysis is in very good agreement with the results of Powell. These calculations do not affect the relative amounts of the other elements and hence all ratios which are independent of iron will be unchanged.

Powell (1971) divided the mesosiderites into three groups on the basis of textural features. The absence of fine grained silicates and obvious brecciation in Pinnaroo, combined with general grain roundness and sutured boundaries, is suggestive of a type 3 classification. This classification is supported by the presence of regions of alteration around many of the olivine megacrysts and the predominance of orthorhombic pyroxenes.

Wasson et al (1974b) examined the metal phase of several mesosiderites and found a fair degree of correlation between Powell's groups and the composition of the metal. Their results for Pinnaroo suggest a type 2 or 3 classification for this meteorite. Subdivision of the mesosiderites on the basis of the chemistry of their silicate portions is potentially difficult due to their polymict brecciated nature. The great variation in quantity and composition of the minerals present is reflected in the bulk chemistry. The silicates consist of both monomineralic clasts such as anorthosites, dunite and orthopyroxenite, as well as polymineralic fragments with textures resembling those found in howardites. Because of the heterogeneity of the mesosiderite silicates, a marked correlation between the chemistry of the metal and silicate portions is not necessarily expected. On the basis of their results from

Figure 8.18 : Q-mode cluster analysis of a group of mesosiderites.



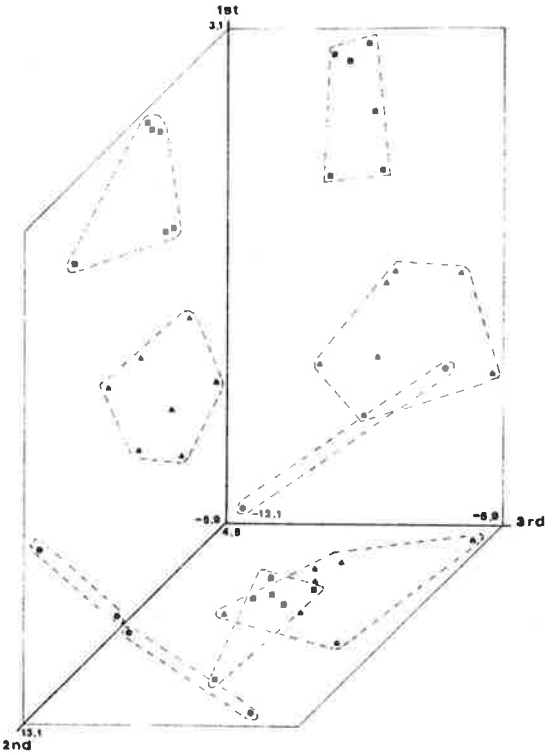


Figure 8.19 : First three principal components for a group of mesosiderites. ● : Lowicz, Veramin; ▲ : Barea, Clover Springs, Emery, Estherville, Mount Padbury, Patwar, Vaca Muerta; ■ : Bondoc, Crab Orchard, Dyarrl Island, Hainholz, Morristown, Pinnaroo.

an examination of metal phases, Wasson et al suggested that members of Powell's group 1 originated in a different location from those of groups 2 and 3. The analyses of the silicate fractions of fifteen mesosiderites were examined in this work to ascertain whether the silicate compositions suggested a similar conclusion.

The groups delineated both by cluster (Figure 8.18) and principal component analysis (Figure 8.19) were the same. The cophenetic correlation coefficient of 0.78 for the cluster analysis is indicative of some distortion but the similarity of the results to those from the principal component analysis indicates that this distortion can be ignored. The largest group in each case is comprised almost entirely of Group 1 mesosiderites except for Barea and Emery which has been given both a Group 1 (Wasson et al 1974b) and Group 3 classification (Hewins et al 1977). In addition, one Group 1 specimen, Crab Orchard, lay outside this group.

Wasson et al found a strong relationship between gallium and iridium in mesosiderite metal phases. They found six meteorites grouped together at low Ga and Ir contents - these are the same six as the ones placed together by the multivariate techniques. Likewise, the other Group 1 mesosiderite which they examined, Crab Orchard, plotted with the Groups 2 and 3 individuals. Mason and Jarosewich (1973) placed the mesosiderites in three groups on the basis of their pyroxene compositions. Five of the Group 1 mesosiderites fell into the group having the most iron-rich pyroxenes. According to Mason and Jarosewich, Pinnaroo also belongs to this group, but, on the basis of the average pyroxene composition reported in this work ($Fs_{31.2}Wo_{4.5}$) it would fall into the intermediate group of these authors.

These results suggest that, like the metal phase, the chemistry of the Group 1 silicates is different from that of the other two groups. This conclusion is supported by the pyroxene data. The results support the assignment of Pinnaroo to Powell's Group 3 and suggest that Barea belongs to Group 1. There is thus a marked contrast between the textural features of the Group 1 mesosiderites, the chemistry of their metal phases, and their silicate compositions. This group is distinguished from the other two textural groups but they are not clearly separated on the basis of the chemistry of either their metal or silicate phases. All of these results support Wasson et al's suggestion of separate locations of formation for the Group 1 mesosiderites, with the proviso, however, that there was not a marked difference between this parent body (or region) and that (those) of the other mesosiderites.

Floran (1978), however, extended Powell's classification scheme. He described three groups possessing metamorphic textures with the progression from group to group corresponding to an increase in the degree of recrystallization which approximately corresponded to Powell's three groups. He placed Pinnaroo with its sub-ophitic texture in a fourth group characterized by the presence of igneous textures. Other members of this group included Hainholz and it was suggested by both Floran and Floran et al (1978) that these textures were consistent with origins as impact melts.

Floran assigned Barea to Group 1 which accords with the suggestion made above but placed another Group 1 mesosiderite, Estherville, in the igneous group with Hainholz and Pinnaroo.

Accordingly, on the basis of the available analyses, the multivariate techniques cannot completely characterize the four subgroups of the mesosiderites. Floran's placement of Pinnaroo in a group of igneous-textured

Table 8.11 : The mineralogy of the mesosiderites and the irons with silicate inclusions.

	Olivine	*Pyroxene*	*Potassium Feldspar*	*Plagioclase*
Mesosiderites	Fa_{20-40} [4]	Fs_{19-44} [3,4]	?	An_{80-98} [3,4]
Group IAB	Fa_{1-8} [2]	Fs_{6-9} [2,3]	*Absent* [2]	An_{8-24} [2,3]
Group IIE	Fa_{9-21} [2]	Fs_{16-22} [2,3]	*Present* [1,2]	An_{2-14} [2,3]

References:
1. *Bunch and Olsen 1968a,b*
2. *Bunch et al 1970*
3. *Mason 1967*
4. *Powell 1971*

mesosiderites is accepted.

8.6 THE IRONS WITH SILICATE INCLUSIONS

Wasson et al (1976) described the Weekeroo Station type irons (Group IIE) and the mesosiderites as having very similar silicates. Weigand (1975) suggested on the basis of the Al-Ti-Cr relationships in the Patwar pyroxenes that this relationship is not too close. Figure 8.20, a plot of these elements for the Pinnaroo pyroxenes, shows that Pinnaroo likewise overlaps with the pyroxenes from both the Group IAB and IIE irons, thereby failing to support the hypothesis of Wasson et al. Table 8.11, a summary of the mineralogy of the mesosiderites and these two groups of irons containing silicate inclusions shows further differences between the three groups.

In terms of metal compositions, the mesosiderites resemble the IIE irons and differ from the IAB (Wasson et al 1974, Scott and Wasson 1975).

Due to a scarcity of material few bulk analyses of the silicate inclusions are available. Of those that have been analysed several have been described as resembling the ordinary chondrites (Table 8.12) thereby further precluding a relationship with the mesosiderites.

The value of the Ca/Al ratio varies considerably from significantly less than the "average chondritic" value in the case of Woodbine to significantly higher in Weekeroo Station. Mention was made in Section 7.2.2 of other meteorites with low values for this ratio and it has been suggested recently (Bild 1977) that at least two of them (Mount Morris (Wis.) and Winona) are closely related to the IAB silicates.

The formation of the IIE silicates by the removal of olivine from chondritic material has been suggested, at least in the case of Weekeroo Station (Olsen and Jarosewich 1970). Various olivine-rich meteorites have been suggested as the complementary fractions - the pallasites, Chassigny or similar material and the ureilites, the mineralogy of the latter being appropriate. However, derivation from each by fractionation processes alone has been shown to be impossible for the ureilites, the IIE silicates and the ordinary chondrites (Clayton et al 1976). Likewise, Chassigny and the ureilites originated in separate parent bodies (Wasson et al 1976). Chassigny-like meteorites are extremely friable (Scott 1977b) which possibly explains their rarity. Nonetheless, it has been suggested on several grounds that it is unlikely that Chassigny is related to the chondrites (Boynton et al 1976, Mason et al 1976).

There thus appears to be no simple relationship between the IIE silicates, the mesosiderites, the chondrites or the achondrites. This conclusion is at variance with that of Wasson et al (1974b) but not

Table 8.12 : Bulk compositions of the irons with silicate inclusions.

El Taco (IAB)	*Similar to H or LL-chondrites*	*Bild (1975,1977)* *Bunch et al (1970)* *Wlotzka and Jarosewich (1975)* *Wasson (1970b)*
Landes (IAB)	*Similar to chondrites*	*Bild (1975)*
Mundrabilla (Anom IAB)	*Unlike chondrites*	*Ramdohr et al (1975)*
Netschaevo (IIE)	*Similar to chondrites*	*Bild (1975)* *Olsen and Jarosewich (1971)*
Weekeroo Station (IIE)	*Similar to howardites*	*Olsen and Jarosewich (1970)*
Enon (Anom)	*Similar to chondrites*	*Bild (1975)*

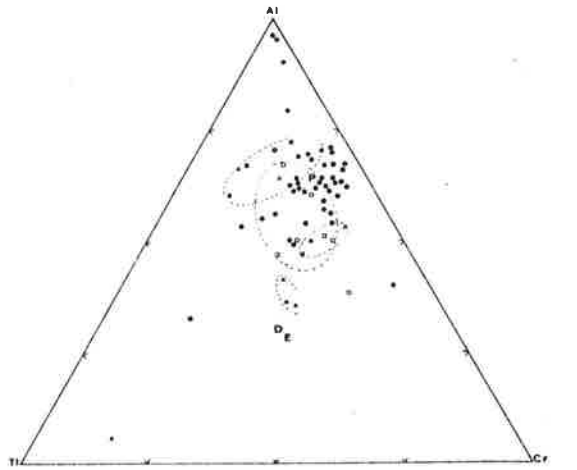


Figure 8.20 : Al-Ti-Cr for pyroxene analyses. ● : Pinnaroo, □ : Copiapo clinopyroxenes, ■ : Copiapo orthopyroxenes, △ : Weekeroo Station clinopyroxenes, ▲ : Weekeroo Station orthopyroxenes, B : Barea, D : Dyarrl Island, E : Emery, P : Patwar. Pinnaroo : this work, Copiapo and Weekeroo Station : Bunch et al (1970), Barea, Dyarrl Island, Emery and Patwar : Weigand (1975).

necessarily with that of Scott and Wasson (1976) who suggested that the sites of formation of the IIE irons, the mesosiderites and the pallasites were not greatly separated. It is possible that there is a "process relationship" between the IAB and IIE irons, the pallasites and the mesosiderites, some of the other achondrite groups, and anomalous meteorites such as Brachina, Chassigny, Shaw (Wlotzka 1972b) and Ramsdorf (Begemann and Wlotzka 1969).

8.7 THE COGNATE ACHONDRITES

8.7.1 Preliminary definitions

The diogenites or hypersthene achondrites were described by Mason (1963d) as a group of meteorites of notably uniform chemical and mineralogical composition consisting almost entirely of orthorhombic pyroxene with compositions in the range Fs_{25-27}.

Mason (1962b) updated previous definitions and defined the eucrites and howardites as pigeonite-anorthite and hypersthene-anorthite achondrites respectively, whereas Wahl (1952) had defined them on textural grounds as monomict and polymict breccias. The two definitions are generally complementary but cases of polymict breccias with dominant pigeonite (e.g. Macibini) and monomict ones with dominant orthopyroxene (e.g. Binda) are known (Mason et al 1978).

The mesosiderites are stony irons containing approximately equal proportions of metal and silicate phases with the chemistry and mineralogy of the latter being similar to that of the howardites.

The recent recovery of several achondrites has resulted in the distinctions between these groups becoming less clear cut. Thus, the range of pyroxene compositions of Fs_{25-27} suggested by Mason for the diogenites has been gradually extended, Fs_{23-28} (Fredriksson et al 1976), Fs_{22-26} (Dymek et al 1976), while even more recent discoveries in Antarctica have extended this range even further to Fs_{22-34} (Takeda et al 1978b). The situation is further complicated by recent finds such as Yamato-7308, in which the orthopyroxenes range in composition from Fs_{17} to Fs_{61}. This meteorite has been described as a howardite (Takeda et al 1976, Yagi et al 1978a,b) or as a polymict diogenite breccia with eucrite clasts (Miyamoto et al 1978). Conversely, the polymict Mauritanian diogenite Aioun el Atrouss, which also contains eucritic clasts, is described as possessing a homogeneous pyroxene with a composition of Fs_{23} (Lomena et al 1976). Yamato-75032, a monomict orthopyroxene breccia, which has been classified as a diogenite, has a pyroxene composition of Fs_{34} (Miyamoto and Takeda 1977, Takeda and Miyamoto 1977, Takeda et al 1978b) making it very similar to Binda with a composition of Fs_{35} (Takeda et al 1976), which has been classified both as a eucrite and a howardite. The possibly incompletely described Yamato-74159 achondrite is a polymict eucrite breccia containing pyroxenes ranging in composition from Fs_{38} to Fs_{75} (Miyamoto et al 1978, Takeda et al 1978a).

The relationship of the mesosiderites to the diogenites, eucrites and howardites, as defined at present, is readily shown by mesosiderites, such as Mount Padbury, which contain both diogenitic and eucritic clasts (McCall 1966). Pyroxene trends in the diogenite clasts in this meteorite are very similar to those in Yamato-7308 (Miyamoto et al 1978). Many of the pyroxenes in Pinnaroo (Figure 8.12) are likewise more iron-rich than the normal diogenitic pyroxenes and thus resemble this Antarctic find. Another find from that continent, ALHA77219, consisting mainly of orthopyroxene, but containing nickel-iron and an olivine enclave (Mason 1978), also points to a relationship between the mesosiderites and the diogenites. The orthopyroxene compositions are in the range Fs_{24-28} while the olivine has a composition of Fa_{26}.

These and other textural studies suggest that the diogenites, eucrites, howardites and mesosiderites are all related to each other - a suggestion which is supported by chemical and isotopic data (Clayton and Mayeda 1978, Clayton et al 1976, Duke and

Silver 1967, Mason et al 1978, Powell 1971, Shimizu and Allegre 1975, Stolper 1975, 1977, Taylor et al 1965, etc.). They likewise illustrate the difficulty of distinguishing between these groups, and so suggest the desirablity of a new classification which would embrace all of them, thereby eliminating the problems which arise when a meteorite cannot be readily fitted into one of the current groups. Present classification schemes tend to separate the mesosiderites from these other three meteorite groups despite suggestions, made as early as 1918 by Prior, of a possible relationship between them and the eucrites and howardites, a relationship stressed by, among others, Wasson (1971a,1974). Other recent authors (e.g. Mason 1963d) have also suggested the possibility of these latter two groups being related to the diogenites. These four groups therefore provide an example of a suite of meteorites which appear to be closely related to each other but which are separated by the classification scheme used. It is for these reasons that the classification schemes of Sections 5.3 and 5.4 did not initially separate the mesosiderites and the pallasites from the other achondrites.

8.7.2 Proposed new meteorite group

For these and other reasons, it is proposed that the diogenites, eucrites, howardites and mesosiderites should all be grouped together under one name to demonstrate their relationship to each other. In order to emphasise the fact that they have all been derived from a common parent, it is proposed that they be collectively known as the "cognate achondrites".

This name has been chosen as the names of meteorites such as Mount Padbury, which best represent all members of the group, do not readily lend themselves to use as group names. A mineralogical name was not used as there is no single mineral species or assemblage which is represented in all four of these groups and is not found in others. Furthermore, names such as "hypersthene achondrite" have already been used for some of these groups (Mason 1962b, 1963d, Bunch 1975, etc.) and so their re-usage would cause confusion.

8.7.3 Origin of the cognate achondrites

Textural resemblances between these meteorites and lunar material (e.g. Bunch 1975, Marvin 1976) suggest that both have been produced by the action of similar processes on materials which were compositionally and structurally similar (Mason and Melson 1970a,b). In the case of the lunar rocks, many specimens are impact produced surface breccias. The role of igneous processes in their formation is likewise obvious.

The cognate achondrites have also undoubtedly been produced by igneous processes. There are currently two theories explaining the mechanism of these processes, one invoking the mixing of two end members and the other a sequence of differentiation products. Both theories recognize the role of impact events in producing the brecciated textures of these meteorites.

Proponents of the two-component model (McCarthy et al 1973, Ehmann et al 1975, Takeda et al 1975, Dreibus et al 1977b, etc.) suggest that the howardites are mechanical mixtures of diogenite and eucrite end members. Mixing model calculations of these authors and others such as Fukuoka et al (1977) involving these two end members produce good first approximations to howardite analyses but close examination reveals them to be incomplete in several aspects. As pointed out by Mason et al (1978) and others, one of the implications of the mixing model theory is a bimodality of pyroxene compositions in the howardites corresponding to the diogenite and eucrite end members. Thus, it would be expected that the howardite pyroxenes would cluster around Fs_{25-30} and Fs_{60-80}, but Muckera, like the other howardites, while having pyroxenes corresponding to both these ranges also possesses many with compositions outside these ranges. The effective range in Muckera is Fs_{15-75}. These results imply the presence of material other than the proposed diogenite and eucrite end members. The increased range in pyroxene compositions in the diogenites described above, tends, however, to weaken this argument.

In textural terms, the Muckera clasts, like those in other howardites, represent a range in crystallization environment from essentially free surface (e.g. the intergranular basaltic-like clasts Nos. 5, 19 and 20 of Figure 8.17) to depths of several kilometres (e.g. the microgabbro clast such as Nos. 2, 3 and 22 In addition to this genomict material, some of the howardites contain exotic material in the form of carbonaceous chondrite xenoliths which resemble the CM meteorites (Wilkening 1973, Chou et al 1976). This material is debris from the impacting bodies which caused the brecciation and reworking of the surface materials of the howardite parent

body.

Stolper (1975,1977) envisaged a process of partial melting and fractional crystallization to produce the eucrites and diogenites as well as the range of other materials found in the howardites, the outer regions of the parent body being ultimately composed of eucrite, diogenite and dunite layers with impact and reworking of these upper layers producing the howardite parental material. The apparent non-existence of anorthositic meteorites points to the absence of an outer anorthosite layer on this parent body (Anders 1977). In this regard, the body differs from the moon and terrestrial igneous intrusions such as the layered Kalka (Goode 1976) which has pyroxene-rich, plagioclase-rich and pyroxene-plagioclase layers. According to Stolper, most of the eucrites were produced by small degrees of partial melting of a source composed of olivine, pyroxene, plagioclase, Cr-rich spinel and metal. These meteorites were then produced by the quenching of nearly primary liquids with the "fe" (molar Fe/(Fe+Mg) ratio) value of the liquid decreasing as the degree of partial melting increased. Crystal fractionation of such liquids would produce cumulates with even lower "fe" values and residual liquids with higher ones. Stolper calculated the "fe" values of residual liquids using a pigeonite/liquid distribution coefficient of 0.3. Table 8.13 shows a similar calculation using the value of 0.33 of Irving and Green (1976). From this table and Figure 8.21 it can be seen that Binda could have equilibrated with liquids similar to the most iron-rich ordinary eucrites. Eucrites like Moama and Serra de Mage produced by more extensive fractionation could have equilibrated with liquids similar to the residual eucrites Nuevo Laredo and Lakangaon, but the most fractionated Moore County must have equilibrated with liquids currently unrepresented in terrestrial collections.

Stolper suggested that after exhaustion of plagioclase from the source further melts could crystallize the magnesian pyroxenes of the diogenites, howardites and mesosiderites. Table 8.13 and Figure 8.21 show, on the basis of the same distribution coefficient, liquids with which the diogenitic pyroxenes might have equilibrated. A comparison of this diagram with Figure 8.10 suggests the possibility that the Muckera pyroxenes could have four "sources" - a. diogenite-like cumulate material, b. eucrite-like cumulate material, c. residual liquids which equilibrated with the diogenites, and, d. ordinary eucrite material. The Pinnaroo pyroxenes (Figure 8.12) on the other hand, appear to correspond to diogenitic and cumulate eucrite fractions only.

Figure 8.21 : "fe" values. DD : diogenites, CC : cumulate eucrites, OO : ordinary eucrites, R : residual eucrites, DL : "liquids" which would be in equilibrium with the diogenites, CL : "liquids" produced by the settling of the cumulate eucrites.

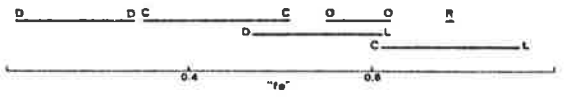


Table 8.13 shows that even though there is a steady decrease in "fe" values for the eucrites to the diogenites through Binda and Yamato-75032, there is a marked change in the calcium and aluminium contents reflecting the virtual exhaustion of plagioclase from the source. Most of the diogenites, however, contain accessory amounts of plagioclase despite this change. It is possible then that the howardites contain clasts of residual liquids presently unknown as eucritic meteorites. If the quantities of these liquids were small, then it is possible that impacts on the parent body incorporated all of the material into the surface breccia leaving none behind intact to be subsequently removed as eucritic meteorites.

Takeda et al (1975,1976) put forward a similar differentiation model, while Mason (1962b) and other authors (eg. Shimizu and Allegre 1975) have also proposed a differentiation model to account for the formation of the cognate achondrites but one which was based on a crystallization sequence. Many authors, including Bunch (1975), Dymek et al (1976) and Reid (1974), have proposed a multicomponent origin for the howardites.

The genesis of the mesosiderites poses a problem in that silicate textures and compositions are indicative of relatively rapid cooling at shallow depths yet cooling rate calculations for the metal phases (Powell 1971, Kulpecz and Hewins 1978) are indicative of greater burial depths. The latter authors suggested that this paradox might be explained by a two-stage cooling process. This suggestion is strengthened by the results of Murthy et al (1977) who determined an internal isochron age of 4.35 ± 0.10 Ga for the Estherville mesosiderite. They compared this to one of 4.60 ± 0.67 for the eucrite Juvinas, reported by Allegre et al (1974), and suggested that the difference might reflect, in Estherville, an extended

Table 8.13 : "fe" values for the cognate achondrites. (Note that many of the analyses listed as coming from Mason et al (1978) have actually been analysed by other authors and their analyses simply compiled by Mason et al. Some of these have been listed with their original sources in Table 8.1.)

Meteorite	Ca/Si $x10^2$	Al/Si $x10^2$	Ca/Al	Fe/(Fe+Mg) $x10^2$
Residual eucrites				
Lakangaon[9]	22.4	27.7	0.81	0.69
Nuevo Laredo[9]	22.5	28.1	0.80	0.67
Ordinary eucrites				
Pasamonte[9]	17.9	29.1	0.76	0.64
Emmaville[9]	20.8	27.3	0.76	0.63
Bereba[9]	22.9	30.6	0.75	0.62
Peramiho[9]	23.5	26.9	0.88	0.61
Palo Blanco Creek[9]	20.8	30.0	0.69	0.61
Adalia[9]	22.0	27.8	0.79	0.61
Padvarninkai[9]	22.5	30.5	0.74	0.61
Mount Padbury enclave[9]	23.0	32.2	0.72	0.60
Haraiya[6]	22.6	30.2	0.75	0.60
Millbillillie No.1[9]	21.0	29.0	0.72	0.60
Millbillillie No.3[1]	21.8	30.7	0.71	0.60
Kirbyville[9]	21.5	28.2	0.76	0.60
Cachari[9]	22.8	31.4	0.72	0.60
Chervony Kut[9]	25.2	32.5	0.78	0.60
Nobleborough[9]	21.4	29.5	0.73	0.60
Allan Hills 7605[9]	21.1	29.4	0.72	0.60
Sioux County[6]	22.6	30.8	0.73	0.60
Juvinas[6]	22.5	31.1	0.73	0.59
Jonzac[9]	22.0	27.2	0.81	0.59
Stannern[6]	23.0	29.2	0.79	0.59
Ibitara[9]	23.8	30.3	0.79	0.59
Yamato 74159[13]	20.7	24.9	0.83	0.57
Yamato 74450[13]	20.6	25.8	0.80	0.56
Cumulate eucrites				
Moore County[6]	20.8	30.9	0.67	0.51
Nagaria[9]	24.2	39.0	0.64	0.48
Pomozdino[9]	24.0	27.8	0.87	0.45
Serra de Mage[9]	30.0	52.7	0.57	0.43
Moama[9]	20.9	33.3	0.63	0.41
Medanitos[9]	23.3	37.3	0.63	0.39
Binda[12]	11.8	16.6	0.71	0.35
Diogenites				
Yamato 75032[13]	6.8	5.2	1.32	0.34
Yamato 7308 (bulk)[16]	7.3	8.4	0.87	0.29
Yamato 74013[14]	2.7	1.6	1.67	0.28
Garland[4]	5.4	7.9	0.69	0.27
Roda - Chelles[4]	3.3	3.4	0.98	0.27
Roda - Chicago[4]	3.2	2.9	1.12	0.27
"Assam"[4]	1.8	1.5	1.14	0.27
Ellemeet[4]	1.9	0.0	2.03	0.27
Johnstown[4]	3.1	2.8	1.11	0.26
Ibbenbueren[4]	3.2	2.0	1.61	0.25
Shalka[4]	1.6	1.0	1.63	0.25
Manegaon[7]	3.7	4.5	0.82	0.24
Tatahouine[4]	1.6	1.2	1.35	0.24
Yamato 6902[11]	2.4	1.5	1.57	0.24
Yamato 7308 (clast)[16]	2.3	1.3	1.82	0.21

Meteorite	Ca/Si $x10^2$	Al/Si $x10^2$	Ca/Al	Fe/(Fe+Mg) $x10^2$
Howardites				
Macibini[9]	21.7	29.0	0.75	0.55
Bialystok[9]	21.3	30.4	0.70	0.56
Petersburg[9]	18.5	25.9	0.71	0.46
Malvern[12]	18.0	24.7	0.72	0.46
Brient[9]	18.9	26.5	0.71	0.46
Jodzie[9]	14.7	19.3	0.76	0.41
Muckera[1]	15.3	19.4	0.79	0.40
Molteno[12]	15.6	21.3	0.73	0.40
Le Teilleul[9]	13.8	17.4	0.79	0.40
Yurtuk[9]	15.8	21.9	0.73	0.39
Bununu[9]	14.9	21.5	0.69	0.39
Luotolax[9]	14.5	21.1	0.69	0.38
Bholghati[9]	13.3	19.8	0.67	0.37
Washougal[9]	11.9	15.7	0.76	0.37
Pavlovka[9]	11.4	14.1	0.80	0.36
Kapoeta[12]	13.9	19.2	0.72	0.36
Zmenj[5]	11.6	15.3	0.76	0.36
Frankfort[5]	7.7	11.7	0.78	0.32
Chaves[9]	11.7	15.6	0.75	0.32
Massing[9]	8.6	9.5	0.91	0.32
Yamato 7308[9]	8.0	9.9	0.82	0.30
Mesosiderites				
Hainholz[10]	12.5	21.4	0.59	0.43
Dyarrl Island[8]	14.4	19.0	0.76	0.43
Morristown[10]	14.0	22.2	0.63	0.42
Pinnaroo[1]	14.1	20.0	0.71	0.41
Crab Orchard[10]	14.3	23.3	0.61	0.38
Budulan[2]	8.0	14.0	0.57	0.36
Patwar[10,12]	14.7	22.8	0.67	0.35
Bondoc[10]	6.1	14.2	0.43	0.34
Vaca Muerta[10,12]	16.2	23.7	0.68	0.33
Barea[8]	12.5	21.8	0.58	0.32
Clover Springs[15]	16.1	39.5	0.41	0.30
Estherville[10,12]	13.0	20.0	0.64	0.30
Emery[8,12]	16.8 -	25.5	0.66	0.29
Lowicz[10,12]	12.0	19.4	0.62	0.25
Mount Padbury[12]	12.6	17.8	0.71	0.23
Veramin[10]	7.5	12.8	0.59	0.22
Mincy[12]	11.9	16.6	0.72	0.19

References:

1. This work
2. Begemann et al (1976)
3. Easton and Elliott (1977)
4. Fredriksson et al (1976)
5. McCarthy et al (1972)
6. McCarthy et al (1973)
7. McCarthy et al (1974)
8. Mason and Jarosewich (1973)
9. Mason et al (1978)
10. Powell (1971)
11. Shima (1974)
12. Simpson & Ahrens (1977)
13. Takeda et al (1978)
14. Wanke et al (1977)
15. Wiik (1969)
16. Yagi et al (1978a,b)

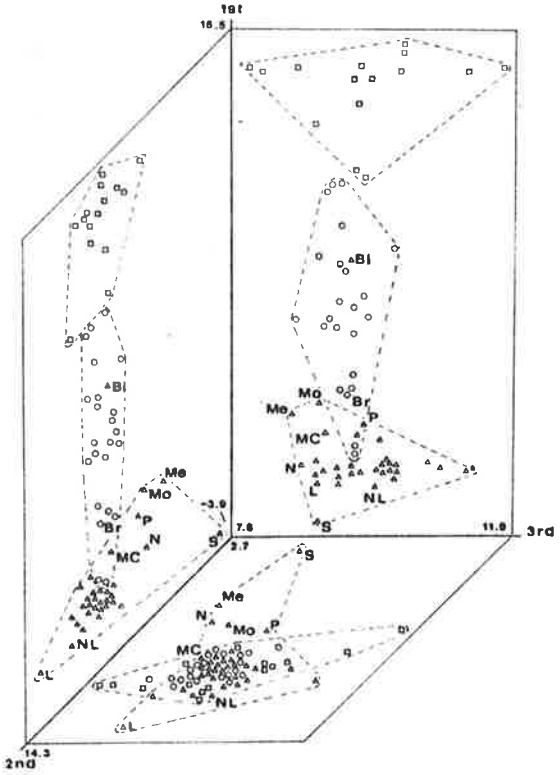


Figure 8.22 : First three principal components for a set of cumulate achondrites. □ : diogenites, △ : eucrites, ○ : howardites, Bi : Binda, Br : Brient, L : Lakangaon, Me : Medanitos, Mo : Moama, MC : Moore County, N : Nagaria, P : Pomozdino, S : Serra de Mage.

period of mesostasis crystallization after the initial melting event.

The powerful nature of the technique of principal component analysis in displaying complex relationships was further emphasised during the study of the cognate achondrites. Figure 8.22, a plot of the first three principal components for a suite of 70 cognate achondrites, like Figure 8.4, clearly shows the distinction between the diogenites, howardites and eucrites. At the same time, this diagram illustrates the transitional nature of the howardites which are positioned between the other two groups. The intermediate nature of Binda is illustrated by its position in the howardite field. An examination of the eucrites shows that most of them plot together in a compact group. Lakangaon, the meteorite with the greatest value in the direction of the second principal component was described above as a residual eucrite as was Nuevo Laredo, which has the next highest value in the direction of this component. In the opposite direction, two of the six meteorites lying away from the main group, viz. Moama and Moore County, were described earlier as cumulates. Of the other four, Stolper (1977) also described Serra de Mage, Medanitos and Pomozdino as cumulates. It is likely that the sixth member of this group, Nagaria, is likewise a cumulate. This conclusion is in harmony with the comments of Mason et al (1978) who stated that Nagaria resembled Moore County chemically, mineralogically and texturally, a resemblance which is clearly illustrated by Figure 8.22. The figure also suggests that Serra de Mage is somewhat different from the other five. These trends were also displayed in Figures 8.1 to 8.5. Stolper also described Binda and Brient as cumulate eucrites. If this is the case, then Figure 8.22 shows that their major chemistry is unlike that of the other cumulate eucrites. Mason et al described Brient as a howardite and its position in Figure 8.22 is consistent with such a classification while the position of Binda is in accord with its somewhat anomalous nature.

Mason et al used plots of CaO vs FeO/(FeO+MgO) and MgO vs Al_2O_3 to show the relationships between the eucrites and the howardites. The variance analysis from this work (Table 8.14) shows that these four elements are responsible for about 98% of the variance in the achondrite suite examined, while the first three principal components which are plotted here account for nearly 99% of the variance. Thus the one diagram used in this work can convey all of the information shown by two. This re-emphasises the utility of the technique of principal component analysis.

The howardites, lying in a somewhat elongated group between the eucrites and the diogenites, are seen to be intermediate in composition between these two groups. A close examination of Table 8.14 shows the variance portrayed by the first principal component arises from magnesium variation. The absolute variation in magnesium content is about twice as great in the howardites as in either of the eucrites or diogenites. Similarly, the range in calcium and aluminium abundances, the other two elements contributing to this first principal component, is about twice as great in the howardites. Conversely, there is a much smaller range in iron contents in the howardites and hence there is little variation parallel to the second principal component. In like manner, a small silicon variation limits the variation of the howardites parallel to the third principal component. The overall result is that the howardites lie in an elongated field parallel to the first principal component while the diogenites and eucrites lie in considerably more planar fields oriented at right angles to this eigenvector. Larger

Table 8.14 : Eigenvalues and eigenvectors for suites of cognate achondrites excluding and including mesosiderites.

Eigenvalues

	Diogenites and eucrites		*Diogenites, eucrites and howardites*	
Eigenvector	*%age variance*	*Cumulative %age*	*%age variance*	*Cumulative %age*
1st	*92.0*	*92.0*	*92.1*	*92.1*
2nd	*6.4*	*98.4*	*6.2*	*98.3*
3rd	*1.0*	*99.5*	*1.0*	*99.4*

Eigenvector elements both as absolute values and as percentages of the total variance

	Diogenites and eucrites						*Diogenites, eucrites and howardites*					
	1st		*2nd*		*3rd*		*1st*		*2nd*		*3rd*	
Fe	*-0.01*	*0.7*	*0.89*	*5.1*	*-0.35*	*0.1*	*0.09*	*0.7*	*0.90*	*5.0*	*-0.31*	*0.1*
Mn			*0.01*						*0.01*			
Ti	*-0.02*		*0.04*		*0.06*							
Ca	*-0.43*	*17.1*	*-0.14*	*0.1*	*-0.11*		*-0.43*	*17.2*	*-0.14*	*0.1*	*-0.08*	
Si	*0.12*	*1.3*	*0.10*	*0.1*	*0.70*	*0.6*	*0.11*	*1.2*	*0.09*	*0.1*	*0.80*	*0.7*
Al	*-0.42*	*16.1*	*-0.37*	*0.9*	*-0.39*	*0.2*	*-0.42*	*16.2*	*-0.36*	*0.8*	*-0.34*	*0.1*
Mg	*0.78*	*56.7*	*-0.19*	*0.2*	*-0.41*	*0.2*	*0.78*	*56.7*	*-0.18*	*0.2*	*-0.37*	*0.1*
Cr	*0.03*	*0.1*			*0.01*		*0.03*	*0.1*			*-0.01*	
Na	*-0.02*	*0.0*	*0.02*		*0.01*		*-0.02*		*0.01*		*0.02*	

Eigenvalues

	Diogenites, eucrites, howardites and mesosiderites		*Howardite inclusions*	
Eigenvector	*%age variance*	*Cumulative %age*	*%age variance*	*Cumulative %age*
1st	*79.7*	*79.7*	*77.2*	*77.2*
2nd	*16.9*	*96.6*	*18.3*	*95.4*
3rd	*2.4*	*99.0*	*3.5*	*98.9*

Eigenvector elements both as absolute values and as percentages of the total variance

	Diogenites, eucrites, howardites and mesosiderites						*Howardite inclusions*					
	1st		*2nd*		*3rd*		*1st*		*2nd*		*3rd*	
Fe	*-0.11*	*1.0*	*0.95*	*15.2*	*-0.01*		*0.55*	*23.6*	*-0.72*	*9.6*	*0.26*	*0.2*
Mn							*0.01*		*-0.03*		*-0.03*	
Ti	*-0.02*		*0.01*		*0.07*				*-0.03*		*-0.06*	
Ca	*-0.43*	*14.9*	*-0.09*	*0.2*	*-0.19*	*0.1*	*-0.39*	*11.6*	*-0.19*	*0.6*	*-0.10*	
Si	*0.12*	*1.1*	*-0.18*	*0.5*	*0.75*	*1.3*	*0.08*	*0.5*	*0.12*	*0.2*	*-0.67*	*1.6*
Al	*-0.42*	*13.7*	*-0.25*	*1.1*	*-0.44*	*0.5*	*-0.56*	*24.1*	*-0.02*		*0.56*	*1.1*
Mg	*0.78*	*48.8*	*-0.02*		*-0.45*	*0.5*	*0.47*	*17.4*	*0.65*	*7.7*	*0.39*	*0.5*
Cr	*0.03*	*0.1*	*-0.02*		*0.01*							
Na	*-0.02*				*0.01*							

iron and silicon variations in the mesosiderites cause them to lie in a more diffuse field than the howardites.

An examination of the data of Bunch (1975) shows that the compositional ranges shown by howardite clasts individually exceeds the range from the eucrites to the diogenites and a principal component analysis of this data (Figure 8.23), readily demonstrates this. The distribution of clasts varies from howardite to howardite thus explaining the greater variation in bulk chemistry of the howardites.

The principal component analysis of the achondrite data set cannot prove which, if either, of the two theories of howardite genesis is correct, but the correlations described here, plus the additional information obtained from Bunch's data, certainly support the continuous differentiation theory of Stolper.

A cluster analysis of the achondrite data (Figure 8.24) with a cophenetic correlation coefficient of 0.78 also clearly distinguishes the diogenites, eucrites and howardites and also subdivides the eucrites in the same way as the principal component analysis, thereby strengthening Stolper's model.

Addition of the mesosiderite data to

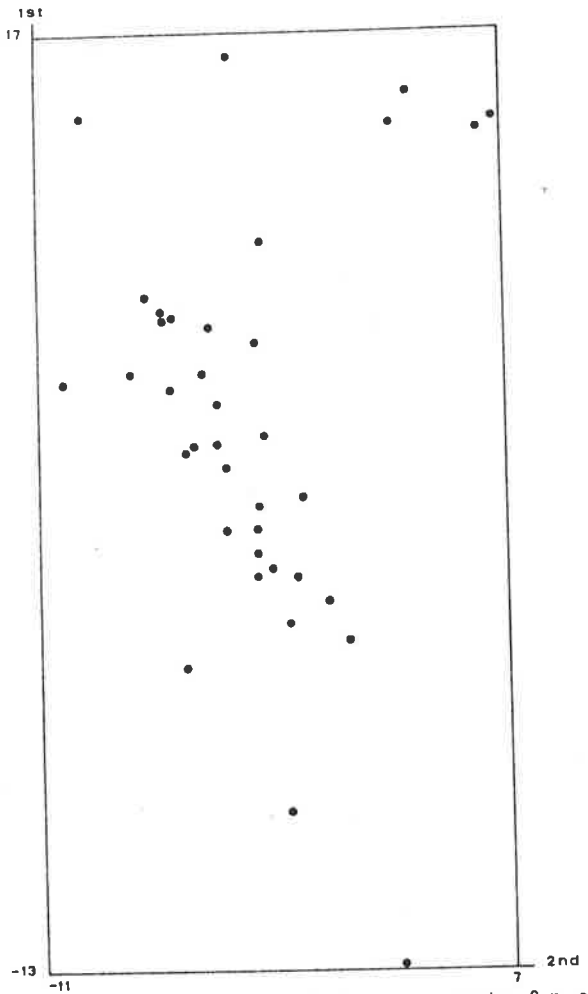


Figure 8.23 : First two principal components for a set of howardite clasts.

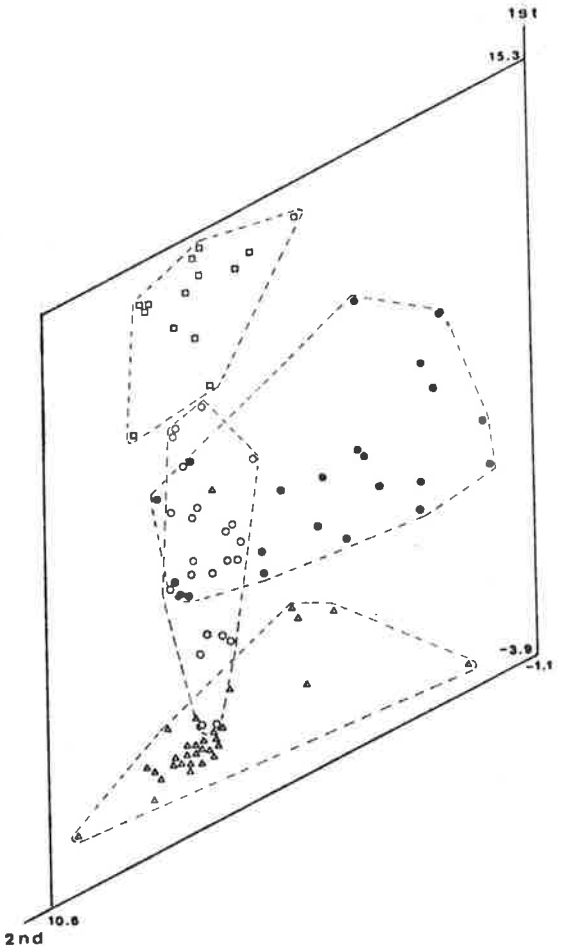


Figure 8.25 : First two principal components for a set a cognate achondrites. □ : diogenites, △ : eucrites, ○ : howardites, ● : mesosiderites.

Figure 8.24 : Q-mode cluster analysis of the cognate achondrites without the mesosiderites.

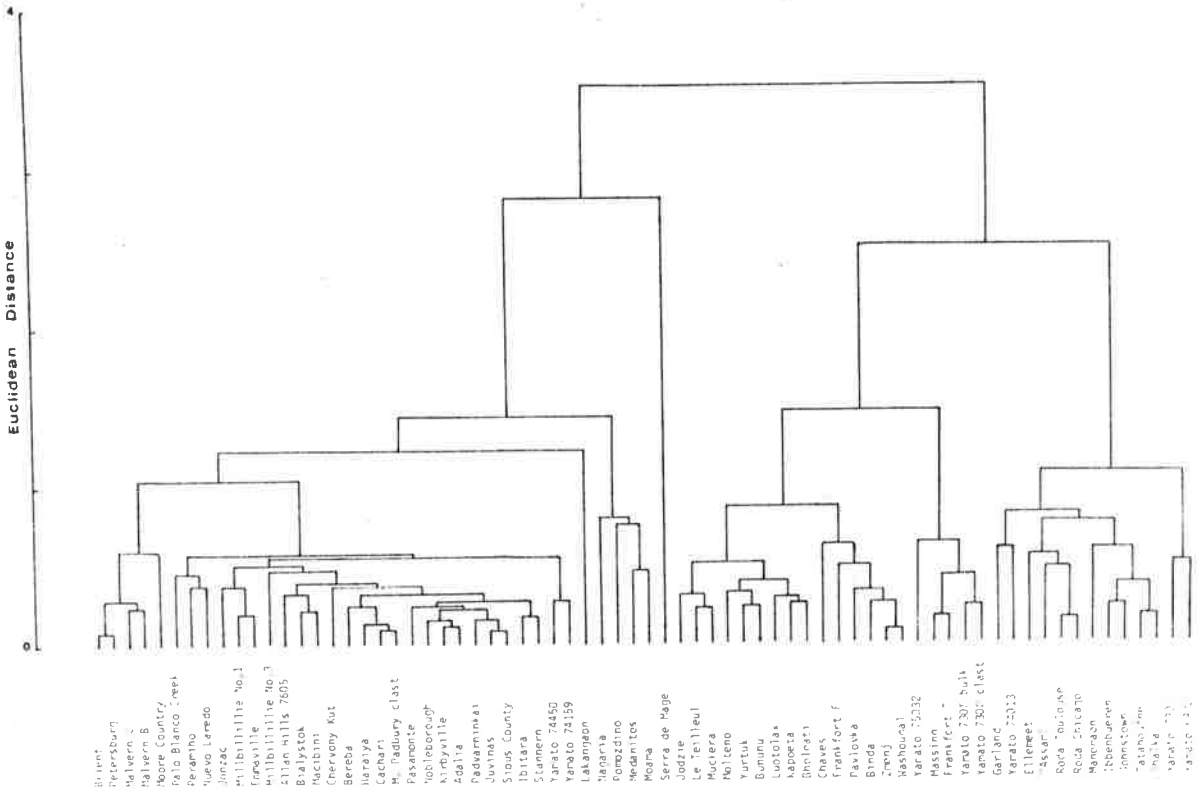
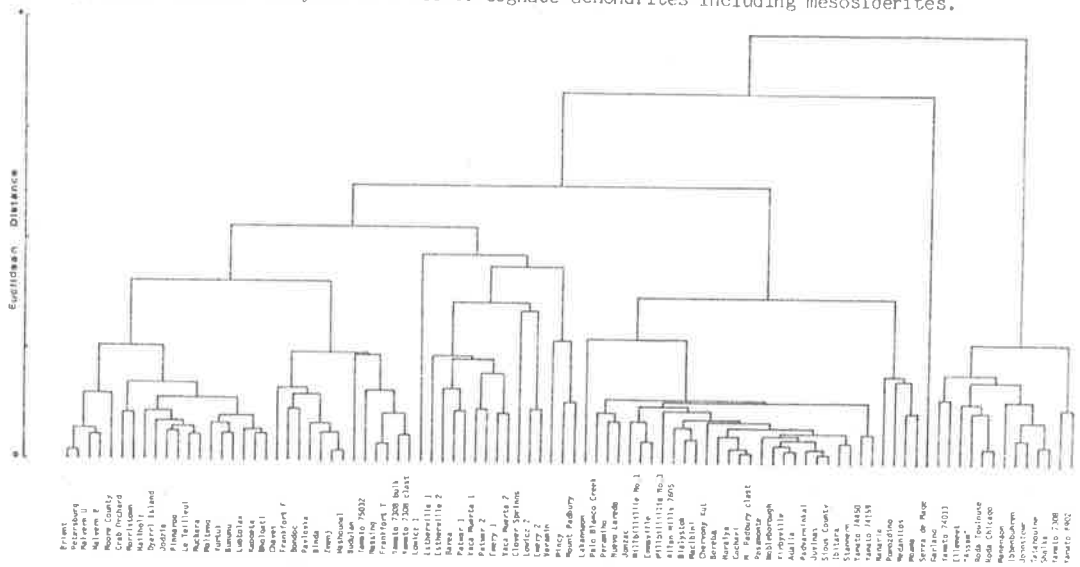


Figure 8.26 : Q-mode cluster analysis of a set of cognate achondrites including mesosiderites.



either the principal component (Figure 8.25) or cluster analysis (Figure 8.26) results in the mesosiderites overlapping the howardites, thereby showing that their proposed relationship with the other cognate achondrites is quite feasible.

Evidence for an asteroidal origin for meteorites is increasing (Chapman 1974, Levin et al 1976 etc.) and recent spectral studies (e.g. Larson and Fink 1975, Gaffey and McCord 1978) suggest that the surface of Vesta, for example, is very similar to the eucrites. Larson and Fink concluded that either Vesta's surface had been at least partly flooded with eucritic lavas or else sub-surface intrusions had been exposed by cratering.

Catastrophic impacts on the parent body could give rise to the cognate achondrites. The eucrites would be samples over a vertical range of such lavas and their deeper seated equivalents (cf. Miyamoto and Takeda 1977), while the howardites would be representatives of heterogeneous material comprised of possibly older surface material and reworked lavas and deeper material as well as meteoritic debris. The diogenites could be produced by impacts which sampled deeper orthopyroxene rich regions with the relative rarity of these meteorites resulting from either the small amount of material available or the violence of impact needed to excavate to these greater depths. If the mesosiderites originated from the same parent body, then such a sequence of events could explain some of the features commented on by Powell (1971) - viz. the presence of lithic and mineral fragments with a variety of origins and crystallization environments and the presence of large olivine and "dunite" clasts. If the mesosiderite metal had its origin in the inner portion of the cognate achondrite parent body as suggested by Stolper (1977), then it is likely that there would be olivine associated with it and such an association could represent part of the assemblage which would remain as a residue after extensive partial melting and fractional crystallization. This close association of metal and olivine would then explain the relative frequency of olivine in the mesosiderites and its virtual absence in the other cognate achondrites. The mesosiderites would then be produced by sampling material generated by mixing the metal-olivine assemblage with overlying material. At this stage, the nature of the process which could produce this intimate metal-silicate mixing is not completely clear, although, Floran et al (1978) suggested that at least in some cases, this occurred by impact melting. Even though Mittlefehldt (1977), on the basis of REE data suggested that the howardites and mesosiderites may have originated on separate parent bodies, it is possible, that they may simply reflect inhomogeneities in the parent body thereby permitting all of the cognate achondrites to have been produced in the one body.

If this is the case, then it is unlikely that Vesta is the source of the cognate achondrites as its apparent silicate crust implies that the deep "mesosiderite regions" have not yet been sampled. It is quite possible that the cognate achondrites have been produced from another asteroid whose outer surface may at one time have resembled Vesta. Gaffey and McCord (1977b) characterized several asteroids (eg. Hebe and Flora) as having surfaces similar to the mesosiderites and one or more of these may well be the source of the cognate

achondrites. As noted by Floran (1978) this hypothesis is supported by the work of Wetherill (1977) who suggested that these asteroids, which might be residual earth planetesimals or their fragments, may be important sources of the differentiated meteorites because of the high probability of the collisional production of earth crossing fragments. This would in turn explain the isotopic data of Clayton and others.

Chou et al (1976) sugested that the pallasites and the Group IIIAB irons were also related to the cognate achondrites as defined here and that we accordingly have samples of all regions of a parent body which has undergone extensive disruption. If this is so, it is possible that future impacts on Vesta could produce another suite of meteorites aranging from eucrites and howardites to irons.

Chapter 9

ALLIED CHEMICAL STUDIES AND GENESIS

9.1 INTRODUCTION

The chapter involves a brief examination of two topics which are germane to each of the previous four chapters and hence could not be readily included in any single one of them. The relationships between lunar, meteoritic and terrestrial materials are discussed followed by an examination of the constancy or otherwise of the Ca/Al ratio in silicate bearing meteorites.

9.2 THE RELATIONSHIP BETWEEN LUNAR, METEORITIC AND TERRESTRIAL MATTER

Like the achondrite parent bodies, the earth and the moon have both experienced periods of differentiation and so specimens of these bodies can be readily distinguished from chondritic meteorites on the basis of their composition relative to that of the sun.

There is a growing body of evidence suggesting the possibility of a genetic relationship between at least some of the differentiated meteorites, the moon and the earth (Clayton and Mayeda 1975, Chou et al 1976, Dreibus et al 1977b, Rammensee and Wanke 1977, Ringwood and Kesson 1976, etc.). Clayton and Mayeda, for example, concluded on the basis of oxygen isotope studies that the earth, the moon and the parent bodies of the differentiated meteorites had differentiated from a single well mixed reservoir within the solar nebula whereas other meteorites had sampled other regions of the nebula.

Subsequent events in the history of the earth, the moon and the so-called eucrite parent body have led to the establishment of differences between them and hence the possibility of distinguishing between specimens of them. Ulbrich (1970) examined three groups of rocks with similar chemistry and texture - terrestrial and lunar basalts and some eucrites - and concluded that the terrestrial material could be readily distinguished from the non-terrestrial samples then known by the use of plots of atomic ratios such as Ca/Na vs Fe/Mg and Ca/Na vs Ti. In the intervening years, the subsequent recovery of other lunar materials (Apollo 14, 15, 16, and 17, etc.) has somewhat blurred this distinction.

The distinction between terrestrial, lunar and achondrite material can, in principle, be made on the basis of Fe/Mn and K/La ratios (Dreibus et al 1977), and the latter ratio, according to these authors, will also characterize the ordinary chondrites.

A data set of one hundred and eighty lunar, meteoritic and terrestrial analyses was examined by principal component analysis. This analysis divided the data into three groups: one contained the chondrites and some of the achondrites, the second the lunar basalts and the remaining achondrites, while the terrestrial material and the remainder of the lunar rocks fell in the third group. The variation parallelling the first principal component was the transition, chondrites to differentiated meteorite and lunar material, to differentiated terrestrial material. This component, which accounted for 73% of the variance of the data set, involved variations in iron, silicon and magnesium, while the next 10% of the variance accounted for by the second principal component was due to further variations in silicon and magnesium.

A cluster analysis of the same data readily distinguished the chondrites but was unable to make any further significant distinctions.

Thus neither technique was able to uniquely characterize lunar, meteoritic nor terrestrial material.

9.3 THE EVOLUTION OF THE Ca/Al RATIO IN THE SILICATE BEARING METEORITES

9.3.1 Introduction

Ahrens and co-workers in a series of papers claimed that, when highly accurate analyses were considered, values of the ratio Ca/Al were almost constant in many meteoritic types including the chondrites and the cognate achondrites as defined in this work. Such a constancy would be remarkable since calcium and aluminium are distributed in several mineral phases (Mason 1971a), although, in the first instance, the

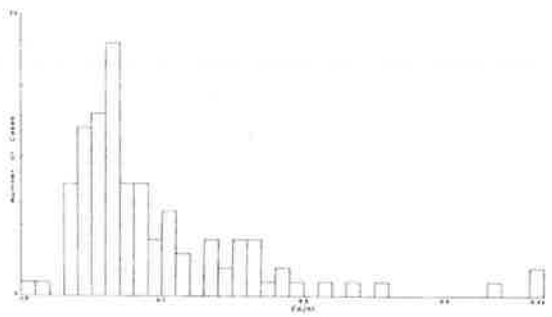
mineralogy is determined by the chemistry, and not vice-versa. Results obtained in this work as well as those of Ahrens and co-workers and others suggest that this ratio is not quite so constant - the value reported above for the carbonaceous chondrite, Adelaide, being a prime example.

9.3.2 The chondrites

Figure 9.1, a histogram of atomic Ca/Al ratios obtained for chondritic meteorites in this work and also culled from the literature, shows that the majority of the values lie between 0.71 and 0.77 with many in the range 0.73 to 0.75, thus explaining why the overall average quoted by Ahrens and other workers is about 0.73. However, the figure shows that there are some meteorites in which the value of this ratio is as great as 0.8 while in a considerably large number the value is as low as 0.5.

Larimer and Anders (1970) proposed a model for meteorite evolution in which the pre-existing solar nebula experienced a catastrophic heating event producing temperatures equal to, or in excess of, 2000°K thereby vapourizing any solid material. This gas subsequently cooled producing solid condensates. Grossman and Larimer (1974) considered the condensation sequence from such a gas and described initial Ca-Al-Ti-rich condensates which have been correlated with Ca-Al-Ti-rich inclusions in Allende and other carbonaceous meteorites. On the basis of the petrography of such inclusions, Grossman and Larimer concluded that they had been removed, possibly as centimetre sized nodules, from their condensation region prior to the condensation of any iron or magnesium silicates. Grossman and Ganapathy (1975) reached a like conclusion. Grossman and Larimer further concluded that some of these condensates subsequently experienced a period of remelting which is in accord with the observations of Mason and Martin (1977) on the Allende inclusions.

Figure 9.1 : Histogram of Ca/Al ratios for chondritic meteorites.



An examination of the condensation sequence of Grossman and Larimer (1974) suggests a possible explanation for the skewed distribution of the Ca/Al ratio. Considering the early condensates, at least 90% of the aluminium present in the nebular gas would have condensed some 50°K prior to the commencement of titanium and calcium condensation. These elements begin to condense with the formation of perovskite ($CaTiO_3$) but since the amount of titanium, relative to calcium, is quite small, condensation of the perovskite does not remove a significant proportion of the calcium from the nebular gas and by the time 90% of the titanium has condensed only about 10% of the calcium will have. If, as suggested by Grossman and Larimer, nodules of these early condensates were removed prior to magnesium and iron silicates condensing, then it is possible that the removal occured over a temperature range thereby resulting in the movement of nodules of varying composition. The calcium-aluminium fractionation so produced could have been emphasised by the accretion of chondrite parent bodies with increasing Ca/Al ratios away from their centres. Furthermore, if the initial condensation of calcium phases took place preferentially on aluminium condensates, or, calcium condensates lacking aluminium centres were too small to accrete, then the formation of a body with such a radially varying and asymmetrical distribution of aluminium and calcium would be promoted. Such radial asymmetry would be enhanced by the subsequent removal of outer layers represented by material such as the C1 chondrites. Anders (1971a) argued persuasively that the composition of these meteorites correspond to pristine cosmic abundances while Larimer and Anders (1970) commenting on the apparent paradox of the last material to accrete having the cosmic composition, stated that only a small portion of the nebula material actually accreted and that the accretion process was biased towards coarser sized aggregates, chondrules and metal grains. The Ca/Al ratio for Orgueil, a C1 chondrite, is 0.73 (Ahrens et al 1969). Observations of aluminium zoning in coarse grained inclusions in Allende (Wark and Lovering 1977) and in clinopyroxene grains (Burnett 1977) support the theory of fractionation during condensation although Wasson (1977) maintained that sequential accretion, in the order of condensation, was most unlikely.

That such inhomogeneities did exist in the chondrite parent bodies is shown by lithic

clasts in Abbott (Fodor et al 1976) and Plainview, Texas, (Fodor and Keil 1976a) for example. In both cases, the fragments showed marked variations in the values of the Ca/Al ratio, the ratio in all cases being either equal to, or less than, that of the meteorite as a whole. These clasts which belonged to the parent body, and may have been exhumed from depth, effectively reduce the Ca/Al ratio of the meteorite. Thus, the asymmetry of Figure 9.1 may simply reflect the quantity of deep seated material present in the meteorites. If this material was buried deeply then it would be expected that only small amounts would be excavated, although, in the case of Adelaide and Bench Crater it appears that larger quantities of calcium-poor material are present. The Ca/Al ratio of 0.42 observed in Adelaide and Bench Crater implies that such calcium-poor material may possess a Ca/Al ratio of even less than 0.4.

That not every aluminium-rich inclusion in Adelaide is deficient in calcium is shown by the analysis of a "chondrule" reported by Davy et al (1978). They commented that this inclusion was high in silica and did not correspond to the composition of a single mineral phase. A least squares mixing calculation showed that the following combination of minerals would have the bulk composition described by these authors:

Diopside	$CaMgSi_2O_6$	34.58%
Anorthite	$CaAl_2Si_2O_8$	31.96%
Silica	SiO_2	23.61%
Spinel	$MgAl_2O_4$	9.05%

There may be other possible mineral combinations having this composition but this appears to be the best fit to the analytical data. The Ca/Al ratio for this inclusion is 0.77.

Thus, it would appear that in the chondritic meteorites there is a significant variation in the Ca/Al ratio, and that this variation may reflect a parent body inhomogeneity brought about by heterogeneous accretion. Furthermore, if the C1 chondrites have cosmic compositions then departures from the value of 0.73 for the Ca/Al ratio are indicative of the presence of either calcium-rich and aluminium-poor phases or the converse.

9.3.3 The differentiated meteorites

In the light of the ease with which calcium and aluminium are fractionated during igneous differentiation (Stolper 1977), claims regarding the similarity of the value of the Ca/Al ratio for the differentiated meteorites and the chondrites ought to be examined carefully.

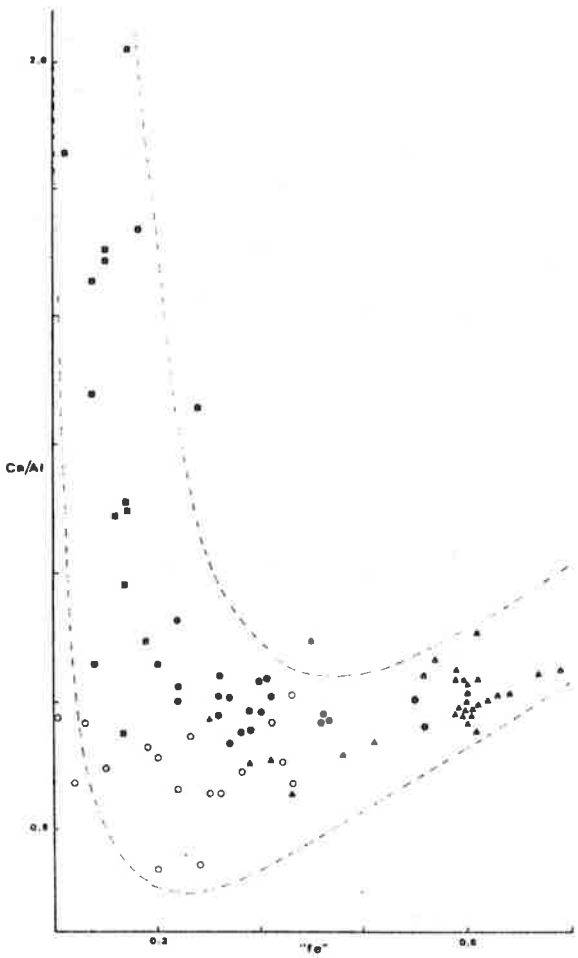
Table 9.1 : Ca/Al ranges in the mesosiderites.

0.42 - 0.75	*Mason and Jarosewich (1973)*
0.60 - 0.74	*Begemann et al (1976)*
0.69 - 0.75	*Simpson and Ahrens (1977)*

Table 9.1 shows, for example, some recent ranges quoted for the mesosiderites, while Figure 9.2, a plot of Ca/Al vs Fe/(Fe+Mg) for a suite of nearly 100 cognate achondrites, shows the relationship between the extent of differentiation and the value of the Ca/Al ratio. (The "fe" value decreases with increasing degrees of partial melting.)

The marked variability of the ratio in the diogenites (see Table 8.13 also) is a function of the low aluminium and calcium contents of these meteorites which causes any distributional inhomogeneities or analytical errors to become quite significant. Figure 9.2 shows an approximate positive correlation between the Ca/Al ratio and the "fe" parameter for the eucrites, whereas, for the diogenites, there is an apparent inverse relationship. Calcium and aluminium results given in Table 8.13

Figure 9.2 : Ca/Al vs "fe" for the cognate achondrites. ■ : diogenites, ▲ : eucrites, ● : howardites, ○ : mesosiderites.



suggest, in the case of the diogenites, a sympathetic relationship between these elements, whereas no marked trends are visible in the eucrite values. The howardites and mesosiderites generally behave in the same manner as the diogenites.

The relationship between the Ca/Al ratio and the differentiation process can also be seen in plots of the ratio versus incompatible elements such as titanium (Stolper 1977).

The cognate achondrites and the lunar breccias are both products of a similar, and possibly unique, process acting on materials of similar composition and structure (Mason and Melson 1970a, Marvin 1976). Taylor (1975) concluded that the lunar highland crust is fractured to a depth of about 25km with the top 10km brecciated and thoroughly stirred and mixed. If, as seems likely (eg. Dreibus et al 1977b), the cognate achondrite parent body had a diameter of the order of a hundred kilometres then most of the cognate achondrites will definitely not be representative of the body as a whole even though they are mixtures of one or more rock types. Toksoz et al (1978) additionally pointed out that bodies with diameters less than 1000km are unlikely to melt unless special conditions are fulfilled. Of all the cognate achondrites, the least differentiated ones (i.e. the "ordinary" eucrites) will most closely resemble the undifferentiated material and as can be seen from both Figure 9.2 and Table 8.13 the Ca/Al ratio for these meteorites is close to the chondritic value of 0.73. This possibly explains the observations of some authors that the achondrites and the chondrites have the same value for this ratio.

Similar variations in the value of the Ca/Al ratio are exhibited by the stony phases of the silicate-bearing iron meteorites and other groups of achondritic meteorites and thus any discussion concerning the nature of the calcium-aluminium relationship in the original solar nebula should not include data from the differentiated meteorites.

Chapter 10

THE IRON METEORITES

10.1 INTRODUCTION

The iron meteorites are the final group to be discussed in this work. Results are presented below for eleven members of the group, one of which, Weekeroo Station, was also mentioned in Chapter 8 as it contains silicate inclusions. Two others, Boxhole and Henbury, belong to the small group of meteorites which produced craters on impact with the earth, while the undescribed Kapunda mass is one of the smallest known iron meteorites (cf. Buchwald 1975b).

Various schemes have been proposed for iron meteorite classification. Major variations in nickel content were recognized early in their study, as was the presence or absence of the Widmanstatten pattern. Further subdivisions were made on the basis of the size of the kamacite lamellae constituting this pattern. Most early classificational schemes were based on these parameters. One simple one that is still used is the threefold division into hexahedrite, octahedrite and ataxite with the octahedrites being further subdivided on the basis of the kamacite lamellae widths.

There is a general increase in nickel content through the sequence hexahedrite, octahedrite, ataxite and accordingly a preliminary classification can be assigned on the basis of the nickel content. In recent years, a comprehensive classification scheme based on nickel, gallium, germanium and iridium contents has been devised by Wasson and co-workers. This work has been complemented by the metallurgical investigations of Buchwald (Buchwald 1975b).

Table 10.1 : Classifications based on bandwidths.

Meteorite	*Structural Classification*
Boxhole	*Medium octahedrite*
Cowell	*Medium octahedrite*
Henbury	*Medium octahedrite*
"S.A. Beta"	*Medium octahedrite*
Kapunda	*Medium octahedrite*
Kyancutta	*Medium octahedrite*
Moorumbunna	*Medium octahedrite*
Mount Sir Charles	*Fine octahedrite*
Rhine Villa	*Coarse octahedrite*
Weekeroo Station	*Coarse octahedrite*
Yardea	*Coarse octahedrite*

10.2 THE CLASSIFICATION OF IRON METEORITES

The meteorites examined in this work were first classified on the basis of kamacite lamellae bandwidth measurements (Table 10.1) using the technique described in Section 4.3.2. The classification was based on the bandwidth ranges of Buchwald (1975b).

The meteorites were next assigned to one or more of the "Wasson groups" on the basis of their nickel contents (Table 10.2), the compositional ranges of Scott and Wasson (1975) being used for this purpose, while the bandwidth ranges of Buchwald (1975b) again enabled them to be assigned to one or more of these groups on the basis of the size of the kamacite lamellae (Table 10.2).

The possibility also exists that one or more of these meteorites may not fit into

Table 10.2 : Classifications based on bandwidth and nickel content.

Meteorite	*Chemical Group*	
	On basis of Ni content	*On bandwidth basis*
Cowell	*IA,IIE,IIIA,IVA.*	*IA,IC,IIIA,IIIB,IIIF.*
Henbury	*IA,IIE,IIIA,IIIF,IVA.*	*IB,IC,IIIA,IIIB,IIIF.*
"S.A. Beta"	*IA,IIE,IIIA,IIIF,IVA.*	*IB,IC,IIIA,IIIB,IIIF.*
Kapunda	*IA,IIE,IIIA,IVA.*	*IB,IC,IIIA,IIIB,IIIF.*
Kyancutta	*IA,IIE,IIIA,IVA.*	*IB,IC,IIIA,IIIB,IIIF.*
Mount Sir Charles	*IA,IIE,IIIA,IIIB,IIIE,IVA.*	*IB,IC,IIIC,IVA.*
Yardea	*IA,IC,IIIF.*	*IA,IC.*

Table 10.3 : Final possible classifications.

Meteorite	*Chemical Groups.*
Cowell	*IA,IIIA.*
Henbury	*IIIA,IIIF.*
"S.A. Beta"	*IIIA,IIIF.*
Kapunda	*IIIA.*
Kyancutta	*IIIA.*
Mount Sir Charles	*IVA.*
Yardea	*IA,IC.*

any of these existing groups and therefore need an "anomalous" classification.

Table 10.3 lists the possible classifications which remain after eliminating any entries in Table 10.2 which did not appear in both the second and third columns. Results on individual meteorites, including those of other workers, are discussed later.

10.3 COOLING RATE CALCULATIONS

As pointed out in Section 4.3.2, the width of the kamacite lamellae in an octahedrite is a function of the nickel concentration and the cooling rate of the body in which they formed. Wasson (1971b) derived an equation from the work of Goldstein and Short which utilized the bulk nickel content of the meteorite and the average width of its kamacite lamellae to calculate its cooling rate. The equation derived by Wasson to calculate the cooling rate and used in this work is:

$$\text{Log}CR = -2.04\text{Log}BW - \text{Log}[Ni] + 8.7$$

where CR is the cooling rate in degrees Kelvin per million years, BW is the bandwidth in millimetres and [Ni] the nickel concentration.

In three cases the average nickel contents as quoted by Buchwald (1975b) were used as they could not be determined during the course of this work. For comparative purposes a set of cooling rates was also calculated using only Buchwald's data.

Table 10.4 shows that the calculated values of the cooling rates are quite sensitive to small fluctuations in either nickel content or bandwidth, thereby emphasising that at most two significant figures ought to be quoted. Wasson (1971b) estimated a minimum error of 40% in these calculations. Goldstein and Short (1967) examined 28 Group IVA meteorites and found a range in cooling rates from 2°K/my to 90°K/my, while Moren and Goldstein (1977) using a model based on the iron-nickel-phosphorus system calculated cooling rates for eight Group IVA irons ranging from 3°K/my to 50°K/my. The value of 63°K/my for Mount Sir Charles, relative to its nickel content, appears to be anomalous but so too are several other features of this meteorite (see also Section 10.7).

10.4 COWELL AND KYANCUTTA

A possible relationship between these meteorites will be discussed on both chemical (Section 10.9) and historical (Section A2.5.2 c) grounds. On the basis of the results obtained in this work and the gallium and germanium data of Reed (1972), it is apparent that the IIIA classification given by Reed to both of these meteorites is correct.

10.5 HENBURY AND "S.A. BETA"

One of the main reasons for examining Henbury in this work was to compare it with Cowell, Kyancutta, Kapunda and "S.A. Beta". The IIIA classification of Henbury by other workers is not at issue and is accepted here. On the basis of the results of this work and an examination of "S.A. Beta" by Buchwald (pers. comm. 1974), it also is assigned to Group IIIA.

Table 10.4 : Bandwidths, nickel contents and cooling rates.

Meteorite	*Bandwidth mm*		*Nickel content %*		*Cooling rate °K/m.y.*	
	This work	*Buchwald*	*This work*	*Buchwald*	*This work*	*Buchwald*
Cowell	*1.13*	-	*8.13*	-	*2.9*	-
Henbury	*0.92*	*0.95*	*7.45*	*7.51*	*9.5*	*8.3*
Kapunda	*0.93*	-	*8.05*	-	*4.6*	-
Kyancutta	*0.98*	*1.05*	*8.10*	*8.15*	*3.9*	*3.2*
Moorumbunna	*0.90*	*0.95*	-	*8.90*	*2.0**	*1.8*
Mount Sir Charles	*0.22*	-	*8.35*	-	*63*	-
Rhine Villa	*1.33*	*1.40*	-	*8.61*	*1.2**	*1.1*
"S.A. Beta"	*0.94*	-	*7.48*	-	*8.8*	-
Weekeroo Station	*2.29*	*2.5*	-	*7.22*	*2.0**	*1.6*
Yardea	*2.08*	*2.0*	*6.81*	*6.8*	*4.0*	*4.1*

**Cooling rates calculated using nickel data of Buchwald (1975b)*

10.6 KAPUNDA

Although early measurements carried out on this meteorite lead to its classification as a coarse octahedrite, the more precise measurements reported here clearly associate it with the medium octahedrite class while its nickel content places it in the common Group IIIA. The nickel content is, however, quite distinct from that of Henbury and accordingly, even though they both belong to the same group, it appears most unlikely that Kapunda is a transported Henbury fragment and so it can take its rightful place among the list of South Australia's meteorites. Henbury material is ubiquitous in Australia (Section 10.10.1) and hence the caution in reporting new Group IIIA meteorite finds.

10.7 MOUNT SIR CHARLES

Reed (1972) analysed 45 iron meteorites and presented results for nickel, gallium and germanium. The meteorites analysed included Mount Sir Charles and Yardea. In a subsequent note in 1974, he pointed out that the analyses of these two meteorites had been carried out on mislabelled specimens and consequently the reported results ought to be interchanged (cf. also Buchwald 1975b). The samples of both meteorites had been provided by the S.A. Museum and prior to their supply, the Mount Sir Charles meteorite had been cut in this Department and the analysis reported in this work is of material obtained during this cutting. The 8.35% nickel result so obtained is in marked disagreement with that of Reed (7.7%) which is surprising as results obtained by the author and Reed for other meteorites (e.g. Cowell 8.13 and 8.2% respectively) are in good agreement.

A possible explanation is that the material analysed by Reed not only had the "Mount Sir Charles" and "Yardea" labels interchanged but neither specimen was Mount Sir Charles. A polished surface of this meteorite shows a distorted octahedral pattern on etching. The kamacite bandwidths were reported above as having dimensions of the order of 0.2mm but lamellae as such are not readily found in the meteorite, but rather, small, isolated grains of kamacite having an approximate linear arrangement, which to the naked eye, has the appearance of a Widmanstatten pattern. This no doubt explains the anomalous cooling rate calculated in Section 10.3. Buchwald described Mount Sir Charles as a cosmically reheated fine octahedrite (Reed 1974) which thus accords with the description given here for Mount Sir Charles and so it appears genuine Mount Sir Charles material was supplied to Reed. Another possibility is that the results reported in this work are in error but this is considered unlikely as the value of 8.35% nickel is the average of nine separate analyses having a range from 8.32 to 8.43%. This large number of analyses was performed to eliminate the possibility of error in this determination. Sample inhomogeneity, or error in Reed's analysis, seem the only likely explanations for the marked differences in nickel content.

The assignment of Mount Sir Charles to Group I (Buchwald 1975b) which is in error, was based on the incorrect data whereas the Group IVA classification given above is in agreement with Buchwald's description of the meteorite as a "reheated fine octahedrite". The IVA classification is consistent with the nickel results of either this work or Reed (1974). The trace element date (Reed 1974) does not, however, accord with the ranges of gallium and germanium normally found in the Group IVA meteorites. Concentrations of 8 ppm for both elements correspond to the relatively small hiatus betwen Groups IIIC and IIID. Mount Sir Charles is thus an anomalous fine octahedrite which, on the basis of its nickel content, belongs to Group IVA, but on trace element content belongs to Group IIIC or IIID and as a consequence it is given an anomalous classification. In the light of the problems associated with the nickel determination, it is also possible that the gallium and germanium results are in error.

10.8 RHINE VILLA

All compilations prior to the 1970's listed Rhine Villa as a medium octahedrite. As shown in Section 10.2, its kamacite bandwidth is appropriate to that of a coarse octahedrite and it was so classified. A similar conclusion was drawn by Scott et al (1973) who classified it as a coarse octahedrite belonging to Group IIIE.

10.9 YARDEA

Yardea was shown in Section 10.2 to be a coarse octahedrite belonging to Group I. Prior to this work, Yardea had been classified as a medium octahedrite but its coarse nature was demonstrated in the early stages of this investigation. Reed (1974) came to a similar conclusion as did Buchwald (1975b) who gave it the same classification as assigned in this work.

The agreement between the nickel result of this work (6.81%) and that of Reed (1974) (6.8%) suggests that the gallium and germanium results quoted by Reed for Yardea

are appropriate for the material examined in this work thereby indicating a Group IA classification for Yardea. Buchwald (1975b) agreed with this conclusion.

10.10 SOME METEORITES POSSIBLY BELONGING TO THE SAME FALL

As pointed out in Section 6.6 in reference to the stony meteorites, neither proximity of find, nor similarity of composition, taken on their own, prove a relationship between two meteorites, but the two factors together are at least suggestive of such a relationship.

10.10.1 Henbury and similar material

Due to the large quantity of material and its nature, the Henbury iron has been of interest to both black and white Australians and they have transported specimens of it over large distances. The following meteorites, as will be discussed in Chapter 13, have all been shown to be samples of Henbury: Basedow Range (Scott et al 1973), Gallipoli Station (Buchwald 1975b), Nuleri (Buchwald 1975b p.1408), and Nutwood Downs (Scott et al 1973). It is possible that the poorly known Glen Helen meteorite may also be a piece of Henbury. The Nuleri meteorite was "recovered" in Western Australia. Hart Range (De Laeter 1973), another transported meteorite, has been shown to be a piece of Boxhole. Although similar, the Boxhole and Henbury material are independent (De Laeter 1973, Buchwald 1975b).

The similarity of the results obtained for Henbury and "S.A. Beta" in this work, together with the uncertainty surrounding the discovery of the latter, are suggestive of a relationship between these two meteorites. Table 10.5 shows the similarity of the results of this work and to those of other workers.

Buchwald examined a specimen of "S.A. Beta" and stated (pers. comm. 1974) that in his opinion there was no doubt that it was a transported fragment of Henbury. Unlike many Henbury masses, this particular piece does not show any evidence of twisting. Examination of six faces during cutting did not reveal any troilite nodules of significant size.

Table 10.5 : A comparison of "S.A. Beta" and Henbury.

Meteorite	*Nickel Analysis (Wt. %)*									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Henbury	*7.48*	*7.54*	*7.52*	*7.44*		*7.62*		*7.2*		*7.47*
Basedow Range							*7.42*			*7.45*
Gallipoli Station					*7.29*					
Nuleri									*7.44*	
Nutwood Downs										*7.66*
"S.A. Beta"	*7.45*									
Boxhole				*7.59*		*7.66*	*7.72*			*7.64*
Hart Range				*7.60*						

References:

1. *This work.*
2. *Alderman (1932b)*
3. *Buchwald (pers. comm. 1974)*
4. *De Laeter (1973)*
5. *Hutchison et al (1977)*
6. *Lewis and Moore (1971)*
7. *Lovering et al (1957)*
8. *Reed (1972)*
9. *Scott and Wasson (1976)*
10. *Scott et al (1973)*

Table 10.6 : Nickel contents of Cowell, Kyancutta and Henbury.

Nickel Content (Wt %)			
Cowell	*Kyancutta*	*Henbury*	*Reference*
8.13	*8.10*	*7.45*	*This work*
-	*8.15*	*7.51*	*Buchwald (1975b)*
-	*8.28*	*7.66*	*Lovering et al (1957)*
-	*8.10*	-	*Moore et al (1969)*
8.2	*8.2*	*7.2*	*Reed (1972)*
8.02	-	-	*Schmidt (1969)*
-	*8.06*	*7.47*	*Scott et al (1973)*

10.10.2 Cowell and Kyancutta

Almost as soon as the discovery of Kyancutta was announced, the charge was laid that it was a Henbury mass. A comparison of some of the nickel analyses for Kyancutta and Cowell with those of Henbury (Table 10.6) indicate that this is not so.

Kyancutta, with mild indications of shock, is chemically and structurally related to Thule, Franceville, Milly Milly and Briggsdale, while Henbury, with some specimens showing evidence of violent

Table 10.7 : Trace element data for Cowell, Kyancutta and Henbury.

	Cobalt %	Carbon %	Sulphur %	Copper %	Gallium ppm	Germanium ppm
Cowell	0.40[4]	0.03[4]	0.03[4]	0.011[4]	21[3]	38[3]
Kyancutta	0.47[2]	0.01[2]	0.01[2]	0.017[2]	21[3]	42[3]
Henbury	0.59[1]	-	-	0.023[1]	19[1]	42[1]
	0.49	-	-	0.019[1]	60[1]	209[1]
	-	-	-	-	20[3]	44[3]

References:
1. Lovering et al (1957)
2. Moore et al (1969)
3. Reed (1972)
4. Schmidt (1969)

deformation, is related to Boxhole, Kenton County, Cape York, Haig and Wabar (Buchwald 1975b) thereby further indicating that Kyancutta is not a transported specimen of Henbury.

These results, plus those of Table 10.7, also support the contention that Cowell and Kyancutta both belong to the same fall.

Also relevant to this discussion is the presence of large troilite nodules in Cowell and Kyancutta. To date, the largest nodule found in Cowell is approximately 30x30x25mm in size, while two nodules measuring 30x25 and 20x15mm respectively were located in Kyancutta material held in the meteorite collection of the Australian National University. On the other hand, an examination of several Henbury masses has failed to reveal any troilite nodules with dimensions in any way approaching the Cowell of Kyancutta ones.

10.11 CONCLUSION

Table 10.8 summarizes the classifications of the iron meteorites discussed in this work.

Table 10.8 : Summary of classifications.

Meteorite	Chemical Group
Cowell	IIIA
"S.A. Beta"	IIIA
Kapunda	IIIA
Mount Sir Charles	Anomalous
Yardea	IA

Chapter 11

TEXTURAL STUDIES AND GENESIS

11.1 INTRODUCTION

Virtually since the time of their discovery, chondrules have provided the stimulus for much discussion and research. The aim of this chapter is to briefly review the results of some of this work and then to propose a new definition for chondrules, followed by a description and discussion of various other textural features and relationships encountered during this work.

11.2 CHONDRULES - THEIR NATURE AND ORIGIN

11.2.1 Introduction

In 1863, while cataloguing the meteorite collection of the University of Berlin, Gustav Rose noticed that a large number of the stony meteorites contained many more or less rounded bodies. He called these bodies "chondri" from the Greek work for a seed grain. He termed the meteorites which contained these bodies chondrites and those from which they were absent, achondrites (Rose 1864). Jaques-Louis Compte de Bournon, a French mineralogist, who was probably the first person to record their existence (Sears 1975), had described chondrules some sixty years before as "small bodies, some of which are perfectly globular, others rather elongated or elliptical" without naming them (Bournon 1802).

Chondrules were probably first seen in this section by Henry Clifton Sorby, who, in describing some British Museum meteorites, commented on the presence of rounded grains (Sorby 1864). He subsequently described these grains at greater length and discussed the evidence for his conclusion that they had had an independent existence as glassy globules. He likened them in this state to "drops of fiery rain" (Sorby 1877).

Rose's name "chondros" gained acceptance for some time but was ultimately supplanted by the term chondrule.

11.2.2 Previous chondrule definitions and related matters

Many definitions have since been proposed for chondrules. Mason (1962b) defined chondrules as "spheroidal bodies commonly about a millimetre in diameter and normally consisting of olivine and/or orthopyroxene"; this definition is fairly typical of the working definitions which have been commonly accepted by most meteoriticists. As discussed in Chapter 5, the chondrites are now defined in terms of their chemistry relative to solar abundances and so Wood (1963), for example, defined chondrules as stony spheroids that occur in chondritic meteorites.

Merrill (1920) carried out an extensive study of chondrules and divided them into five groups while Van Schmus (1969b) described six. He distinguished between a. barred olivine, b. radiating pyroxene, c. porphyritic, d. glassy, e. agglomeratic or accretionary, and, f. lithic chondrules. In connection with this last type, Van Schmus commented that they might not be chondrules but dismissed the matter as being merely one of semantics. Such is not the case as an adequate chondrule definition must embrace all bodies which ought to be so defined and exclude all others.

Numerous theories have been advanced to explain the origin of chondrules. These include that of Fermor (1938) who invoked the metamorphism of garnets to explain the rounded forms. Currently there is fairly universal agreement that at least some of the bodies currently referred to as chondrules were once molten but there is no such agreement as to the method of the production of these bodies. Most current theories fall into one of two groups involving either condensation or impact mechanisms.

Mason (1967d) commented that he would hesitate to assert that everything referred to as a chondrule originated by the same process and it is in the light of such observations that the chondrule definition ought to be examined.

Desirably, the definition should not to contain any genetic connotations. If several diverse mechanisms are subsequently required to explain the formation of different chondrule types then the definition may be too general. In order to circumvent this problem, Fredriksson et al (1973) went

further than Mason and suggested that not even all rounded fragments are chondrules. They defined a "chondrule" as a "once wholly or partly liquid individual body which cooled, solidified or crystallized rapidly", while Grossman and Olsen (1974) defined true chondrules as "objects containing the following unambiguous evidence of being the solidification products of rapidly quenched molten droplets - interstitial glass and/or barred and/or radial crystalline textures". Both these definitions tend to involve genetic judgements on the part of the observer and, furthermore, there is little universal agreement as to the origin of the so-called quench textures on which these judgements are to be based.

In meteorites containing primary feldspar, it is present in the high temperature or disordered form (Mason 1965b). Ringwood (1966) and others have seen this as evidence of rapid cooling, whereas Van Schmus and Ribbe (1968) suggested that this is not necessarily so as the sluggish nature of the transformation from the high to low temperature form would be sufficicient explanation. After examining several meteorites of low petrologic grade, Binns (1970) concluded that the monoclinic pyroxenes present were formed from high temperature polymorphs during comparatively rapid cooling which was also responsible for the presence of glass.

Chemical and mineralogical similarities between the chondrites and terrestrial ultramafic rocks suggest their textures may be compared. The least metamorphosed chondritic meteorites commonly contain spheroidal bodies of skeletal crystals set in a glassy matrix (Figures 11.1 a,b). These textures so closely resemble ones found in terrestrial ultramafic rocks that the term "spinifex texture" as defined by Nesbitt (1971) to describe the terrestrial features can be applied to the meteoritic analogues. The term was originally applied to the range of textures occuring in rocks from the greenstone belts of Western Australia which exhibited skeletal forms of their original mineral components. Nesbitt claimed that this texture was produced by in situ crystallization through fast cooling of a superheated liquid, nucleation being restricted to a few sites, i.e. a quench process. (Fodor and Keil (1976b) have used this term to describe the texture of a lithic fragment in the Eva chondrite.)

On the other hand, Drever et al (1972) stated that such hollow olivine crystals were indeed typical of rapid crystallization but rapid crystallization does not necessarily imply rapid cooling. They distinguished between supersaturation, undercooling and quenching and showed that small degrees of undercooling can yield high degrees of supersaturation. Nevertheless, they concluded that randomly oriented microlites are typical quench products. Since cooling is not the only process which will initiate nucleation, the sine qua non of crystallization, Donaldson (1974,1976) also emphasised the use of the term supersaturation rather than supercooling and stated that neither the size of the crystals nor the skeletal and dendritic shapes characteristic of rapid growth can be used as an index of cooling rate or crystallization environment.

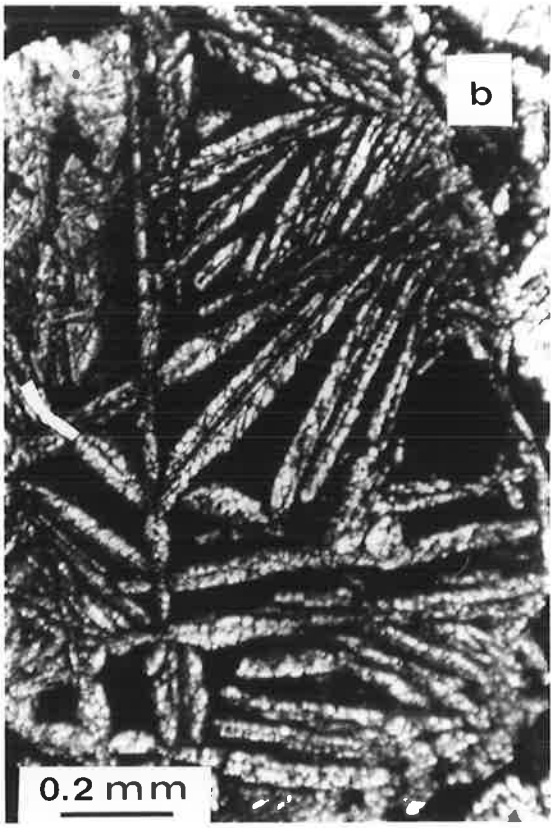
It is convenient to think of glasses as liquids cooled below their freezing points without crystallization, thereby existing in a metastable state. The free energy of this state is higher than that of a mixture of crystalline phases of the same composition and to transform itself from the metastable state the glass must undergo the two reactions of nucleation and crystal growth. These two processes have different rate-controlling mechanisms with the rate of maximum nucleation occuring at a lower temperature that that at which growth is significant (Rogers 1970).

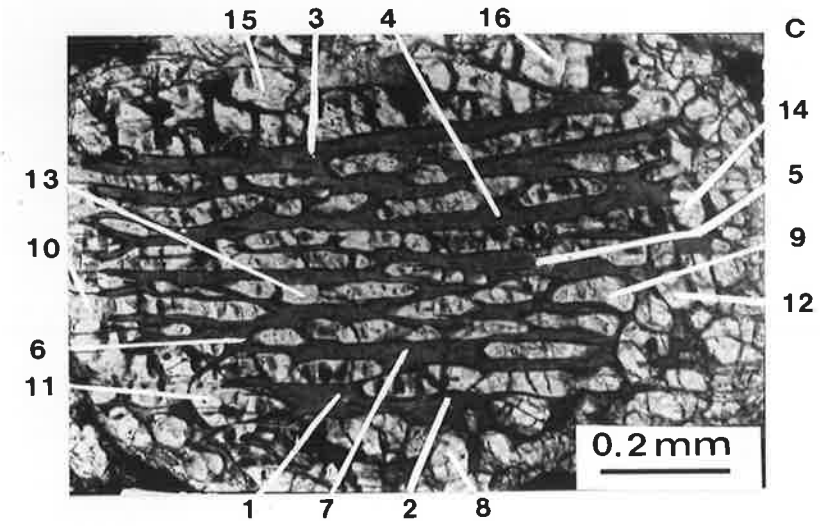
Extensive work on spherulitic and dendritic crystal growth (Keith and Padden 1963, 1964a,b and Lofgren 1971, 1974) was summed up by Fleet (1975) who pointed out that for crystals grown under a high cooling rate from undercooled and supercooled melts, kinetic factors tended to become dominant and the resulting crystal habit may bear little resemblance to crystals grown under equilibrium conditions. Crystallization under near-equilibrium conditions tends to produce equant crystals as this habit represents a minimization of specific surface area, whereas at higher cooling rates elongation or flattening, parallel to the directions of easy growth, will occur.

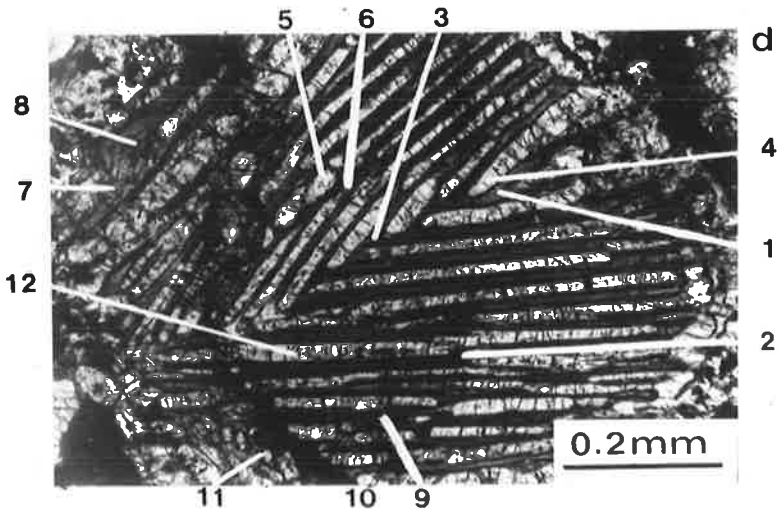
At the higher cooling rates, the two major kinetic factors are the growth rate (i.e.

Figure 11.1 a. Carraweena chondrule.
b. Carraweena chondrule.
c. Carraweena chondrule.
d. Carraweena chondrule.


a
0.2mm


b
0.2 mm


15
3
4
16
c
14
13
5
10
9
12
6
11
0.2mm
1
7
2
8


5
6
3
d
8
4
7
1
12
2
0.2mm
11
10
9

the velocity of advance of the growing crystal face) and the diffusion coefficient. These factors are functions of the melt viscosity and in turn of the temperature. When the growth rate exceeds the diffusion rate, a thin layer of impurity or low-temperature component builds up in the liquid at the solid-liquid interface. Chance perturbations on this surface may pierce this layer and this, coupled with increases in supercooling away from the crystal, will lead to filamentous growth. At very high growth rates, crystallographic continuity is not maintained giving rise to skeletal and dendritic forms as the growth rate is great enough to preclude the complete infilling of the crystal which is growing in the direction of easiest growth (Fleet 1975). Different crystal forms thus reflect different modes of crystallization and in turn varying crystallization conditions. Bryan (1972) illustrated this with a series of submarine basalts.

Dodd (1971a) claimed that the spherical form and skeletal nature of certain chondrules indicated that they were quenched droplets and that the relatively high calcium content of their olivines was consistent with the results of Smith (1966) who found that basaltic and doleritic olivines contained more calcium than gabbroic ones. Dodd (1971b) also pointed to high calcium and aluminium contents of olivine as indicators of rapid crystallization but, as pointed out above, the rapid crystallization necessary to allow the large calcium ion to be incorporated into the olivine lattice is not necessarily produced by rapid cooling and hence a high calcium content is not an unambiguous indicator of rapid cooling.

Reid et al (1974) attempted to reproduce the texture of a glassy chondrule from Vigarano (C3V) and concluded that it had been formed at an extremely high temperature and that cooling had been rapid to preserve the glass. Cooling rate calculations suggest that chondrule-sized bodies will quench in at most a few seconds, yet glass is not an abundant feature of most meteoritic "chondrules". Reid et al explained this apparent anomaly by suggesting that the formation of glass was a function of the droplet's composition, or, alternatively they cooled more slowly. Subsequent devitrification or recrystallization is another possible explanation, as is the use of an inadequate chondrule definition.

Lofgren et al (1974), while examining the relationship between texture and cooling rate in a synthetic quartz normative basalt, found that it was possible to produce porphyritic textures at linear cooling rates, a finding contrary to generally accepted theories. Dowty et al (1974) explained this, in the case of a pyroxene-plagioclase mixture, by postulating an intial nucleation and growth of phenocrysts of pyroxene until the pyroxene-plagioclase cotectic was reached. Nucleation of plagioclase on the pyroxene then resulted in supercooling of the melt with respect to pyroxene, thus producing as accelerated pyroxene nucleation and so abundant groundmass crystals. These results are significant as they suggest it may be possible to produce porphyritic chondrules along with barred and radiating types without having to invoke a separate mechanism. On the other hand, if porphyritic chondrules are merely fragments of pre-existing rock (Dodd 1978a,b) should they be called chondrules?

Prior to the Apollo missions, chondrules were thought to be uniquely meteoritic but many lunar samples contain objects closely resembling meteoritic chondrules. As the chemistry of these lunar particles is very similar to that of the rocks in which they occur, they have been called lunar chondrules to emphasise that they are indigenous to the moon.

Keil et al (1973) examined a series of laser-melted droplets which had cooled and solidified while falling under gravity and found that many were very similar to lunar chondrules. Since the composition of the starting material was not the same as lunar or meteoritic chondrules, no quantitative conclusions were drawn but merely the generalization that lunar chondrules had formed by the spontaneous crystallization of high supercooled molten droplets, thus supporting earlier results of Kurat et al (1972).

Kurat et al also discussed the relative frequency of spherules and chondrules at the Apollo 11 and 14 sites. (The lunar spherules, which were not characterized by spherulitic forms, were described by Kurat et al as clear glass spheres commonly containing a few very small, equidimensional, feldspar crystals near the surface.) They concluded that the Apollo 11 material had been produced in small scale events and hence the molten droplets so produced cooled rapidly, solidifying to glass spherules, whereas the Apollo 14 material had been produced in large scale impact events with low cooling rates due to shielding in the large impact plume, increasing the possibility of

crystallization due to an increase in the probability of nucleation. Furthermore, they found that ANT chondrules were common whereas no glass spherules of this composition were found, while conversely, KREEP and basaltic glasses were far more abundant than chondrules of this composition. The chemical composition thus appears to affect the probability of nucleation, a situation which is paralleled in meteoritic chondrules by the common presence of pyroxenic glasses and the absence of olivine composition. Kurat et al's distinction between glass spherules and chondrules is significant in that it implies a spherule becomes a chondrule once its content of crystalline material exceeds a certain value, but these authors did not comment on the extent of crystallization necessary to achieve chondrule status.

Various lines of evidence suggest that the chondritic meteorites have been formed on several different parent bodies and, at least in the case of Allende, possibly over a large time interval (Fireman et al 1970, Tanaka and Masuda 1973). Chondrules may thus have been formed in several different localities by a similar set of processes. A reduction in the number of these processes is appealing and thus for example, if chondrites are considered to be essentially impact-generated breccias (Fredriksson et al 1973) and the chondrule definition restricted so as to include a set of bodies, possibly with different structures, but all produced by the same phenomenom, then there is no necessity to predicate the occurence of several different processes occuring in several different localities.

11.2.3 A new chondrule definition in the light of this work

Several authors (e.g. Dodd and Walter 1972, Dodd 1978 a,b, Olsen and Grossman 1978) have concluded that many so-called chondrules are either rounded rock fragments or original nebular condensates rather than bodies that were once individual molten droplets. The author proposes that only these latter objects be termed chondrules and puts forward the following definition without attempting to indicate a mechanism of formation be it simple or complex.

> Chondrules are spheroidal bodies of about one millimetre diameter which are characterized by the presence of varying amounts of crystalline material, in dendritic, skeletal or similar form, and glass, which may or may not be devitrified.

This definition implies that chondrules were once molten globules but no subjective judgements as to the method of formation of these droplets, or their subsequent fate, is necessary in identifying a chondrule on the basis of the definition proposed here as it contains objective criteria only.

The definition also implies that all other rounded or semi-rounded objects occuring in chondritic meteorites ought to be given another name. Terms such as "aggregate", "clast" or "inclusion", which are already in use, should be adequate for this purpose. This restricted definition is in direct contrast with those of authors such as Wood and McSween (1977) who envisage all inclusions, both rounded and otherwise, as having been formed by the one process.

On the basis of the chondrule definition proposed above, Van Schmus' (1969b) type a, b, d and posssibly some type c chondrules are true chondrules while his groups e and f do not fit the definition and are best described as inclusions etc. The group c porphyritic chondrules present a problem in that on the one hand the results of Lofgren et al (1974) suggest that it is possible to produce porphyritic chondrules by the same process responsible for say barred olivine ones, while the results of Dodd (1978a) and Olsen and Grossman (1978) suggest that such bodies are not chondrules as defined above, but rather rounded rock fragments. The general absence of skeletal or similar forms in most of these inclusions excludes them from being chondrules on the basis of the proposed definition. Nonetheless, this does not preclude the existence of some porhyritic chondrules.

11.2.4 The origin of chondrules

As already mentioned, most of the current theories of chondrule genesis invoke either impact or condensation mechanisms, other methods (e.g. volcanic activity) having been shown to be untenable (e.g. Wood 1962).

The impact theories fall into two groups; those involving the impact of small bodies with significantly larger ones (e.g. Dodd and Walter 1972, Taylor 1975) and the impact of two small bodies of approximately equal dimensions (e.g. Kieffer 1975). Wasson (1974) concluded that condensation processes could not explain chondrule formation whereas impact ones could and proposed such a model. McSween (1977c) likewise discussed several problems associated with the impact theories and put forward a condensation model which explained many of the observed facts but one with which he, himself, was not completely satisfied. Thus, it appears that both groups of theories are beset with

difficulties and will be modified or rejected with further investigation.

The chondrule definition proposed here is compatible with both the impact and condensation models as both give rise to droplets of molten silicate material which on cooling partially or completely crystallize to produce the objects defined as chondrules.

Subsequent to their formation chondrules were thoroughly mixed with other material. In some cases this material is debris, often unshocked, from the breakup of other chondrules, while in other cases its exact provenance is not obvious. The mixing occured without any pronounced segregation taking place although a sorting mechanism, resulting in the vast majority of chondrules having diameters of the order of 1mm, was operative then or earlier. At least some chondrites (Dodd 1965) exhibit a foliation which was probably acquired at this time. Rajan (1974) who studied track densities in Fayetteville concluded that the granular components of this meteorite, for example, had existed in a well stirred regolith prior to lithification for at least 10^4 years.

11.3 THE NATURE AND COMPOSITION OF CHONDRITIC GLASSES

In discussing the formation of chondrules as condensation products, Blander and Abdel Gawad (1969) pointed out that each drop constituted a separate physicochemical system. This statement would appear to apply whether chondrules have been formed by impact or condensation methods.

Since most chondrules are mafic or ultramafic, the glass which occurs in them was often described by early writers as mafic or basaltic. Van Schmus (1967) studied the glass in several Mezo-Madaras chondrules and found that it was rich in sodium and aluminium and poor in iron, magnesium and calcium with the result that it varied from quartz-normative to nepheline-normative, the other major normative minerals being feldspar and pyroxene or olivine. He then concluded, like Dodd et al (1967), that these glasses were neither mafic nor basaltic.

Blander et al (1976) examined a series of synthetic "magnesium silicate chondrules" with compositions ranging from forsterite to enstatite. The only crystalline phase they found after quenching was olivine, the residual glasses being silica rich, quartz pyroxene-normative. No crystalline phases were produced when the composition was close to that of enstatite, the whole droplet solidifying as a glass. They suggested that this could be due to a constraint on quartz and pyroxene crystallization combined with olivine crystallizing on the metastable extension of its liquidus due to a high degree of supercooling. Fodor and Keil (1975b, 1976a,b) reported similar assemblages of olivine and quartz-normative glasses in Eva, Plainview (1917) and other meteorites and also suggested that this was produced by preferential olivine crystallization. Kurat (1971) described crystalline olivine associated with olivine-nepheline-normative glass in Tieschitz and Graham et al (1976) found olivine associated with quartz-normative glasses in Bovedy.

Roedder and Weiblen (1977) proposed an immiscibility mechanism to explain the formation of silicon and iron rich lunar glasses. Green (1973, 1976), in studies of equilibrium partial melting of pyrolite under water saturated conditions, recorded olivine phenocrysts associated with siliceous glasses and ascribed the formation of these non-equilibrium glasses to the precipitation of iron-rich olivine mantles on the olivine phenocrysts and the nucleation of quench phases. Donaldson (1975), in a study of skeletal olivines from DSDP basalts, found a similar Ca-Al-Si enrichment and Fe-Mg depletion in glasses adjacent to the edges of olivine crystals and concluded that the concentration gradients had probably been produced by quenching reactions.

Some sixty meteoritic glasses and other material showing minimum devitrification were examined in the course of this work. These materials generally occurred between crystalline olivine phases in barred chondrules or porphyritic inclusions, or as the centres of pyroxene chondrules. Full analytical results are presented in Appendix C. After allowing for the effects of overlapping of crystal and glass volumes (Donaldson 1975) and alteration effects such as limonitic staining, it appears that examples of all of the glasses mentioned above have been encountered in this work.

The glasses were readily divided into two on the basis of normative mineralogy - one group contained normative olivine and feldspar plus corundum and/or nepheline whilst the other contained quartz, pyroxene and feldspar but neither corundum nor nepheline. The silica content of the first group ranged from 34 to 58% and that of the second from 56 to 69%. Because of this overlap, when principal component analysis and cluster analysis subdivided the glasses into four groups, the groups cut across the quartz normative - olivine normative

Table 11.1 : Eigenvalues and eigenvectors for meteoritic glasses.

Eigenvalues

	Olivine-Normative Glasses		Quartz-Normative Glasses	
Eigenvector	*%age variance*	*Cumulative %age*	*%age variance*	*Cumulative %age*
1st	*69.6*	*69.6*	*79.0*	*79.0*
2nd	*22.5*	*92.1*	*13.1*	*92.1*
3rd	*5.0*	*97.1*	*5.2*	*97.4*

Eigenvector elements both as absolute values and as percentages of the total variance

	Olivine-Normative Glasses						Quartz-Normative Glasses					
Fe	*0.37*	*9.3*	*0.28*	*1.7*	*-0.06*		*0.34*	*9.3*	*-0.27*	*1.0*	*-0.18*	*0.2*
Ti	*-0.02*		*0.01*		*-0.01*		*-0.01*		*-0.01*		*-0.01*	
Ca	*-0.04*	*0.1*	*-0.50*	*5.6*	*0.77*	*3.0*	*-0.04*	*0.1*	*0.90*	*10.6*	*-0.09*	
K	*-0.01*		*0.01*		*-0.01*		*-0.03*	*0.1*	*-0.01*		*-0.03*	
Si	*-0.33*	*7.5*	*-0.53*	*6.4*	*-0.59*	*1.7*	*-0.27*	*5.6*	*-0.12*	*0.2*	*0.85*	*3.8*
Al	*-0.47*	*15.1*	*0.61*	*8.4*	*0.17*	*0.1*	*-0.51*	*20.9*	*-0.29*	*1.1*	*-0.48*	*1.3*
Mg	*0.70*	*34.4*	*0.02*		*-0.12*	*0.1*	*0.71*	*39.4*	*-0.10*	*0.1*	*0.04*	

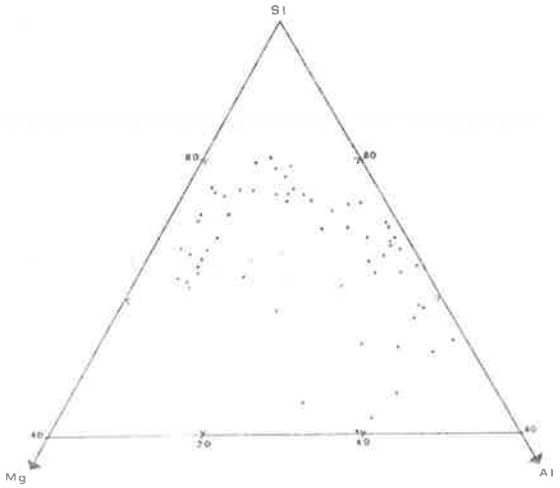


Figure 11.2 : Mg-Al-Si for the full data set.

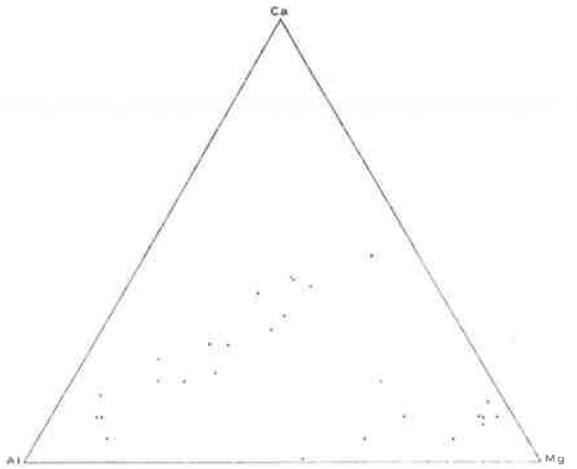


Figure 11.4 : Ca-Al-Mg for the quartz normative glasses.

boundary, reflecting abundances of aluminium and magnesium as well as silicon. As a triangular plot of these three elements (Figure 11.2) shows a wide range in values without any natural breaks, the data was arbitrarily subdivided into two groups on the basis of normative mineralogy. Principal component analysis of these subsets divided each of them into two. In both cases, the silicon variation is still significant and the eigenvectors (Table 11.1) show the subdivisions are based on variations in Fe, Ca, Si, Al, and Mg.

Plots of Al, Ca and Mg (atomic) (Figures 11.3, 11.4, 11.5) divided both the full and

Figure 11.3 : Ca-Al-Mg for the full data set.

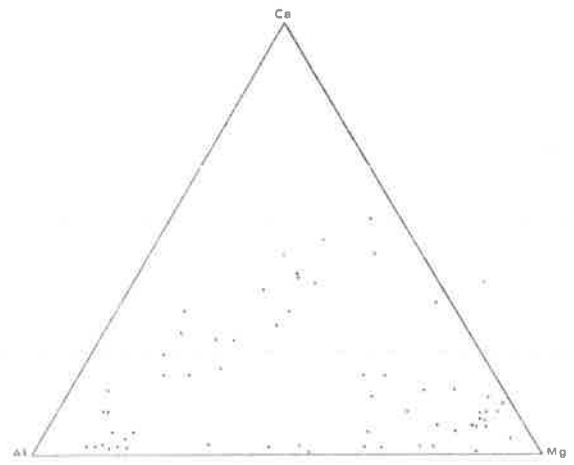
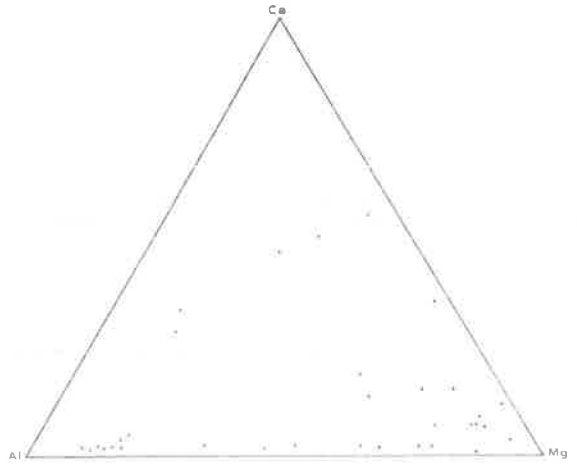


Figure 11.5 : Ca-Al-Mg for the olivine normative glasses.



reduced data sets into two or three groups while plots of Al, Fe and Mg and Al, Na and Mg (Figures 11.6 to 11.11) illustrate that the ratios Fe/Mg and Al/Na are approximately constant despite large variations in absolute abundances with the average Al/Na ratio being about 2.0. Van Schmus (1967) reported a value of 1.0 for this ratio - the difference could be due to volatilization during microprobe analysis. In those glasses containing less than 0.5% Na_2O the sodium figure could be in error by as much as 100% without causing the analytical total to deviate greatly from 100%, but this is not the case for those glasses containing several percent Na_2O thereby suggesting that at least in these latter cases the observed Al/Na ratio of approximately 2 is real. The

Figure 11.6 : Fe-Al-Mg for the full data set.

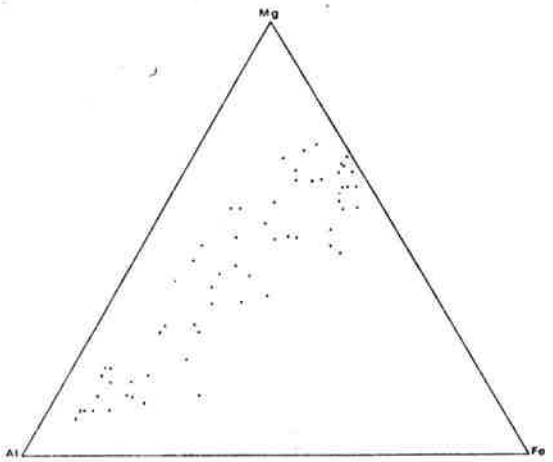


Figure 11.7 : Fe-Al-Mg for the quartz normative glasses.

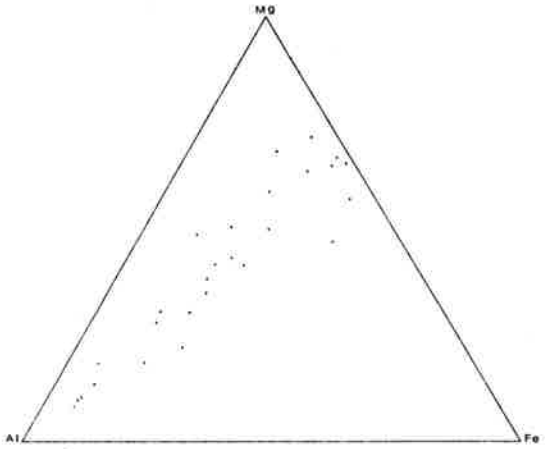


Figure 11.8 : Fe-Al-Mg for the olivine normative glasses.

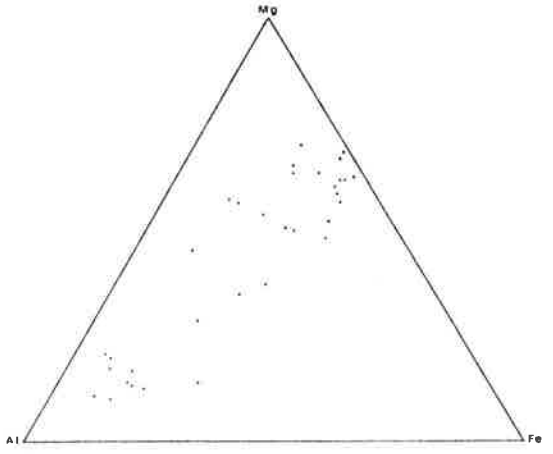


Figure 11.9 : Na-Al-Mg for the full data set.

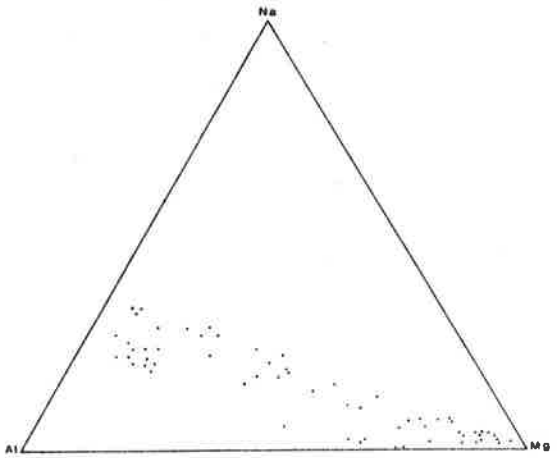


Figure 11.10 : Na-Al-Mg for the quartz normative glasses.

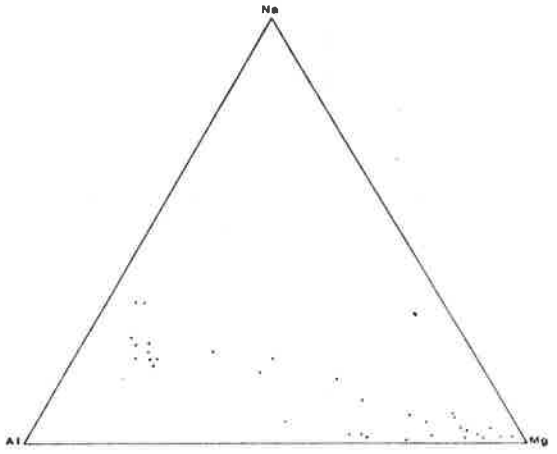


Figure 11.11 : Na-Al-Mg for the olivine normative glasses.

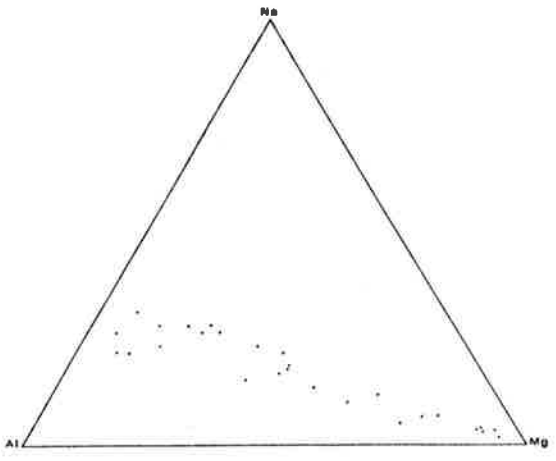


Table 11.2 : Distribution of glass types.

Meteorite	Material Analysed			
	Barred olivine chondrules	Porphyritic olivine chondrules or inclusions	Pyroxene chondrules	Other chondrules or inclusions
Barratta				Olivine normative B2
				Quartz normative B1
Carraweena	Olivine normative C4, C5, C6, C8, C9, C10, C11, C12, C13, C14, C15, C16, C17, C18, C19	Olivine normative C21, C22, C23	Olivine normative C24, C28, C31	
		Quartz normative C1, C7, C20, C25, C32, C33, C34, C35	Quartz normative C2, C3, C29, C30, C35, C37	Quartz normative C26, C27
H0 06		Olivine normative H1, H2		
	Quartz normative H4, H5	Quartz normative H3		
Moorabie	Olivine normative M4, M6, M7	Olivine normative M1		Olivine normative M12
	Quartz normative M5, M8, M9	Quartz normative M2, M3, M10	Quartz normative M11	
Oberon Bay				Olivine normative O2, O3
				Quartz normative O1
Toonarunna				Olivine normative P1

mean value of the ratio Fe/(Fe+Mg) was 18, a value less that that of many of the crystalline silicates.

Several of the glasses are similar to those described by Van Schmus (1967) but they are not all sodium aluminium glasses poor in Fe-Mg-Ca. Even though many of the silica-rich ones have silica contents in the basic range as well as colour indices appropriate to a basaltic classification, none of them has a normative composition which would allow it to be so classified thereby agreeing with Van Schmus' comment concerning basaltic classifications.

Table 11.2 gives the distribution of different glass types in the six meteorites examined. Two Carraweena chondrules (Figures 11.1 c,d) were studied in some detail. In Figure 11.1 c, the positions 1 to 7 in the glass, analyses C8 to C14, were all olivine normative. The olivine at positions 8 to 16 had an average composition of $Fa_{26.0}$. In the case of the radiating olivine chondrule (Figure 11.1 d), positions 1, 3, 7, 8 and 9 correspond to analyses C15 to C19 all of which are also olivine normative. The olivine of the bars has an average composition of $Fa_{26.5}$.

For olivine in equilibrium with a basaltic liquid, the value of the distribution coefficient K_d where

$$K_d = \frac{Fa_{ol} \cdot Fo_{gl}}{Fo_{ol} \cdot Fa_{gl}}$$

Table 11.3 : Distribution coefficients for olivine glass pairs.

	Fa_{ol}	Fo_{ol}	Fa_{gl}	Fo_{gl}	K_d
Barred	26.0	74.0	39.4	60.6	0.54
Radiating	26.5	73.5	37.4	62.6	0.60

should equal about 0.3 (Roeder and Emslie 1970, Shih and Schonfield 1976, Irving and Green 1976). Table 11.3 gives the appropriate values for the two Carraweena chondrules.

Even though it has been shown that these glasses are not basaltic, this calculation should give an indication of the order of magnitude of the distribution coefficient for these glasses. The difference between the calculated value and the "basaltic value" is so great as to suggest that the olivine is not in equilibrium with the glass in which it is set, thus further attesting to the rapidity with which crystallization

Table 11.4 : Distribution coefficients for pyroxene glass pairs.

Analysis (Glass)	Fe/Mg Pyroxene	Glass	K_d
C2	0.12	0.25	0.49
C3	0.28	0.39	0.74
C4	0.31	0.34	0.89
C29	0.19	0.44	0.43
C30	0.22	0.29	0.76
C35	0.21	0.31	0.69

took place. Such non-equilibrium precludes the use of calculations (e.g. Roeder and Emslie 1970, Leeman and Scheidegger 1977) to estimate the temperature of olivine crystalliazation.

Table 11.4, calculated K_d's for several Carraweena glass bearing pyroxene chondrules, shows an average value of 0.67 which is greater than the suggested equilibrium value of 0.23 (Roeder and Emslie 1970). Once again the value of 0.23 will only be approximate but even the smallest calculated value of 0.43 is so different from it as to suggest a lack of equilibrium. This apparent iron depletion in the glass parallels the results of Donaldson (1975) and may be due to iron-rich mantles on olivine and other grains, similar to the ones reported by Green (1976).

Comparison of the composition of the centres and rims of several chondrules composed entirely of glass shows that in some instances the iron content increases from the centre towards the rim while in other cases the reverse is the case.

In conclusion, the chondrites examined here have provided examples of various glass types and it is possible that they were produced by some or all of the mechanisms described above. The analyses given here are similar to those reported by others. The glasses are apparently out of equilibrium with the crystalline phases they contain and so cannot represent the composition of the starting material. These results also highlight the uniqueness of each chondrule.

11.4 THE ASTEROIDAL ORIGIN OF METEORITES

Meteorites are generally thought to have originated in asteroidal sized bodies which probably condensed in the region between the earth and Jupiter (Zellner et al 1977a). Wetherill (1976) suggested that the present source of meteorites is probably multiple, possibly both comets and asteroids having contributed to the meteorite flux. Chapman (1974, 1976) concluded from spectral albedo studies that more than 90% of the asteroids with diameters greater than 60 kilometres fall into one of two groups, i. the C or carbonaceous type of low albedo, and ii. the S or silicaceous type of higher albedo. The proportion of these two types is about 4:1 in favour of the C type.

Chapman envisaged that most of the asteroids were initially of carbonaceous composition and others of ordinary chondritic composition and that some of the chondritic ones underwent a chemical differentiation (possibly due to the presence of higher concentrations of short lived radio-nuclides) forming iron cores of roughly half their diameter. The spectral properties of Vesta, for example, show that its surface is extremely similar to the eucrites.

Subsequently, according to Chapman, fragmentation of the asteroids by collision became important, and the C-type asteroids particularly, because of their assumed low crushing strengths, became a fragmented population. The outer layers of both differentiated and undifferentiated S-type asteroids were substantially fragmented and in the case of some of the rare differentiated objects this stripping continued until such time as the nickel-iron cores were reached. These cores having much higher crushing and tensile strengths were rarely hit by objects massive enough to fragment them. Some of these relatively small chips were perturbed into earth crossing orbits and eventually fell to earth as meteorites, the carbonaceous and ordinary chondrites being fragments of C- and undifferentiated S-type bodies while the achondrites originated as parts of the outer layers of the differentiated S-bodies. The stony-iron meteorites originated as fragments of the mantle-core interface while the iron meteorites had their origin in rare, catastrophic events which were able to fragment the iron cores.

Other workers in the field of spectral reflectivity have arrived at substantially similar conclusions as regards the surface composition of several of the asteroids. Wetherill (1976) suggested that the clustering of the chondrite classes suggested that most of them had been derived from a few asteroids. Furthermore, he suggested that the Apollo asteroids, which he claimed were the most likely sources of meteorites, resembled the equilibrated chondrites and the basaltic achondrites rather than the carbonaceous chondrites.

The very large number of asteroids having spectral characteristics which apparently correlate in reasonably good detail with the carbonaceous chondrites is consistent with the various carbonaceous chondrite groups. These meteorites are at least as diverse a group as the ordinary chondrites and so it is to be expected that they may have originated on a variety of parent bodies which, while having basic similarities, would show some variations. The small number of carbonaceous chondrite groups relative to the large number of asteroids apparently having a carbonaceous chondrite composition is surprising and may point to a relative constancy in composition thereby indicating

the primitive nature of these bodies. On the other hand, Gaffey and McCord (1977b) pointed out that many of the asteroids having these "flat black" spectral curves, and hence designated type C, may not be carbonaceous in the currently accepted meteoritic sense.

The comments made in Chapter 9 on the relationship between the earth, the moon and the eucrite parent body are relevant at this stage also, as all of these bodies may have formed by the accretion of asteroidal material.

11.5 CONCLUDING REMARKS

An attempt has been made in this chapter to re-examine the nature of chondrules. The fact that similar bodies have been formed in lunar material highlights the ubiquity of the chondrule forming process, but also suggests that there ought to be a limited number of different objects that such a process will produce. A chondrule was re-defined as a spheroidal body containing varying amounts of glass, which may be devitrified, and crystalline material which is commonly skeletal. Further discussion supported the contention that each chondrule represents an isolated and unique system. An important corollary of the chondrule definition is that a number of bodies currently called chondrules are eliminated.

Results obtained in this work did not enable a distinction to be made between impact or condensation mechanisms as being responsible for the formation of the molten droplets from which the chondrules formed. It has been shown that the glass which remained after the rapid crystallization of either olivine or pyroxene chondrules in the unequilibrated Caraweena chondrite is not in equilibrium with the crystalline phases, thus supporting the observations made by others for different meteorites.

It is suggested that these chondrules accumulated to form parts of some of the asteroids. The retention of chondrule glass places limitations on the size and subsequent processes which occured on these asteroids as does the quantization of chemical composition observed among the different meteorite types. The cognate achondrites, which apparently formed as surface breccias, flows or near surface intrusions, likewise suggest that the parent bodies on which they originated suffered only minimal attrition prior to their ejection. The production of iron and pallasitic meteorites as central regions of differentiated bodies also appears quite feasible while the mesosiderites appear to require a special set of processes to bring about the union of metal, sulfide and silicate phases with at least parts of the latter having the appearance of a surface breccia.

An asteroidal origin for meteorites appears to be compatible with, and even to explain, two dominant features - the observed diversities in composition, and, the relative constancy of processes responsible for various facets of their nature.

Chapter 12

METEORITE ORIGINS—EXTENSIONS AND CONSTRAINTS IMPOSED BY THE PRESENT STUDY

The prime aim of the study of meteorites is to elucidate their origins and hence contribute to an understanding of the origin of the solar system. Two of the possible approaches to this problem have been taken in this thesis - the comparison of properties, mineralogical, chemical and physical, that is, classification, in order to find common parameters, and the study of previously undescribed meteorites to determine whether they fit present conceptions or impose new restraints.

The present study suggests that modifications to current classification schemes are necessary. A summary of the evidence found and conclusions reached follows.

Petrographic descriptions of twenty eight new or previously undescribed meteorites were given. In some cases the reason was simply that they were previously undescribed but, in other cases, the need for such a description was increased because of the possibility of two or more of the specimens being closely related to each other.

In the main, the results obtained while examining the chemistry of the iron meteorites were negative ones - several methods were shown to be innapplicable to the analysis of such material. Of the methods examined the only reliable ones found were those utilizing standard techniques of wet chemistry. The standard X-ray fluorescence technique for the determination of major and minor (not trace) element concentrations in terrestrial rocks, using fused glass buttons, was adapted for meteorite analysis by changing several aspects of the method of button preparation. Furthermore, the analytical technique was extended to enable nickel and chromium to be determined. A method for calibrating standards for such analysis was described. The method of processing the results of such X.R.F. analysis was examined, improved and extended both to allow for these developments and to refine the method of data processing. In the case of the chondritic meteorites a modified version of the standard CIPW norm calculation was devised to take cogniscance of several unique meteorite features. The work of Dowty (1977) on the exact nature of meteoritic phosphates was too late to be included, however, since phosphorus had been incorporated in the calculations as whitlockite rather than apatite the results can be readily modified simply by substituting "merrillite" for "whitlockite" as both minerals have the same formula.

Use of the statistic, the Coefficient of Variation, was shown to be the best measure of equilibration in meteoritic olivines and pyroxenes.

Many schemes based on chemical and/or mineralogical parameters have been advanced for use in classifying meteorites. Primacy has generally been given in this work to chemical-based classifications. Following the lead of Wasson (1974) the first distinction to be drawn was that between the differentiated and undifferentiated specimens. The latter group, with compositions similar to that of the sun, contains all of the known chondritic meteorites as well as certain other meteorites which do not appear to contain chondrules but whose chemistry is indicative of their undifferentiated nature. Two slightly different, but complementary, schemes were advanced, one which utilized absolute elemental abundances and the other, abundances relative to silicon. In the latter instance the abundances were expressed as atomic percentages whereas in the first case elemental percentages were used, the same method as used to report all meteorite compositions. These schemes were not always able to completely characterize the chondritic meteorites and accordingly several ratio ranges, which when taken together enabled the carbonaceous, enstatite and ordinary chondrites to be uniquely characterized, were proposed.

Such classifications used the analytical results for, at most three elements, however, the development of the technique for chromium and nickel analysis resulted in data being available for thirteen major and minor elements. Because of this abundance of

data recourse was had to several techniques of multivariate analysis so that most of the data could be used simultaneously. These mathematical manipulations enabled the number of variables to be reduced in such a way that the data could be viewed in three or less dimensions. This resulted in the loss of some information but such losses can be minimised by a careful choice of techniques. The four techniques of multiple discriminant analysis, principal component analysis, canonical correlation analysis and cluster analysis were investigated to determine their suitability for meteorite classification. Various methods of displaying the results from principal component analysis were investigated and a computer programme written to facilitate the use of what appeared to be the best technique. Other programmes had been written or modified to carry out the mathematical manipulations.

The four techniques were all able to effectively distinguish between the achondrites and the chondrites and also between the high and low iron chondrites. Discriminant analysis was also able to differentiate between H and C chondrites as could both cluster and principal component analysis if the data was first normalized.

Thirty four ordinary chondrites were examined and in most instances the classifications based on chemical and mineralogical criteria were in agreement. Elemental associations in the analytical results for these meteorites, as revealed by cluster analysis, correlated well with the geochemical affinites of these elements.

Analytical results for the recently discovered Brachina meteorite which had been classified as a Chassignite were re-examined. On the basis of available evidence it was suggested that its chemistry was similar to that of the undifferentiated meteorites and accordingly it was suggested that Brachina ought to be reclassified as an anomalous chondrite. Such a classification underlines the significance of this meteorite and the role it may play in future theories of meteorite genesis.

Several compositional and mineralogical parameters of the chondritic find, Moorabie, appeared to be at variance with each other and led to conflicting classifications. For example, the analytical results for iron suggested an L classification while the olivine composition falls in the range appropriate to the H chondrites. It was concluded that lack of equilibration in the silicates was responsible for some of these anomalous results and Moorabie was given an L3 classification.

The relationship between several meteorites discovered in the northeastern corner of the State was investigated. It was concluded that the Monte Colina meteorite is a fragment of the outer surface of Carraweena and that this meteorite and Accalana belong to the same fall. In a like manner the possibility of a relationship between Artracoona, Cartoonkana and Yandama was examined.

By contrast, this group of meteorites, Moorabie and the witnesses Mount Browne fall appear to be independent.

Nine recoveries from the Cockburn area were investigated and it was concluded that these finds represent at least two different falls. The chemistry and mineralogy of seven of these individuals relative to that of the poorly located Silverton find were investigated and it was concluded that they were consistent with a relationship but did not unambiguously point to one, all meteorites being L chondrites. The other two recoveries, both H chondrites, appear to be independent from these eight but may be related to each other. Six out of a group of some fifty meteorites recovered to the east of this area were also investigated but few positive conclusions could be drawn. Three of the group are H chondrites and three L. Textural amd chemical results alone were insufficient to determine the number of falls represented.

The subdivisions of the carbonaceous chondrites were re-examined and new limits for the A and B chemical subgroups proposed. At the same time, it was shown that this division could not be adequately made on the basis of iron content alone. (It had previously been shown that the carbonaceous chondrites were not uniquely characterized by an Mg/Si ratio greater than 1.)

The multivariate techniques separated the carbonaceous chondrites into the four groups Ivuna, Mighei, Ornans and Vigarano with varying degrees of effectiveness. An examination of the R-mode cluster analysis of the carbonaceous chondrite data revealed a good correlation both with the geochemical and thermal properties of the elements concerned along with their distribution in various mineral phases.

The carbonaceous chondrite Karoonda was reinvestigated and its classification examined. The exact affinites of this meteorite have been the subject of some controversy with the application of various criteria giving rise to differing classifications. On the basis of the results of this work Karoonda belongs to the

Vigarano subgroup of the carbonaceous chondrites and so accordingly a C5V classification is appropriate. It was further shown, on the basis of the properties of Karoonda and other strongly metamorphosed carbonaceous chondrites, that, at high petrologic grades, the distinction between the Ornans and Vigarano subgroups, on the grounds of mineralogy or major element chemistry, tends to become blurred. Conversely, on the basis of certain trace elements, the difference is marked and thus the distinction is best made on the basis of the relative abundance of elements such as copper and cadmium. Fractionations in these trace elements suggest that the A and B subgroups are samples of slightly different regions of the solar nebula with the possibility that the A group sampled material more distant from the sun. It was suggested that the more highly metamorphosed meteorites of these groups accreted before the less metamorphosed members and that, as regards major elements, they sampled very similar material. By contrast, the later condensed, less metamorphosed members of the group sampled compositionally different regions of the solar nebula. Further investigations need to be carried out to clarify this situation.

The unusual carbonaceous chondrite, Adelaide, was investigated in some detail and it was found that it resembled the Vigarano subgroup in several ways. Close examination of the data, however, revealed the inadequacy of such a classification as the meteorite has several unusual features such as the very low Ca/Al ratio. These features distinguish Adelaide from all other described meteorites so far recovered on the earth's surface. A recovery from the moon, the Bench Crater meteorite, resembles Adelaide in many ways and it too deviates from the remainder of the carbonaceous chondrites in the same manner as Adelaide. Because of these resemblances and differences a new subgroup, the K or Kakangari group, was erected to accomodate these meteorites. This name was chosen, as on the basis of available information, Kakangari showed marked similarities to both Adelaide and Bench Crater. More recent data, however, suggest that this resemblance is not so close. The low Ca/Al ratio in Adelaide and Bench Crater is the result of a marked calcium depletion and an aluminium enrichment. Two alternatives were suggested to explain this - either Adelaide and Bench Crater are representatives of very early aluminium-rich condensates or of late ones low in calcium due to its depletion. The second alternative appeared more likely. These two meteorites must assume an important place in any theory of meteorite genesis and further chemical and mineralogical examination may clarify the situation.

Most of the achondrites can generally be classified on the basis of either absolute or relative elemental abundances, distinctions which were also performed with varying degrees of success by the multivariate techniques. In particular, the eucrite, howardite and mesosiderite groups were shown to grade into each other with the howardites and mesosiderites occupying a position intermediate to the diogenites and eucrites.

The recently reported achondrite Muckera was examined and its chemistry, mineralogy and texture found to be consistent with a howardite classification. Pyroxene determinations for this meteorite, the Pinnaroo mesosiderite and the eucrite Millbillillie No.3 led to a consideration of the iron-manganese relationship in such meteorites. Because of the wide range in values, it was concluded that care must be exercised in attempting to use estimates of this ratio, derived from bulk analyses, to distinguish between the chondrites and various achondrite groups. Only in the eucrites was a close correspondence found between the values of the ratio for the pyroxenes and the bulk meteorite. Several of the clasts in Muckera were examined and representatives of several of the groups described by Bunch (1975) identified.

New analytical results for the non-magnetic portion of the Pinnaroo mesosiderite confirmed the results of Alderman (1940) and these, combined with petrologic observations, confirm that Pinnaroo belongs to a fourth subgroup of the mesosiderites, characterized by textures apparently resulting from impact melting, as suggested by Floran (1978).

The transitional nature of many chemical and mineralogical properties of the diogenites, eucrites, howardites and mesosiderites often give rise to problems in classifying individual meteorites into one of these four groups. These resemblances are reinforced by the results of isotopic and other analyses and taken together suggest that the four meteorite groups are closely related. Accordingly, it was suggested that all four be grouped together under the generic title "cognate achondrite" with the name being indicative of the proposed relationship within the group. Such a move then obviates the problems associated with

classifying a meteorite which clearly belongs to this group but which does not readily fit into one of the categories diogenite, eucrite, howardite or mesosiderite. Recent discoveries in Antartica, for example, suggest that this point should be pursued further.

Various lines of evidence such as trace element and pyroxene compositional data suggest the inapplicability of a two-component mixing model to completely explain the origin of the cognate achondrites and thus lend weight to the theories invoking differentiation processes to explain this origin. Of these latter theories, that of Stolper (1975,1977), invoking both partial melting and fractional crystallization seems best able to explain the observed features. Principal component analysis of a set of cognate achondrite analyses produced a transformed variable plot which clearly illustrated this proposed relationship. This plot illustrated both the relationships between the four groups as well as that within the eucrites. It was suggested that impacts on an asteroidal body which was layered as a result of such igneous processes could give rise to the different cognate achondrites.

The contention that the Ca/Al ratio is constant in the chondrites and cognate achondrites was examined. It was shown that even though the value of the ratio for many chondrites lies in the range 0.73 to 0.75 (atomic) there are a significant number of meteorites having values outside this range, the upper and lower limits being about 0.8 and 0.4 respectively. The ratio exhibits an even greater spread in the cognate achondrites as would be expected in materials produced by differentiation. Accordingly, discussions concerning the value of the Ca/Al ratio in the original solar nebula ought not be based on achondrite data. A consideration of chondritic values led to the conclusion that variations may be due to heterogeneous accretion and that if the C1 chondrites adequately represent pristine nebular compositions then the other chondritic meteorites contain varying amounts of calcium-poor and calcium-rich phases and/or variations in the nature and quantity of aluminium bearing phases.

Structural and compositional data obtained for several iron meteorites led to a re-evaluation of their classification. Thus Rhine Villa and Yardea, both formerly classified as medium octahedrites, were re-classified as coarse octahedrites with the former being placed in Wasson's Group IIIE and the latter in Group IA. Both of these re-classifications are in line with the conclusions of other recent work.

Conflicting results obtained for Mount Sir Charles led to an "anomalous classification". The disparity between major element, trace element and structural data for this meteorite was highlighted by cooling-rate calculations.

The previously undescribed Kapunda iron was given a Group IIIA classification and shown to be independent from the Henbury fall as were Cowell and Kyancutta. In the latter instance compositional, structural and historical evidence all suggest that these two meteorites belong to the same fall. On the other hand, data obtained for the poorly located meteorite known as "S.A. Beta" indicate that it, like several other supposedly individual Australian meteorites, is a transported fragment of Henbury material.

Theories concerning the nature and origin of chondrules have exercised the minds of many people for a considerable period of time. Skeletal textures in several meteoritic chondrules were examined and it was suggested, in the light of various lines of evidence, that such textures are produced by rapid crystallization not necessarily accompanied by rapid cooling. After considering various chondrule properties and the occurence of these bodies in lunar rocks the following new chondrule definition was proposed. "Chondrules are spheroidal bodies of about one millimetre diameter which are characterized by the presence of varying amounts of crystalline material with dendritic, skeletal or similar form, and glass, which may or may not be devitrified." This definition implies that chondrules were once molten droplets without specifying the methods of their formation. Likewise, certain other bodies which are often currently called chondrules do not fit this definition. The definition is compatible with an origin for chondrules from either condensation or impact mechanisms.

An examination of the glass phases in chondrules in several meteorites provided examples of both olivine-normative and quartz-normative materials, none of which, however, could be described as basaltic. Despite this, values of the distribution coefficient calculated from Fe/Mg ratios for olivines and pyroxenes and the glasses in which they were set were compared to those for basaltic glasses. The differences were so great that it was concluded that the crystalline phases were not in equilibrium with the glasses thus pointing to the

rapidity of their cooling. This lack of equilibrium indicates that the glass compositions cannot be used to approximate the original chondrule composition.

Various theories have been advanced which ascribe an asteroidal origin to meteorites. The retention of chondrule glasses such as the ones described in this work limits the depth to which the chondrules could have been buried after accretion and prior to fragmentation of the parent body. They indirectly place constraints on the size of these bodies and subsequent processes.

Overall, an asteroidal origin for meteorites is consistent with their known properties, both the ones described here and elsewhere, and, in some instances, helps to explain them.

Probably the most significant meteorite examined in this work is the unusual carbonaceous chondrite Adelaide, which, along with the "lunar meteorite" Bench Crater, were shown to be representatives of a meteorite type previously undescribed from terrestrial occurences. One of the most diagnostic features of these two meteorites is their low Ca/Al ratio (atomic) of about 0.5. The apparent undifferentiated nature of the chondrule-less Brachina find is also worthy of re-emphasis.

APPENDICES

APPENDIX A: A SURVEY OF "CENTRAL" AUSTRALIAN METEORITES

Chapter A1

Introduction

In 1913, Dr. Charles Anderson, the Australian Museum's mineralogist, published a "Catalogue and Bibliography of Australian Meteorites" in which he listed known meteorites, their weight, the time and place of their find, the finder's name where possible, and the location of specimens at the time of printing. He gave relevant literature references for each meteorite.

Dr. Thomas Hodge-Smith, Anderson's successor, revised this publication in 1939 and his stated aim was that it would be accurate to December 1937.

In 1968, Dr. David Corbett, Honorary Associate in Mineralogy in the South Australian Museum, published a "Catalogue of Meteorites in the South Australian Museum" containing information for meteorites held by that institution. In general, the bibliographic references were restricted to those papers treating the fall and/or finding of the meteorites. Less detailed information was given for the foreign meteorites represented in the collection.

Dr. Brian Mason, of the Smithsonian Institution, spent part of 1973 working in Australia and, while here, prepared and published a list of Australian meteorites with their classification and discovery sites.

On the occasion of the 25th International Geological Congress held in Sydney in 1976, Dr. G. Gibbons, of the New South Wales Institute of Technology, prepared a display of meteorites in the Australian Museum accompanied by an "Index of Australian Meteorites".

In 1969, Dr. Raymond Binns, of the Geology Department of the University of New England, proposed compiling a bibliography of Australian meteorites with Dr. Joseph McCall, of the University of Western Australia, and Mr. Donald McColl, Museum Curator in the Department of Geology and Mineralogy in the University of Adelaide. Binns suggested that the country be divided into three sections - "east", "west" and "central" - and that McColl be responsible for the central portion comprising South Australia and the Northern Territory. He suggested they should prepare a more detailed account than the ones described above, especially in regards to the literature survey. However, this work did not eventuate.

In 1972, the author began work on such a catalogue for the central part of Australia, which, it is believed fufills, and possibly exceeds, the aims envisaged by Binns. Results of this research constitute the final part of this thesis. Chapter A2 is an account of the fall and/or finding of the meteorites and their subsequent fate, an account carrying many corrections and modifications to existing literature, while Chapter A3 summarizes all analytical and other work carried out both prior to, and during, this work. That chapter cites all the appropriate references which could be found.

In general, the meteorites which will be discussed fell or were found either in South Australia or the Northern Territory. However, for a number of reasons, some meteorites from outside this region have been included. They may, however, all be included under the generic title of "central" Australian meteorites without distorting the meaning of the word "central" as envisaged by Binns.

Chapter A2

Authentication of the Meteorites of the Region

A2.1 INTRODUCTION

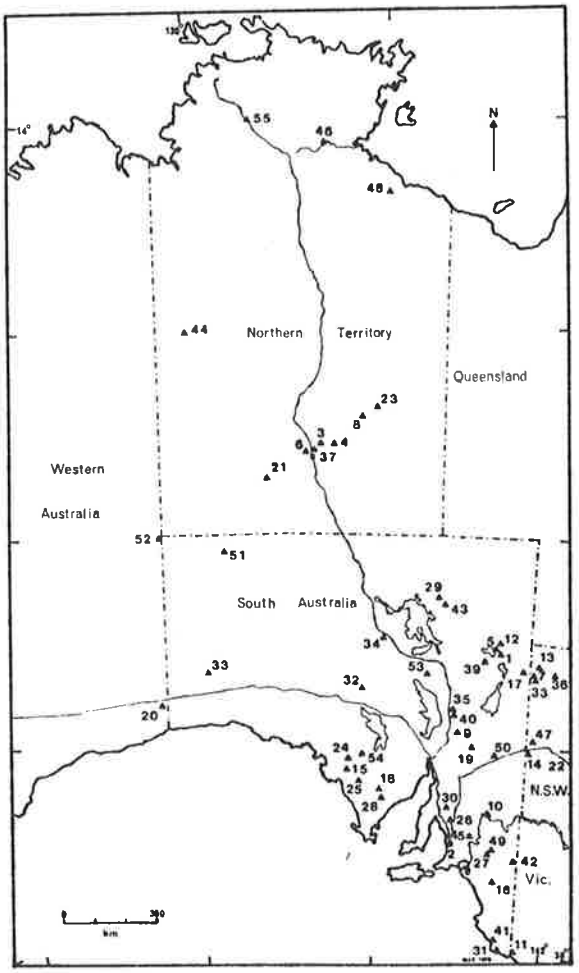
The sources of information for this chapter are many and varied. Where possible, information has been obtained from the finders. Failing this, newspaper and other accounts, both published and unpublished, have been used. In some cases, the information is rather sparse, either because little data was recorded at the time or because those people who have the relevant information have refused to release it. In all cases where information which is at variance with previously published accounts is presented, it is so in the belief that the new data are more reliable.

The meteorites which are the subject of this study have been grouped into somewhat arbitrary geographical divisions, the distribution being shown again in Figure A2.1. Within each subdivision, the meteorites are treated in the order of their recognition. This procedure was followed because of the existence of a number of clusters of meteorite recovery sites on the map. Generally, these clusters reflect population distribution. In some instances however, the concentrations have been heightened by specific human activites, e.g. the establishment of the Kyancutta Museum.

For convenience, Table A2.1, which summarizes the highlights of the chapter, lists the meteorites in alphabetical order. Following a recommendation of Dr. Hutchison of the British Museum (pers. comm.) two events in the early terrestrial history of a meteorite find have been recognized, viz. the date of the actual find and that of its recognition as a meteorite. This is at variance with the recommendation of Huss (1971) who advocated recording only the latter date. Table A2.1 shows that meteorite recoveries have not been distributed evenly in time. The peaks evident in this table usually correspond to interest generated by individuals or significant meteoritic phenomena.

Chapter 1 detailed the approach adopted to the naming of several meteorite recoveries in the same area.

Figure A2.1 : Meteorite recovery sites. Numbers as in Table 1.1.



A2.2 NORTH EASTERN METEORITES

Figure A2.1 shows several finds in the vicinity of the South Australia - New South Wales border. Figure A2.2 shows the northern group in greater detail.

A2.2.1 Silverton (New South Wales)

This meteorite, which was probably one of the earliest finds in Australia, was mislaid in a suburban museum for many years after its discovery. During the 1880's the Port Adelaide Museum was at the height of its activity. This activity gradually waned and the Museum was neglected for about 30 years until 1933 when it was decided to convert it to a nautical museum and discard any

Table A2.1 : Summary of meteorite finds, locations and classifications.

Meteorite	Fall/Find	Finder	Identified/ Named	Location	Weight	Classification
Accalana	1913-1914	Thomas Flinders Gill	July 1915 November 1916	29° 15'S 139° 58'E	2.85kg	L3 chondrite
Adelaide			September 1972 February 1974		1.931kg	C2K chondrite
Alikatnima	1931 or earlier		?January 1931	23° 20'S 134°07'E	15.87+kg	Anomalous iron
Arltunga	September 1908	Daniel Pedler	1908	23° 28'S 134° 40'E	18.14kg	Anomalous IID iron
Artracoona	ca. 1914	William George Amesbury		29° 04'S 139° 55'E	20.81kg	L6 chondrite
"Basedow Range"	pre-1957			25° 06'S 132°33'E		IIIA iron(Henbury)
Bond Springs	1891-1898			23° 33'S 133°54'E	6.18kg	H6 chondrite
Boolka	June 1968	Lindsay H. Russell	July 1968	30° 04'S 141° 03'E	2-3kg	Chondrite
Boxhole	August 1937	Brunhild Bedford and others	When found	22° 37'S 135° 12'E	360+kg	IIIA iron
Brachina	May 26, 1974	Brian Martyn Eves	May 1974	31° 18'S 138° 23'E	203g	Anomalous chondrite
Cadell	April 14, 1910	Charles H. Bannear	May 2, 1910	34° 04'S 139° 45'E	3.29kg	L6 chondrite
Caroline	ca. 1930	Stuart Keith McEarchern	ca. 1940	37° 58'S 140° 58'E	800g	H5 chondrite
Carraweena	1913-1914	William George Amesbury and Thomas Flinders Gill	February 6, 1914	29° 10'S 139° 56'E	28.8kg	L3 chondrite
Cartoonkana	1914-1924	Thomas Flinders Gill	April 1924	29° 21'S 141° 10'E	340g	L6 chondrite
Cockburn No.1	1946	James Eric Johnson	When found	32° 07'S 141° 05'E	10.1g	L6 chondrite
Cockburn No.2	October 1967	Lois E. McColl	When found	32° 07'S 141° 05'E	5.0g	L6 chondrite
Cockburn No.3	June 6, 1972	James Eric Johnson	When found	32° 07'S 141° 05'E	83.0g	L6 chondrite
Cockburn No.4	July 2, 1972	James Eric Johnson	When found	32° 07'S 141° 05'E	75.0g	L6 chondrite
Cockburn No.5	July 2, 1972	Roderick Jeffery Hill	When found	32° 07'S 141° 05'E	31.0g	L6 chondrite
Cockburn No.6	July 22, 1973	Brian Harold Mason	When found	32° 07'S 141° 05'E	2.207kg	L6 chondrite
Cockburn No.7	July 22, 1973	Brian Harold Mason	When found	32° 07'S 141° 05'E	53g	?L6 chondrite
Cocunda	1945	Alice Mitton	?1946	32° 49'S 134° 44'E	482g	L6 chondrite
Coomandock No.1	1939	G. Minnis	1940	35° 29'S 139° 50'E	1.0kg	H6 chondrite
Coomandock No.2	January 1967	Rex Arnold Goodall		35° 32'S 139° 52'E	4.54kg	?H6 chondrite
Coonana	June 7, 1962	John Rattus	When found	29° 51'S 140° 42'E	6.8kg	H4 chondrite
Cowell	March-April 1932	Robert Jack McDonald	?March 1956	33° 18'S 136° 01'E	5.717kg	IIIA iron (Kyancutta)
Crocker's Well	1956	James Eric Johnson	When found	32° 01'S 139° 47'E	3.8g	Chondrite (?Ethiudna)
Ethiudna	February 20, 1977	Michael James Larrett	When found	31° 59'S 139° 46'E	74.318kg	?L chondrite
Forrest Lakes	1948 or earlier	T. Dimer		30° 15'S 128° 55'E	500g	LL5 chondrite
"Gallipoli Station"	1970				6kg	IIIA iron (Henbury)
"Glen Helen"	1963 or earlier	An aboriginal		#23° 41'S 132° 40'E	727g	Iron (?Henbury)
"Hart Range"				#23°S 131°E		IIIA iron (Boxhole)
Henbury	1902 or earlier (Nuleri)		1906 (Nuleri)	24° 35'S 133° 08'E	ca. 2.5 tonne	IIIA iron

Meteorite	Fall/Find	Finder	Identified/ Named	Location	Weight	Classification
Hollmayer No.5	1969-1975	Werner Hollmayer	April 1975		72.2g	H5 chondrite
Hollmayer No.6	1969-1975	Werner Hollmayer	April 1975		68.2g	H5 chondrite
Huckitta	pre-June 1937	Michael Laughton	June 1937	22° 22'S 135° 46'E	1415+kg	Pallasite
Kaldoonera Hill	?1916 ca. 1954-1966	E.G. Voumard and Noel Everard Gosling	1956	32° 37'S 134° 51'E	12+kg	H6 chondrite
Kappakoola	September 1929	Frederick W. Daniel	October 1935	33° 15'S 135° 32'E	392.5g	H6 chondrite
Kapunda	ca. 1965	Ann Marie Peters and Heather Shakes	June 11, 1972	#34° 19'S 138° 56'E	541.5g	IIIA iron
Karoonda	November 25, 1930 December 9, 1930	Kerr Grant and George Frederick Dodwell	When found	35° 05'S 139° 55'E	41.73+kg	C5V chondrite
Kielpa	March or April 1940 January 3, 1978	Andreas Benjamin Brooks Geoffrey Allan and Joseph Raymond Elleway	1948 When found	33° 36'S 136° 06'E 33° 36'S 136° 06'E	13.6kg 2.090kg	H5 chondrite H5 chondrite
Kingoonya						See Naretha
Kittakittaooloo	August 1970	Anthony Fyfe Williams	When found	28° 02'S 138° 08'E	3.6kg	H4 chondrite
Kyancutta	June 1932	Donald Henry McDonald	July 1, 1932	33° 18'S 136° 01'E	32.6kg	IIIA iron
Kybunga No.1	?September 7, 1941	Glen Charles Wiech	February 15, 1969	33° 54'S 136° 30'E	2.76kg	?L5 chondrite
Kybunga No.2	?September 7, 1941	Glen Charles Wiech	When found	33° 53'S 138° 29'S	2.37kg	?L5 chondrite
Kybunga No.3	?September 7, 1941	Ian David Schumacher		33° 53'S 138° 28'E	2.37kg	L5 chondrite
Lake Borney	October 21, 1961+	Bertha Grace McDonald	1961+	37° 45'S 140° 18'E	2.768kg	L6 chondrite
Lake Labyrinth	?February 5, 1924 ca. February 19, 1924	Billy Austin	October 1934	30° 33'S 134° 45'E	25.85+kg	LL6 chondrite
Monte Colina					116.8g	See Carrawcena
Moorabie	pre-1965	Lindsay H. Russell	?October 1967	30° 06'S 141° 04'E	14.05kg	L3 chondrite
Moorumburra	1943	An aboriginal		28° 55'S 136° 14'E	76.57kg	IIIA iron
Motpena	August 10-11, 1968	Bruce A. Jahn and Norman A. Bartlett	When found	31° 06'S 138° 16'E	8.82kg	L6 chondrite
Mount Browne	July 17, 1902 July 17, 1902	W. Jordan		29° 47'S 141° 46'E	11.45+kg	H6 chondrite
Mount Sir Charles	1942	T. Williams		23° 50'S 134° 02'E	22.91kg	Anomalous iron
Muckera	May 1-2, 1951	Cornelius Patrick Doyle	1951 and 1972	30° 05'S 130° 02'E	513+g	Howardite
Murnpeowie	?1904-1909	A. Hamblin and others	1909	29° 35'S 139° 54'E	1145.4kg	Anomalous iron
Naretha			Pre-March 1927			L4 chondrite
Nilpena	June 4, 1975	Donald Hugh McColl	When found	31° 57'S 138° 18'E		Chondrite
Nine Mile	1969-1975	Werner Hollmayer	April 1975		172.0g	L6 chondrite
Nora Creina	1962	Bertha Grace McDonald	When found	37° 19'S 139° 51'E	283.5g	L4 chondrite
"Nutwood Downs"	?1970					IIIA iron (Henbury)

Meteorite	Fall/Find	Finder	Identified/ Named	Location	Weight	Classification
Pinnaroo	May 1927	Stanley Hamilton	1939-1940	35° 23'S 140° 56'E	39.4kg	Mesosiderite
Poonarunna	Mid 1970	James Dunn		27° 46'S 137° 51'E		H5 chondrite
Popilta	1969-1975	Werner Hollmayer	April 1975		158.5g	L6 chondrite
Popio	1969-1975	Werner Hollmayer	April 1975		747.3g	L6 chondrite
Rabbit Flat	1974	A road gang		ca. 20° 22'S 130° 07'E	295g	H chondrite
Rhine Villa	pre-November 1900	Allen George Payne	November 1900	#34° 39'S 139° 17'E	3.325kg	IIIE iron
Roper River	1921	An aboriginal		?14° 45'S 134°E	6.257kg	IIIB iron
Silverton (N.S.W.)	1880's		1933	#31° 53'S 141° 12'E	350.7g	L6 chondrite
"S.A. Beta"	?1963	Arthur Shepherd			1.490kg	IIIA iron (Henbury)
Tawallah Valley	1937	Mr. Condon	?April 1939	15° 42'S 135° 40'E	75.75kg	IVB iron
Thackaringa No.1	March 24, 1974	Donald Hugh McColl	When found	32° 07'S 141° 05'E	432.2g	H5 chondrite
Thackaringa No.2	June 8, 1975	Wayne Desmond Mussared	When found	32° 07'S 141° 05'E	6.4g	?H5 chondrite
Twin Wells	1969-1975	Werner Hollmayer	April 1975		198.3g	H5 chondrite
Un-named Stony Iron						Unclassified
Vincent	1926	Edmund Arthur Paul Hoff	?1956	35° 01'S 139° 56'E	425.2g	L5 chondrite
Weekeroo Station	1924	James Lane	?1927	32° 16'S 139° 52'E	94.1kg	IIE iron
Wilbia	May 1965	James Eric Johnson	When found	26° 27'S 131° 00'E	94g	H5 chondrite
Wingellina	1958	James Eric Johnson	When found	26° 03'S 128° 57'E	200g	H4 chondrite
Witchelina	1920	Thomas Phillip Gourlay	?1967	#30° 01'S 138° 03'E	3.637kg	H4 chondrite
Yandama	1914-1924	Thomas Flinders Gill	April 1924	29° 21'S 141° 10'E	5.68+kg	L6 chondrite
Yardea	November 1875	James Martlew		32° 27'S 135° 32'E	3.29kg	IA iron
Yenberrie	July 30, 1918	John Hoare		14° 15'S 132° 01'E	131.83kg	IA iron

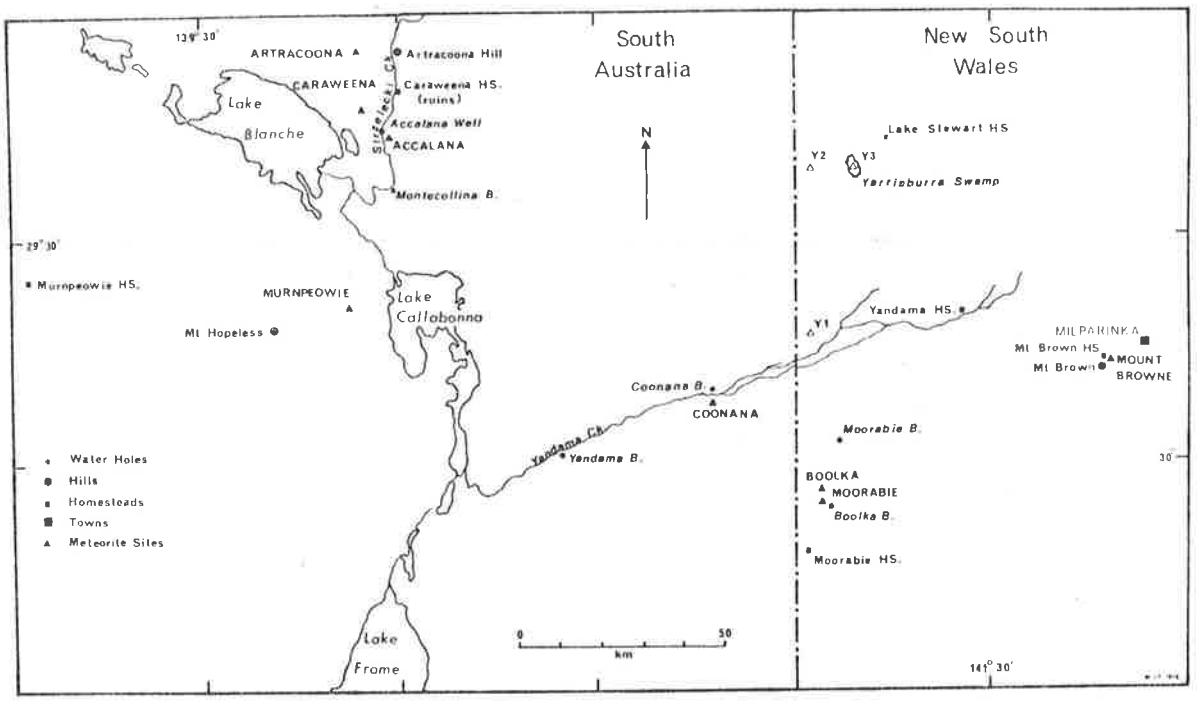


Figure A2.2 : Meteorite recovery sites in the north eastern corner of South Australia. Y1-Y3 : Suggested finding locations of Cartoonkana and Yandama. 1 : Alderman (1936), 2 : Mason (1968 and pers. comm.), 3 : This work.

irrelevant material. Mr. R. Bedford, the Director of the Kyancutta Museum (See A2.5.2 below), agreed to sort out the material in the museum. As the museum had little money Mr. Bedford agreed to accept, as payment, any of the discarded material which he could use in his own museum. He and his daughter, Miss Hilda Joan Bedford, went to Port Adelaide in June or July 1933 and during the clean up he discovered a small specimen labelled "meteoric stone from Silverton" among some rock and mineral debris.

On Wednesday August 23, Mr. Bedford sent the meteorite to the British Museum where it arrived on Tuesday October 17, and gave them permission to cut the meteorite in order to examine it, and to retain a portion. The bulk of the specimen (319 of the original 351g) was returned to Kyancutta where it remained until 1939 when most of it was exchanged with the Australian Museum in Sydney. The British Museum also presented a cast of the original specimen to the Kyancutta Museum.

When found by Mr. Bedford, the specimen's label appeared to be of the 1880's vintage. Silverton was proclaimed a town in 1883 and Cockburn one on Thursday April 29, 1886 while nearby Thackaringa attained its maximum population the following year. Thus the Silverton meteorite must have been found during or after 1883. The possibility of the meteorite being related to the Cockburn shower has been suggested above and if this is the case the meteorite was probably found prior to 1886 or else its location would probably have been described relative to Cockburn. On the other hand, it is surprising that if the meteorite were found near the site of the Cockburn finds that its locality was not given relative to Thackaringa.

Unfortunately another meteorite found in America in 1938 was named Silverton in 1940. This name duplication has necessitated the modification of the Australian find's name to Silverton (New South Wales).

A2.2.2 Mount Browne

This was the third Australian "fall". The meteorite fell at approximately 9:30am on Thursday July 17, 1902, at Mount Browne, a small gold mining town in far western New South Wales. In 1886 Mount Browne was a thriving town as was Milparinka some 6km to the north east. Nothing now remains of the township of Mount Browne and little of Milparinka. (The hill from which the town took its name is now shown on maps as Mount Brown.)

A loud explosion was heard and a hut, near the observers, was seen to catch fire. This was followed by a whizzing sound and then the meteorite struck the ground some distance away from the onlookers. When picked up a few minutes later by Mr. W. Jordan it was still warm.

The meteorite was acquired by the Australian Museum in 1903 when it weighed 11.4kg. It appeared that at least 500g of

the material had been removed by the finder.

A2.2.3 Murnpeowie

In August 1909, a team of men employed by the Beltana Pastoral Company was sent to repair fences on the company's Murnpeowie run near Mount Hopeless. The country in which they were working was very flat and in the evening they often had difficulty in locating their transport, donkeys, which had wandered away during the day. At one time to assist in their search someone used to climb an isolated rock to get a better view. One evening this rock was accidentally struck and it "rang like a bell". With difficulty, one of the men managed to remove a small specimen which was sent to the School of Mines in Adelaide for identification. There it was recognized as an iron meteorite and an offer was made to purchase it for £200.

The nearest transport to Adelaide was the railway line passing through Farina, west of the site of the find. It took two men and twenty six donkeys twenty seven days to cover the round trip of 450km to recover the meteorite. The finders were paid £200 for the meteorite and on its arrival in Adelaide it was placed in the S.A. School of Mines Museum where it remained for many years. At present it is on loan to the S.A. Museum where it is on display. It is the largest South Australian meteorite so far discovered.

The men who found the meteorite discovered three holes to the west of it, the furthermost about 65m away. This, the largest, measured about 5 by 3.5m and was some 1.2m deep, the greater dimension being in an east-west direction. The other two holes were successively smaller towards the meteorite, thus suggesting it bounced before coming to rest.

The men were quite adamant that the meteorite had not been there in 1904 when the fence was erected and suggested that the fall was recent as the holes would have soon filled with sand. The finders are recorded as "A. Hamblin and others". Mr. Hans Mincham, formerly of the S.A. Museum, suggested that one of the others may have been Mr. George Amesbury, of whom more is said below.

Very little material has been cut from the mass. A mass of some pounds was removed to enable the original description by Smith to be made. On the suggestion of Mr. R. Bedford, of Kyancutta, about 900g was cut from this piece and presented to the British Museum by the Council of the S.A. School of Mines some time soon after August 1933. The British Museum actually received an 875g mass and 28.5g of cuttings. As a mark of their appreciation of his efforts on their behalf, the British Museum presented a 66g slice of this to Mr. Bedford late in 1933. This specimen was placed in the Kyancutta Museum but is now in the National Museum of Victoria in Melbourne. The other kilogram or so of material now distributed between the Smithsonian and the Australian Museum are probably also parts of the original fragment.

A2.2.4 The Gill meteorites

The confusion and ill-feeling surrounding the post-discovery fate of this group of meteorites sets them apart from all others under discussion.

a. The Gill Family

A brief digression on various people named Gill who lived in Adelaide in the period 1910-1930 is necessary at this stage.

Mr. Thomas Gill, C.M.G., I.S.O., J.P., was born at Glen Osmond on Friday February 23, 1849. He was employed in the State Treasury Department and was appointed Under Treasurer in 1884, a position he held until his retirement in 1919. In 1896, he was appointed as one of the Governors of the Public Library, Art Gallery and Museum Board. He held this position until his death on Saturday July 21, 1923. During this period Mr. Gill presented various objects to the Museum. He had two sons and three daughters. Thomas Flinders, the elder son, was born in 1884 and died on Sunday July 11, 1948, while the younger, Franklin, died in 1953. During the early years of the second decade of this century Mr. T.F. Gill, the elder son, worked on one or more stations in the north-east of the State near the Queensland - New South Wales border.

Mr. Walter Gill, Conservator of Forests and Head of the State Forestry Department, the son of an English clergyman, appears to have been unrelated to Mr. Thomas Gill. His name, however, appears at least once in the following narrative.

b. Carraweena and other meteorites

On Friday February 6, 1914, Mr. W.S. Chapman, the School of Mines Analyst, submitted an analysis of a meteorite to the Geological Survey of South Australia. The meteorite was described as having come from Montecollina Station near Lake Blanche, where it had been found by the son of Mr. Gill, who had forwarded it to the Geological Survey. The Montecollina station was owned by the "cattle baron" Mr. S.K. Kidman.

The following Monday, Mr. T. Gill wrote to

the Museum informing them his son had collected some bones from Strzelecki Creek and asking whether they would like them. By Wednesday, when the Director, Mr. E.R. Waite, replied to Mr. Gill that they would be interested in the bones, news of the meteorite find had apparently reached the Museum for the Director commented in his letter that the Museum would be interested in buying the meteorite were it for sale.

The next relevant event in the available records was the Wednesday December 2, 1914, meeting of the Museum Committee. Mr. (later Professor) Walter Howchin, the chairman of the Museum Board, made a formal approach to this committee on Mr. Gill's behalf and offered the meteorite to them for £150. The committee were prepared to pay only £50, an offer they thought very generous considering the sum paid for Murnpeowie. A letter conveying this offer to Mr. Gill on Thursday December 3 is the first record that the meteorite was found by Mr. Gill's son and a friend. This is significant as by the time the ensuing conflict was over this friend was to be recorded as the sole finder of the meteorite! Mr. Gill replied the next day that the Museum's offer was unacceptable.

Mr. T. Gill subsequently informed the Museum that his son had another meteorite but no details were given as to the time or place of its find. On Monday July 19, 1915, he lent both to the Museum so that casts could be made. This was done and they were returned to him on the following Saturday. The Museum Committee conveyed their thanks to him in a letter on Thursday August 5.

In 1916, Mr. Waite led a Museum expedition to the north eastern part of the State. He recorded the following in his diary on Tuesday September 19 :

"...Our route now lay up Strzelecki Creek...meteorites not yet described have been found at Accalana and Carraweena. We got good water at Carraweena Well...This day we passed Howitt's 32nd camp at Artracoona..."

On his return Waite wrote to Mr. T. Gill on Wednesday November 15, 1916 asking him to name his meteorites as, if Mr. Gill agreed, the Museum wished to send casts to the British Museum. Waite reported to the Board Chairman on Monday 27 that, at his suggestion, Mr. Gill had named the meteorites Accalana and Carraweena. On Thursday December 7 the Board Secretary wrote to Mr. Gill thanking him for permission to send the casts to London. The Board's Annual Report for 1916-1917 states that both meteorites were the property of Mr. Gill's son. It is likely that he was involved with the finding of both of them.

Mr. T. Gill died in 1923 and in 1924 his son, Mr. T.F. Gill, approached the Museum concerning the sale of several meteorites. He had apparently found at least two others on another Kidman property, "Yandama", east of Montecollina Station on the eastern side of the State border. Mr. Gill's first approach to the Museum was apparently in connection with two of these meteorites which were later to be called Cartoonakana and Yandama.

Waite reported in an office memo on Thursday April 17, 1924 that Mr. T.F. Gill had promised to donate the small Cartoonkana meteorite to the Museum provided it purchased Yandama from him for £5 and a slab of Yandama. Approval was given and the purchase completed later that day. On the surface this appears a simple transaction. In 1936 Dr. (later Professor) Alderman recorded that both these meteorites had been found on Yandama Station and gave the exact locality as "Blacks' Camp, Big Plain, Yandama Station". He further stated that the name Cartoonkana had been suggested by Waite. This is borne out by Waite's office memo of Wednesday November 6, 1925 in which he wrote "The smaller Yandama I named Cartoonkana to distinguish it from the larger piece". (This memo was actually written in connection with Accalana.) Alderman, however, also stated that the Museum had acquired the meteorites in 1914. To add further confusion, the Tate Museum, University of Adelaide, catalogue carries the following entry for Yandama "1915 (Kidman) from Blacks Camp by Plain, Yandama. Thomas Flinders Gill bought Yandama from the Treasury on 15/11/24". Some notes forming an early catalogue of "Meteorites in S.A. Museums", apparently compiled prior to 1930 as Karoonda is not mentioned, carries the following entry for Yandama "From Blacks Camp. Big Plain, via Milparinka, N.S.W. Found 1914. Belonged to T.F. Gill. Brought by Walter Gill from the Treasury 15/11/14 to Museum. Purchased from T.F. Gill for £5 and a slice of the meteorite. Slice of the meteorite missing (has gone to T.F. Gill)". In this same catalogue Accalana is recorded as being obtained from Central Australia in 1917 and yet, as shown above, the Museum "cast" it in 1915.

The confusion of dates, names, locations and "bought" as against "brought" makes it difficult to unravel the truth. As mentioned above, both Thomas and Walter Gill were prominent in the Public Service but it is unlikely that the latter was involved. Likewise Thomas died in 1923 and so couldn't

have been involved in 1924. If the 1914 data is correct, it seems odd that these two meteorites were not mentioned along with Accalana and Carraweena. Likewise, the implication that they were in the Museum for ten years prior to being cast is also difficult to understand.

A close check of the original hand written version of the early Catalogue shows that the author used Roman numerals to designate the month and so it appears that the typed 15/11/14 should have been 15/II/14 with the author meaning February 15 and not November 15 as subsequent interpretations have suggested. This is further evidenced by his use of 6/XI/25 elsewhere.

It is reasonable to conclude that the two meteorites were brought to the Museum by Mr. T.F. Gill on Friday February 15, 1924 and that neither his father nor Mr. Walter Gill nor the Treasury had anything to do with the matter. This is in accord with the memo (referred to above) from Waite to Marshall (the Secretary of the Museum Board) on Thursday April 17, 1924 stating that he (Waite) had the two meteorites and that he had handed a slice of Yandama to Mr. Gill. The two month delay between their reception at the Museum and the payment to Mr. Gill would have allowed the decisions on the names to have been made. Also it would have been impossible for Mr. Gill to have received a slice of Yandama some seven months before he actually presented the meteorite at the Museum.

At the same time as this transaction there was apparently some new discussion concerning the sale of Accalana and Carraweena. On Saturday May 24, 1924, Mr. Gill wrote to the Museum and set what he described as a final price on them - £60 for the pair. He also nominated an expiry date for this offer. The letter did not reach Waite until after this expiry date and so he wrote to Mr. Gill on Wednesday July 2 concerning the possibility of re-opening negotiations. The latter replied on Thursday August 14, that he would consider any reasonable offer for Carraweena. Mr. Waite asked in a letter on August 16, as to what Mr. Gill would consider a reasonable offer. He in turn replied on Friday August 29 that he wouldn't accept less than £63. At the same time he mentioned three other meteorites which still remained in the area.

The Board Secretary replied on Friday September 6 that £40 was their limit. Mr. Gill responded to this offer on Monday October 20 stating that he was prepared to split the difference and accept £51/10/0. Waite replied that this would have to be considered by the Board at their November 5 meeting but he doubted that they would agree to the price.

Presumably because of this, Mr. Gill offered the meteorite at public auction on Friday October 31. The Museum commissioned Mr. J.T. Quigley to attend the auction and bid on their behalf. He was bound to silence as to the identity of his principals and further instructed that the money expended on the bid, plus any other fees incurred, should not exceed £40.

Neither Mr. Gill's offer nor the auction appear on the agenda for the November 5 Board meeting. However, the minutes of that meeting incorporate the Museum Committee accounts for previous month and included on this list was a payment of £40 for a meteorite to Megaw and Hogg, an Adelaide firm of auctioneers.

In an attempt to prevent a repetition of these events, Mr. Carl Schunke, a friend of Mr. T.F. Gill, approached the Museum on his behalf on Tuesday October 20, 1925 and offered to sell Accalana for £30. Waite declined the offer. Mr. Schunke wrote again on Wednesday October 28 suggesting that the Museum make an offer. This they did, suggesting £5. Mr. Schunke accepted this offer on Mr. Gill's behalf and the Museum forwarded the sum on Friday November 6, 1925.

Another meteorite should now be mentioned. Some time during the period 1914-1930 a meteorite was brought to the Geology Department of the University. This meteorite, according to Dr. A.W. Kleeman, had been found on Carraweena Station by Mr. G. Amesbury in 1914. Kleeman stated that the site of the find was described in a letter from Mr. Amesbury as having been found on the side of a sandhill 3.2km east of Nott's Hill and 9.5km west of Artracoona Hill thus making the site 13km NW of the Carraweena Head Station. This meteorite received several early names - "University Meteorite", "Carraweena No.2" and "Amesbury Meteorite". After consulation with an expert on aboriginal names it was finally named Artracoona.

In a letter to the author, Mrs. E.V. Pierpoint of Copley wrote, "The late William George Amesbury was my brother and it was he who discovered two meteorites on Murnpeowie Station, one was found on Mount Hopeless. Mr. Gill I knew. He was working with my brother and I believe he took one down to the Museum for my brother." The Murnpeowie meteorite was found near Mount Hopeless and thus there is a possibility that Mr. Amesbury was connected with Murnpeowie find.

Since Alderman described him as the finder of Carraweena it seems safe to assume that he was "Mr. Gill's son's friend". Thus it is possible that he was connected with the finding of three meteorites.

If, as Kleeman stated, Artracoona was found in 1914, it is strange that it was not mentioned in any of the early correspondence, nor was it mentioned by Waite in his expedition account (unless, at that stage, it was still being called Carraweena No.2 and so was included by implication). Weighing nearly 21kg, it would not have been easily overlooked. The Museum's indignation at the acquisition of Murnpeowie by the School of Mines may have been further aroused when this meteorite came to the University and so they may have chosen to ignore it. No acquisition date was quoted by Kleeman nor are there any other documents in the Department giving this date.

The last "meteorite" forming part of this saga is Monte Colina. In the 1960's while working in the South Australian Mines Department, Mr. James Eric Johnson came across a specimen in their museum labelled "Montecollina meteorite" which had a small piece cut from one end (Figure A2.5 a). As no other information was found, it was recorded as a new meteorite. Unfortunately, Corbett published the name as Monte Collina in 1966 and Monte Colina in 1968. It was acknowledged at the time that details of its discovery were unknown. Mason and Wiik concluded that it was at least part of the same fall as Carraweena. It is even more likely, however, that it is the original piece of the outer surface of Carraweena submitted to the Mines Department for identification by Mr. T. Gill in 1914. Outer pieces of this meteorite in the Tate Museum are similar to it and chemical analyses quoted above support this contention. With the help of Dr. N.H. Ludbrook, the author was able to locate an old thin section in the Mines Department labelled "Meteorite Montecollina". The age and location of this section were compatible with it belonging to the 1914 era.

There is even some confusion concerning the location of the recovery sites. According to Kleeman, Artracoona was found 12.9km north west of the Carraweena Head Station and 9.7km west of Artracoona Hill, Accalana near Accalana Wells, and Carraweena 9.7km south east of the Carraweena homestead. Alderman, however, stated that the Carraweena site was to the south west of the homestead while his map is even more confusing. On Pastoral Plan Sheet No.11 (South Australian Government Printer 1946), the site of the meteorite find is shown to the south west of the homestead (the Murnpeowie site is also shown) and on this basis Alderman's location is accepted. (The Pastoral Plans were prepared on the basis of information supplied by local residents.)

The "big plain" of the Yandama find is also difficult to locate. Mason (pers. comm.) suggested that it is now part of the Lake Stewart Station. A letter from the present owners of this Station suggested that a swampy area to the west of the homestead, now know as Yarriarraburra Swamp, was formerly a dry area known as the Big Plain. Mason searched an area in 1963 which definitely was dry but the co-ordinates of latitude and longitude which he gave for the area he searched correspond to a position some 12.5km west of Yarriarraburra Swamp. These adjacent regions are 46km north of the position on Yandama Creek which is specified by the coordinates given by Alderman.

Suggestions were made in Chapter 6 concerning possible relationships between these meteorites. The historical account given here is quite consistent with such relationships. Brief mention of the matter will be made again in Sections A2.2.8 and A2.2.9 below. Despite some remaining uncertainties, the situation concerning these meteorites has been clarified.

A2.2.5 Weekeroo Station

This meteorite was found by Mr. James Lane on Weekeroo Station, north of Mannahill, in 1924. Mr. Lane stated that he had found it on the brow of a large hill where it was resting on a quartz reef level with the surface. The meteorite was purchased by the Australian Museum in 1927. Due to cutting problems, the sectioning was done in 1928 in the Eveleigh Railway workshops through the courtesy of the Railway Commissioners. Some of it was sold to Ward's Natural Science Establishment in New York as this was the source of the American Museum specimen.

It is an unusual meteorite and for some time its name was used to designate a sub-type of the iron meteorites. Even though this nomenclature has now been replaced with that of Wasson and co-workers, Weekeroo Station remains one of Australia's rare meteorites.

A2.2.6 The Cockburn meteorites

Nine finds, ranging in weight from 5g to 2.2kg, and having a total weight of approximately 3.3kg, have been recovered from an area of approximately one square kilometre about 10km south east of the

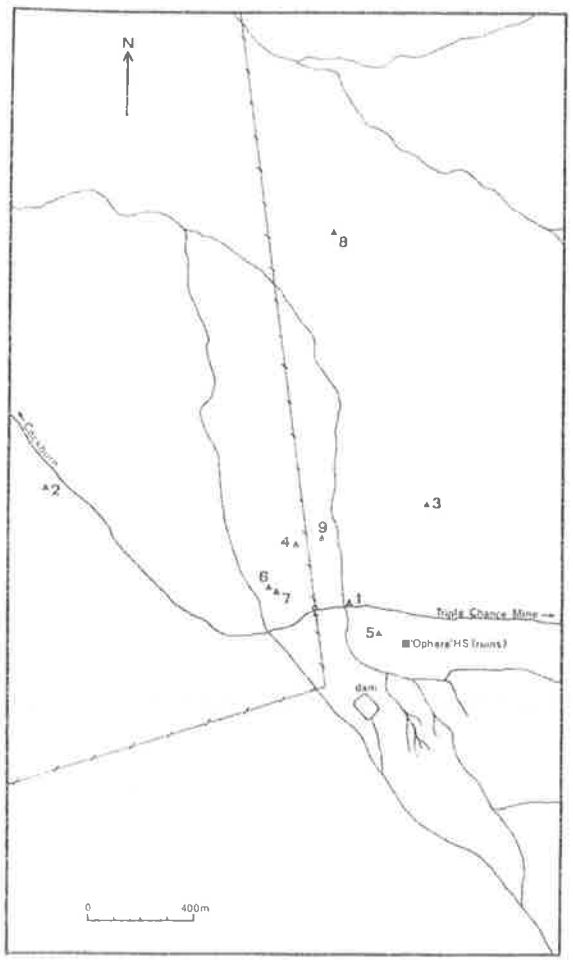


Figure A2.3 : The Cockburn strewn field.

border town of Cockburn. The recovery period spans some thirty years. Figure A2.3 shows the recovery sites in detail while the proximity of the area to the town of Silverton is shown in Figure A2.4.

The first seven finds, which were very similar, were named Cockburn No.1 to 7 in the order of their recovery and when the eighth was found it was assumed that it was the same and was temporarily named Cockburn No.8. Some fifteen months later when the ninth specimen was found, it and the eighth were closely examined by the author who found that they were fundamentally different from the others and accordingly they were renamed.

Huss (1971) suggested using letters a,b,c etc. after the same name to distinguish meteorites whose area of recovery overlap, but since more than one specimen of each as been recovered, the use of the name Cockburn for both groups would cause confusion. The recovery area is devoid of significant topographic features, being characterized solely by clay pans, extremely small sand dunes and ephemeral streams and thus the name of a prominent topographical feature was not available.

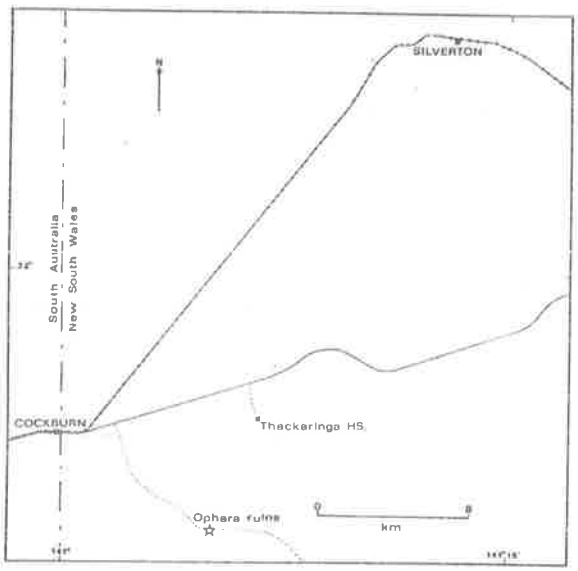
All have been recovered adjacent to the Ophara Homestead ruins, the fifth being picked up about 100m from the old building. The new finds, however, could not be named Ophara since Johnson had at one stage used this name to refer to the first find. The site of the finds is about 7km away on a bearing of 210° from the ruins of the town of Thackaringa which had its beginnings in the early 1870's. The town which was situated on the Terowie to Medindee track took its name from the nearby Thackaringa Station which belonged to the pastoral firm of Elder Smith. The town increased in size and importance with the discovery of silver-lead on the property in 1876. Other finds followed and the town achieved a maximum population in 1887. By 1890 no-one remained, finds at nearby Silverton and Broken Hill having attracted the residents when local reserves were exhausted. (Thus, if the Silverton find mentioned above had been found in the area in the late 1880's, Silverton would have been the largest nearby town.)

The last two finds were hence named Thackaringa No.1 and No.2. Although the only remaining geographic "feature" of this name is Thackaringa Station, this name does not completely conflict with the recommendations of Buchwald and Wasson (1972) concerning the use of station names for meteorites, as the finding site is located on the Thackaringa 1:100 000 sheet of the International Index (MENINDEE SI/54.3 Thackaringa 7133).

a. Cockburn No.1

This, like several other meteorites found by Mr. J.E. Johnson, was picked up while he was looking for australites (Australian tektites). When the meteorite was found in

Figure A2.4 : Cockburn and Silverton.



1946, Mr. Johnson was working at the nearby Triple Chance Mine and he discovered it on an old aboriginal camp site. Mr. Johnson placed his find in his mineral collection which he later gave to Sir Douglas Mawson, then Professor of Geology and Mineralogy in the University of Adelaide. The collection came to the Geology Department and the meteorite was rediscovered some years later by the then curator of the Tate Museum, Mr. Donald Hugh McColl.

b. Cockburn No.2

During the third week of October 1967, Mr. D. McColl and his family travelled to Broken Hill in connection with the Moorabie meteorite (A2.2.9 below) and on their way examined the site of the Cockburn No.1 find. After a few hours searching, Mrs. Lois E. McColl found this specimen which she generously donated to the Geology Department. The find is remarkable not only for its size (5g) but also because, due to a misunderstanding, they were searching well away from the site of the Cockburn No.1 find. Cockburn No.2 is still the most distant find from the centre of the area.

c. Cockburn No.3

Mr. Johnson returned to the area in June 1972, and at 2:45pm on Thursday June 8, found this specimen on a clay pan after searching for about four hours. He brought it back to Adelaide and gave it to the University.

d. Cockburn Nos.4 and 5

After the Cockburn No.3 find it was decided to search the area more fully. A party consisting of Mr. Johnson, Mr. (now Doctor) Roderick J. Hill and the author travelled to the area on Saturday July 1, 1972. The group searched all day in vain. The search resumed the next day and Cockburn No.4 was found on a clay pan at 9:50am by Mr. Johnson (Figure A2.5 b). Encouraged by this success, the systematic search of the area continued and Mr. Hill found Cockburn No.5 at 2:50pm on a quartz littered clay pan. Both specimens were donated to the University.

e. Cockburn Nos.6 and 7

While in Australia on study leave in 1973, Dr. Brian H. Mason of the Smithsonian Institution visited the area and found both specimens on July 22. The larger one, Cockburn No.6, was partly buried in the ground, about one third being covered. The smaller mass was found a metre or so away. The major part of both specimens was taken to America although Dr. Mason generously gave some 50g of Cockburn No.6 to the University.

Unlike the previous five finds, which had complete, or almost complete, fusion crusts, the "above ground" surface of Cockburn No.6 was devoid of one, having been sandblasted. Cockburn No.7 had no trace of a crust and may be a fragment of Cockburn No.6.

There is no obvious relationship between any of the Cockburn specimens and so they presumably represent a shower of meteorites rather than fragments of a mass which broke up immediately prior to impact with the earth's surface.

f. Thackaringa No.1

Mr. McColl (by this time Curator of Minerals in the Bureau of Mineral Resources, Canberra) revisited the area in March 1974 and found this specimen on Sunday 24. This specimen was returned to the B.M.R.. However, about one tenth of it was subsequently acquired by the University.

g. Thackaringa No.2

A party of searchers organized by Mr. McColl and the author visited the area again in June 1975 in an attempt to locate more specimens. At approximately 10:45am on Sunday June 8, the small Thackaringa No.2 mass was picked up by Mr. Wayne Mussared of the University of Adelaide who subsequently donated this small crusted individual to the University.

A2.2.7 Crocker's Well

In 1956, while working on the East Crocker uranium prospect near Crocker Well, north of Mannahill, Mr. J.E. Johnson found this meteorite on a granite hill. This hill is about 0.4km north of the prospect and the meteorite is to date South Australia's smallest meteorite, weighing only 3.8g. Later in the same year Mr. Johnson donated this meteorite, found while searching for australites, to the S.A. Museum. It is possible that this tiny chondrite is part of the Ethiudna find (Section A2.2.11 below) which was recovered only 6.5km away.

The recovery area is often known locally as "Crocker's Well" and unfortunately this name was given to the meteorite in early published accounts of its find.

A2.2.8 Coonana

Mr. John Rattus, a Mines Department driver, found this meteorite during a Departmental survey in the north east of the State. The party was camped near Coonana Bore on Yandama Creek when Mr. Rattus saw

the meteorite on a clay pan 5.5km west of the bore on Thursday June 7, 1962. Suspecting its meteoritic nature he showed it to a geologist who broke it with a hammer and said it was only laterite. Mr. Rattus, not convinced, collected the major portion and placed it in his vehicle. It remained there until the party reached the Flinders Ranges where they met another Departmental party. Mr. Rattus showed the meteorite to Mr. J.E. Johnson, a member of this second party, who confirmed the identification.

On his return to Adelaide, Mr. Johnson submitted a specimen of the material to AMDEL (Australian Mineral Developement Laboratories, Adelaide, S.A.) on Thursday July 5, 1962, requesting a petrological report. This report, on Friday September 28, confirmed the tentative identification. The meteorite was subsequently acquired by the S.A. Museum. (There are several spellings given on different maps for the word Coonana, the one used here is the meteorite's correct name.)

Despite the proximity of its find to the Gill meteorites, Coonana cannot be related to the known ones as it is an H chondrite while they are L chondrites. It is possible though, that it is one of the three meteorites which Mr. T.F. Gill claimed were still in the area.

A2.2.9 The Russell meteorites

Several meteorites have reputedly been found by Mr. Lindsay H. Russell on Moorabie Station. This station, which belongs to Mr. Russell, is north west of Broken Hill. The station is near both the South Australian border and Yandama Station as can be seen from Figure A2.2.

a. Boolka and Moorabie

On Tuesday October 10, 1967, Mr. J.E. Johnson saw a large meteorite in the Broken Hill shop of Mr. Joseph McLellan. The meteorite belonged to Mr. L.H. Russell. After returning to Adelaide, Mr. Johnson informed the University of the meteorite. The Geology Department's Museum curator, Mr. D.H. McColl, journeyed to Broken Hill the following week, photographed the meteorite and spoke to Mr. Russell. It was decided to name the meteorite Moorabie, and to cut a portion from the mass for analytical purposes. Mr. Russell brought it and another meteorite, which he had found earlier in the month, to Adelaide at the end of July 1968. The second meteorite, which had been found near Boolka Bore, was named Boolka. Mr. Russell did not wish to cut it and stated that it had been found a few kilometres north of Moorabie. Both Boolka and Moorabie were returned to Mr. Russell.

b. Other meteorites in Broken Hill

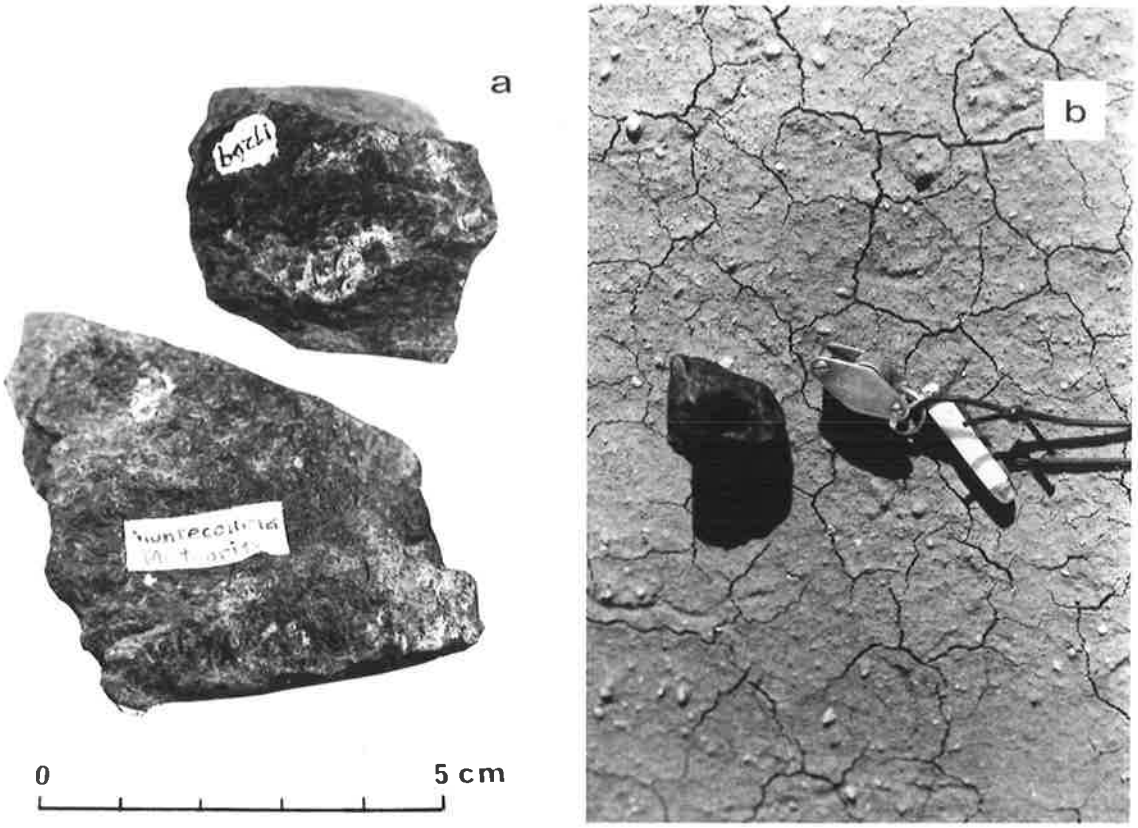
On a trip to Broken Hill in March 1972 to carry out a further search at the Cockburn site, a search prevented by heavy rains, Mr. J.E. Johnson and the author visited Mr. McLellan's shop. There were then five meteorites there: a. Boolka, b. Moorabie, c. a small piece of a stone (ca. 0.25kg), d. a fresh looking stone of about 5kg weight, and, e. a rough textured "house brick" shaped meteorite. The last one of these was reported to have been found in Queensland while the others were all said to have come from Mr. Russell's property. Unfortunately no agreement was reached concerning the examination or naming of these bodies. The last two specimens were recently purchased by the S.A. Museum.

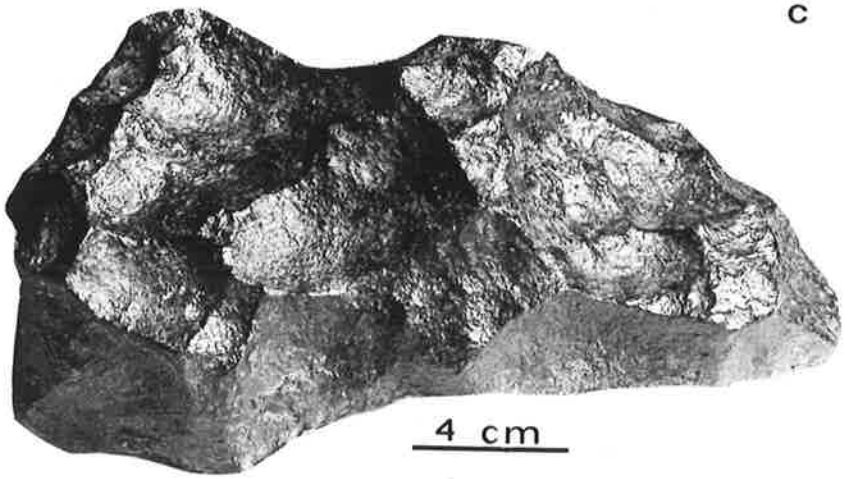
The number of meteorites which have been recovered from Moorabie Station suggest the possibility that some of them may be related to the Mount Browne fall which was only 70km distant. Figure A2.2 shows the relative locations. Mr. T. Gill claimed, as described above, that there were still three unrecovered meteorites in this area so a further connection may be possible. None of these possibilities can be tested, however, until all of the Russell meteorites have been examined and analysed.

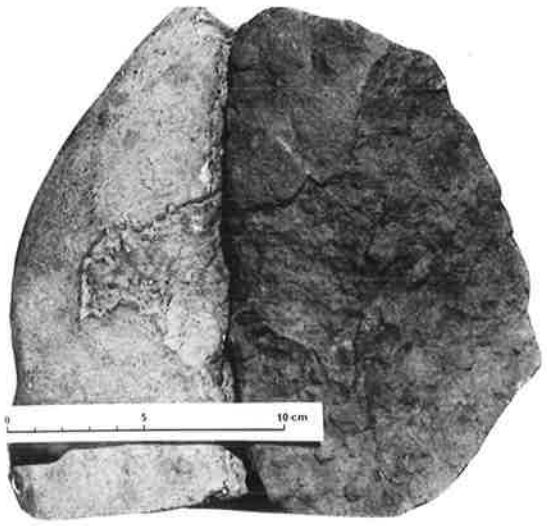
A2.2.10 The Hollmayer meteorites

During the period 1969-1971, Mr. Werner Hollmayer lived near Popio Lakes, south east of Broken Hill. At the time he was earning his living trapping rabbits. While checking his traps he kept an eye out for any unusual rocks which might be meteorites. In 1971 he moved into Broken Hill but continued to take home any strange brown rock he saw. The attention of Mr. McColl, of the B.M.R., was drawn to this large collection and so he went to inspect it. While there he saw several specimens which he thought might be meteorites and he was given permission to take six to Canberrra for examination. These

Figure A2.5 : a. Monte Colina and a portion of the outer surface of Carraweena (Carraweena Fragment).
b. Cockburn No.4 in situ.
c. The Cowell meteorite.
d. Matching fragments of Kielpa.


a
b
0
5 cm


c
4 cm


d
0
5
10 cm

were sectioned by Mr. McColl and the author in April 1975 and all were found to be meteoritic.

Later examination of Mr. Hollmayer's brown rocks revealed many more meteoritic specimens, and a search in the finding area by Mr. McColl, resulted in the recovery of at least one more specimen. In all, 56 specimens, many of which are wholly or partly crusted, have been identified. Those whose recovery site is known accurately have been named accordingly, the majority have simply been identified with a B.M.R. code as little is known of their exact history. (The ones examined in this work fit both categories - Nine Mile, Popilta, Popio, Twin Wells and H05, H06. These meteorites were named by Mr. McColl.) As all have not been examined, no firm conclusion can be made concerning the number of separate falls represented by this material. On the basis of results obtained in this work, at least two are represented.

A2.2.11 Ethiudna

This large meteorite was found on the surface of a plain about 6.8km distant, and on a bearing of 340° from Ethiudna Hill on Plumbago Station north of Mannahill.

The meteorite was identified and recovered on the morning of Sunday February 20, 1977 by Mr. Michael J.W. Larrett who was working in the area on survey project for AMDEL, the nature of which has not been disclosed. Mr. Larrett had been told of the location of the meteorite, which was lying on a flat, loamy surface in an area devoid of any rocks or evidence of a crater. The recovery site is about 6.5km away from that of Crocker's Well (Section A2.2.7 above) and it is quite likely that that tiny fragment is a piece of Ethiudna. The degree of weathering of the latter suggests that it is not a recent fall.

Ethiudna, which was named by the author, is the largest recovered South Australian chondrite and probably the only Australian one which exceeds it in weight is Barratta No.5.

A2.3 SOUTH EASTERN METEORITES

Eight, or possibly nine, meteorites have been recovered in the area of South Australia which, for the purpose of this work, has been termed the South East.

A2.3.1 Karoonda

At 10:53pm on Tuesday November 25, 1930, a bright meteor lit Adelaide's night sky with a brilliance comparable to that of daylight. The meteor was seen up to 400km from Adelaide and in Mannum some 60km east of Adelaide, for instance, two men walking down the main street, prostrated themselves on the ground to avoid being hit.

A report of the meteor appeared in the "Advertiser" the next morning as well as various opinions as to where it had landed. The Torrens River, Waterfall Gully and Morphettville racecourse (all localities in Adelaide's suburbs) were mentioned. Mr. George Frederick Dodwell, the Government Astronomer, expressed the hope that it might have fallen on his property in the Adelaide Hills and stated that he would check.

Many reports came to Adelaide, the most useful being that of Messrs. Honeyman and Millard of Karoonda who stated: "The disappearance of the the meteorite was followed by a large detonation as though a very heavy charge of explosive had been fired underground. This caused a distinct vibration of buildings nearby. This sound was followed after an interval of three seconds by a large crackling and rending sound from the sky in the direction in which the meteorite was last seen, then by a low rumbling of thunder which gradually died away in the darkness". (Mr. E.A.P. Hoff, the finder of Vincent, commented many years later that he was in Karoonda that night visiting a friend, who lived near the railway line, and that they heard a noise similar to that of an approaching train. This was unusual as no train normally passed at that time. Likewise the increase in sound was not followed by a diminution.) This evidence, plus the fact that nothing had been heard by other observers, encouraged Professor (later Sir) Kerr Grant, Professor of Physics in the University of Adelaide, and Mr. Dodwell to go to Karoonda to search for the meteorite.

A party comprised of Observatory staff and Physics and Engineering students from the University went to Karoonda on Saturday December 6. They camped about a kilometre of so from the town in the direction in which Mr. Honeyman had seen the meteor disappear. They spent Saturday and Sunday gathering information from people who had seen the meteorite and plotted this information on a map thus locating the fall into an area of some 3 to 5 square kilometres. They searched the area in vain on Monday. Tuesday morning Professor Grant rose early to visit a farm they had missed the previous day as the owners were absent. Acting on information supplied by the farmer's daughter he walked towards a distant tree and in doing so crossed a fallow paddock belonging to Mr. D. Lawrie. As he did, he noticed what at first

looked like the blackened remains of a fire. Closer examination showed that the "ashes" were actually fragments of a dark rock. The pieces lay in a crater about 40cm deep and 60 across, while smaller pieces were scattered over an area of about 3m radius.

Overjoyed at his find, but somewhat disconcerted that he had "stolen a march on the others", Professor Grant returned to camp. After breakfast the party returned to the find and collected some 42kg of material, the largest piece weighing 3.2kg. Professor Grant steadfastly claimed that most of the credit for the find was due to Mr. Dodwell for his painstaking recording and compilation of information and for this reason both men have always been credited with the find. An account of this appeared in the "Advertiser" and the "Register" on Wednesday December 10.

Two or three weeks later, Mr. Paul Benno Sontagg and his brother found some more of the meteorite about twenty metres away from the crater. The specimen was either one large piece which they subsequently broke into four, or found small pieces. At least one of these pieces still exists.

Some eighteen months later on Friday May 27, 1932, a column (frontpiece) bearing the following inscription was unveiled in the main street of Karoonda:

> "This column is erected to commemorate the fall and finding of the Karoonda meteorite which fell as a brilliant fireball at 10:53pm on November 25th. 1930 and was found by Professor Kerr Grant and G.F. Dodwell Esq. 1 1/4 miles east of this point. Erected by the University of Adelaide and the Karoonda School Committee".

Karoonda, an unusual carbonaceous chondrite, has been widely distributed and studied as can be seen from Chapter 14.

A2.3.2 Pinnaroo

This meteorite was dragged from the ground with a set of harrows in May 1927 by Mr. Stanley Hamilton who was working on his property about 14.5km south of Pinnaroo. Mr. W.A. Hamilton, the finder's uncle, wrote to Professor Kerr Grant on Saturday May 21 and Monday May 30, 1938 concerning the find. Mr. Hamilton enclosed a sketch map, drawn by his nephew, showing the discovery site, with the second letter. He stated in this second letter that his nephew requested that the meteorite be called Pinnaroo.

At some stage, probably during the period between these two letters, the meteorite was brought to Sir Douglas Mawson for identification and was subsequently acquired for the University.

Due to its mineralogy (Pinnaroo is a mesosiderite) the meteorite was difficult to cut and so was taken to the Islington railway workshops where it was cut with the saw which had been designed and built the previous year to cut the Huckitta pallasite (Section A2.8.8 below).

A2.3.3 The Coomandook meteorites

a. Coomandook No.1

This was found in 1939 by Mr. G. Ninnis on his property 13km east of Coomandook township. The area's upper soil horizon contains many kunkar nodules which are brought to the surface during cultivation and must subsequently be removed. It was during one such operation that Mr. Ninnis found this stone. He presented it to the S.A. Museum in 1940 and it was named Coomandook.

b. Coomandook No.2

This specimen was also found while clearing calcareous debris from a ploughed paddock. Mr. Rex Arnold Goodall picked it up on his property 7.5km from the town of Ki Ki in 1967. It was initially named Ki Ki. However, because of its similarity and proximity to the first find (about 16.5km), it was renamed Coomandook No.2 by Dr. D.W. Corbett of the S.A. Museum, while the name of the original find was changed to Coomandook No.1. Coomandook No.2 was also presented to the S.A. Museum.

c. Other Coomandook material

A badly weathered fragment (51g), allegedly from the Coomandook area, was recently acquired by this Department. It was supposedly found near Ki Ki and was subsequently given to the late Mr. Clem Latz of Adelaide. This third find which is superficially quite similar to the outer portions of Coomandook No.1 suggests that further material may be present in the area.

A2.3.4 Caroline

In 1930 Mr. Stuart Keith McEarchern (co-finder of the spectacular Princess Margaret Rose Caves) found an unusual stone about a kilometre north east of his home, Dry Creek Station. The find site, about 2km north west of the Princess Margaret Rose Caves, was about 500m into Victoria as the homestead was only about 100m west of the State border. (Only the ruins of Dry Creek Station, which was located in Section 539 of the Hundred of Caroline, now remain.) This location varies from earlier published accounts but since it was supplied by Mr.

McEarchern it is considered to be more accurate. Mr. McEarchern also pointed out that the meteorite was not found on an aboriginal campsite as suggested by some writers.

The stone was used as a doorstop for about ten years until the family moved to another house. Mr. McEarchern then decided to send it to Melbourne because of its unusual appearance and it was given to Mr. R.A. Keble of the National Museum of Victoria.

A2.3.5 Vincent

This meteorite was found by Mr. Edmund Arthur Paul Hoff, while working on his property 9.5km NNE of Karoonda township in 1926. In 1956, Mr. Hoff donated the meteorite to the S.A. Museum. It was named Vincent from the Hundred in which it was found as the name Karoonda had already been used. When interviewed by the author, the late Mr. Hoff was unable to remember any details of the find.

A2.3.6 The McDonald meteorites

Mrs. Bertha Grace McDonald and her husband found five stony meteorites in the South East during the period 1961-1962.

a. Lake Bonney

Mrs. McDonald, then a Millicent resident, used to spend many weekends searching the area northwestwards from the town, towards the coast, for aboriginal artifacts. On Saturday October 21, while searching an old camp site on Jacky Point, a small peninsula jutting into Lake Bonney, she found a strange stone. This was taken home and subsequently sent to Adelaide to the S.A. Museum where it was identified as a meteorite.

As a result, a search party, organized by Dr. D.W. Corbett, visited the area later in the year. During the search, Mrs. McDonald found another stone, now in her possession, some 5 to 6km away from the site of the first. A little later and about 500m away, Mr. and Mrs. McDonald found another 0.5kg of fragments which fitted together while a short time later Mrs. McDonald found another stone. Inspection showed that each of the four stones had a "complete" fusion crust. Mrs. McDonald donated three of the stones to the S.A. Museum in 1961.

b. Nora Creina

Some months later in 1962, while searching for artifacts north of Nora Creina Bay, Mrs. McDonald found a large stone resembling the Lake Bonney meteorites. Examination confirmed her initial identification.

Due to the similarity of its appearance to the Lake Bonney material found 68km to the south, it was suggested that this stone might have been part of the Lake Bonney fall. Mineral analyses by Mason suggested this was not so and accordingly the meteorite was named Nora Creina. Mason's conclusion is borne out by this work.

A2.4 NEAR NORTHERN METEORITES

Four of the following meteorites have been found immediately north of Adelaide. The last two are described here for convenience.

A2.4.1 Rhine Villa

Prior to November 1900, while working on one of the family properties near Rhine Villa, Mr. Allan George Payne found a rock different from the local limestone. He took it home and tried in vain to crack it with a sledge hammer.

In November 1900, his brother, Mr. Howard William Payne, brought the iron meteorite to Adelaide and gave it to the S.A. Museum where he was recorded as the finder. The meteorite was named Rhine Villa. During World War I, anti-German feeling was high in South Australia and many South Australian towns having Germanic names were renamed. The name Rhine Villa was changed to Cambrai and so the former name does not appear on current maps.

Most of the meteorite was ironically sent to Germany. Buchwald, on the basis of his examinations, suggests that it went to F. Krantz, the Bonn mineral dealer, and that he subsequently cut and distributed it to several museums in 1902. Much of the meteorite is now missing, possibly having been lost in Germany during the war.

A2.4.2 Cadell

This is the first stony meteorite recovered in South Australia. When found on Thursday April 14, 1910, by Mr. Charles H. Bannear of Morgan, it was lying almost completely buried on the side of a sand hill, with only one tip exposed. The sandhill, on the eastern side of the River Murray in the Hundred of Cadell, was about 4.8km from Morgan. It was given to the S.A. Museum on Monday May 2, 1910, and named Cadell.

A2.4.3 Kybunga

At about 4:20pm on Sunday September 7, 1941, the residents of the town of Kybunga and surrounding districts to the north of Adelaide were disturbed from their Sunday rest. The following selection of subsequent reports from some of these residents gives

an idea of the event:

"It appeared overhead and then there was a terribly loud noise and a roll of like thunder and a whistle like a rifle bullet, then more explosions, nine or ten in all and with these there was a puff of smoke."

"It disturbed all the birds."

"Rumblings as if the local quarry (Clare) had collapsed."

"Sounds like the boom of a cannon."

"Horses ran away with their tails up and cows ran home"

"Like the crack of doom."

The most obvious difference between this and the Karoonda fall was the greatly decreased visual effect - the pyrotechnic effect of the latter having been enhanced by the darkness of night. Nevertheless, the meteorite's passage through the atmosphere was observed by many people in Adelaide and surrounding areas. Mr. Mervyn Howard, a Gawler schoolteacher, who was visiting his parents at Nairne, a town some 30km east of Adelaide, was in the garden with them when he saw a bright fireball flash across the sky. As he was holding a camera, he photographed the fireball and obtained a clear picture of the brilliant meteor.

Dr. Charles Fenner of the Geography Department in the University of Adelaide, and Mr. G.F. Dodwell, who had played a significant role in the discovery of Karoonda, visited the Kybunga area on Friday and Saturday November 28-29 after many reports had been gathered and they had delineated a region in which they thought the meteorite had fallen. The presence of crops in many of the paddocks precluded a thorough search. Later in the year, a farmer from the area reported five or six burnt spots in one of his paddocks and a party returned to the area and again searched in vain. They intended to return at a later date when the war time petrol restrictions were lifted but as far as is known this trip never eventuated.

By comparing the size of the meteor with that of Karoonda, they estimated that the meteorite ought to have had a mass in the vicinity of 77kg, while Lapaz (1952) on the basis of Mr. Howard's photograph and other observations, estimated a heliocentric velocity in the range 46 to 76km per second and a minimum extra-terrestrial mass of 210kg.

Little more happened until 1963 when Mr. Glen Charles Wiech of Kybunga ploughed an unsual rock from one of his paddocks. He retained this specimen until Saturday 15, 1969 when he donated it to the S.A. Museum after viewing their meteorite display. He later found another small piece which had been broken from the first, probably on impact, and the two pieces were together known as the Kybunga meteorite. (Fenner, in a book of collected essays, wrote in 1946, "One of these days when the meteorite is found, the story will be published in some scientific journal, and the object will be called the Kybunga stone meteorite.". These somewhat prophetic comments may well have been forgotten when the meteorite was found as it was initially known as the "Blyth meteorite", the site of find being only a few kilometres south of that town.)

In 1971 Mr. Wiech found another large crusted individual which did not fit together with the first finds. This new find was named Kybunga No.2 and the earlier material renamed Kybunga No.1. Mr. Wiech retained this second find as well as the small fragment of the second mass. Later in the same year, a neighbouring farmer, Mr. Ian David Schumacher, found another mass which was also crusted and did not match any of the other material. This was named Kybunga No.3 and is the source of material for nearly all the determinations which have to date been carried out on Kybunga. This third find was ultimately purchased in 1972 by two private collectors and half of it donated to the University. At present about 85% belongs to the University. Mr. Wiech subsequently donated the fragment of Kybunga No.1 and part of Kybunga No.2 to the S.A. Museum.

All three masses have complete fusion crusts suggesting the meteorite broke up prior to impact. Marked flow lines can be seen at least on Kybunga No.3. The total mass of 8kg recovered to date is somewhat less than one eighth of Dodwell and Fenner's estimate. All three masses also bear marks, probably produced by a plough or other agricultural equipment, attesting to the shallowness of their burial and the bad luck that they weren't recovered earlier.

The three masses have all been found more or less within the elipse of impact as predicted by Dodwell and Fenner, but 1 or 2km north of their estimate of the mean position of the probable site. Considering that most of the observations reported to Dodwell and Fenner were approximate bearings made without the aid of compasses etc., the agreement between the predicted and actual site is a further tribute to Dodwell's skill in locating meteorite falls. Investigations in the area by the author have shown, for example, that the site of Kybunga No.3 is almost exactly north west of what was

Pengilly's farm and so this fragment may well be the piece seen by Mrs. Pengilly and her daughter as reported by Dodwell and Fenner. (This property is now owned by the Schumacher family.) On the other hand, viewed from Findon Farm, still owned by the Clarke family, the recovery sites are almost in a straight line of bearing N 30° E, which, once again, is in very good agreement with Mr. Clarke' original account.

A2.4.4 Kapunda

On Saturday June 10, 1972, the author visited Mr. Ben Peters at his Adelaide home (See also Section A2.5.2 below). Mr. Peters stated that his cousin Mr. Oswald Peters owned a meteorite supposedly from Hermannsburg in the Northern Territory. Mr. Peters and the author visited Freeling the next day and searched in vain for this meteorite. Another, smaller meteorite, however, was found in Mr. Peter's shed and recognized as such by Mr. B. Peters and the author.

This meteorite had been collected as a specimen of slag by Mr. O. Peter's daughter, Ann Marie, and a friend, Miss Heather Shakes, as part of a "Girl Guide" project. (The area is a former copper mining and smelting district.) The girls' recollections of the event are extremely vague but Mr. O. Peters recalls that the meteorite was picked up in a paddock on a side road near a bridge over Allen's Creek about 2km south east of Allandale North. (Probably in Sections 1463, 1505, 1552 or 1553 of the Hundred of Kapunda.)

Mr. O. Peters also thought that there may have been more fragments in the area but a search by Mr. B. Peters and the author failed to locate any further material.

Mr. O. Peters donated the meteorite to the University and because of the uncertainty of the location of the finding site the author named it Kapunda.

A2.4.5 Adelaide

Very little is known of the terrestrial history of this meteorite, it having lain unrecognized on an office desk in the S.A. Mines Department for an unknown period. It had possibly been brought to the Department to be identified but no one can remember any details. Since some people in the Department thought it was a basalt specimen it is possible that it was found in the volcanic areas in the south east of the State. The meteorite was sent to AMDEL on Tuesday May 2, 1972 with a request for a detailed chemical and mineralogical examination. The report, submitted to the Mines Department on Thursday September 28, 1972, described the meteorite as a Type 2 carbonaceous chondrite.

Initially the meteorite was referred to as "S.A. Alpha" due to lack of information concerning the site of its find. Acting on the advice of the Meteoritical Commission via Dr. R. Binns, it was named Adelaide by the author. It ought to be emphasised, however, that this name is not meant to imply that the meteorite was originally recovered in Adelaide. Prior (1953) used this name as a synonym for Rhine Villa but this usuage has been discontinued for so long that the new application seems justified.

A2.4.6 Un-named stony iron

Little also is known of the history of this meteorite. It was seen in a mineral shop in Hindley Street, Adelaide, by the late Mr. Clem Latz, who brought it to the author's attention. Through the kind offices of Mr. Latz, the author was able to obtain the meteorite for a time and after no little effort section it and polish the two faces. It consists of nodules of sulfides and silicates set in nickel-iron although the silicates may predominate in a larger specimen.

The shop's owner stated that the meteorite's previous owner, a Mrs. Brown, had said that the meteorite had originally belonged to her father who had picked it up many years previously, possibly near the Western Australian border. Because of this, the author sent a piece to Western Australia for examination. Ga and Ge determinations carried out at the Western Australian Institute of Technology confirmed that it was not part of Mundrabilla, while Dr. Binns of the University of Western Australia suggested that the specimen resembled Donnybrook.

Specimens of this meteorite are now held by the S.A. Museum, the National Museum of Victoria, the Western Australian Museum and the University of Adelaide. Until more information is available as to the site of its find, it is proposed that it should simply be referred to as an un-named stony-iron.

A2.5 THE EYRE PENINSULA METEORITES

To date, seven meteorites have been recovered in this area.

A2.5.1 Yardea

This was the first recorded South Australian meteorite find. It was found in November 1875, by Mr. J. Martlew in mallee

scrub about 6km south of Yardea Station and some three quarters of a kilometre to the north of the foot of the Gawler Ranges. It was about 40cm below the surface and was surrounded to a distance of about 1m by pieces of broken limestone. (There is generally only 10 to 20cm of soil over the limestone in this area.)

It was given to the S.A. Museum prior to 1883 but the name Yardea was apparently not used for it until 1895 when it appeared in Brezina's catalogue. Mr. Martlew apparently broke a piece from the meteorite while it was still in his possession and there is also a chisel mark on the surface where an attempt was made to remove a larger piece.

On Tuesday May 25, 1976, Mr. Robert J. Clarke rang the University in reference to a crater-like depression which he and his family had seen a few days before on Thurlga Station, north west of Kimba, on Eyre Peninsula. The description of the depression, plus its proximity to the finding location of Yardea, prompted a visit to the location. On Friday June 4, 1976, Dr. Richard F. Jenkins of this Department and the author travelled to Thurlga Station to examine the depression. Its exact locality was described by Mr. R.D. McKay, the owner of the station, and his wife.

The depression was very nearly circular in shape with a diameter of 5m. It was bounded by two crescentic mounds, which were about 40cm above mean plain level at their highest point, while the centre of the depression was about 50cm below. These mounds tapered away virtually to plain level at their extremities. The diameter joining these two points of zero height had a bearing of 120° while the diameter joining the highest points had one of 30°. The mounds were about 1m wide at their base below the highest point. The walls below these points had dips of approximately 22° and 20°, while those at the lowest points dipped at about 16° and 20°.

A trench dug through the centre of one of the mounds revealed numerous pieces of white calcareous sub-soil material, whereas none of this material was found in excavations in the floor of the depression or in the flat regions between the ends of the two mounds. A 40cm deep excavation in the centre of the depression did, however, expose several fragments of Gawler Range Porphyry which outcrops as a hill some 300m south of the depression. The vast majority of these fragments were rounded from weathering processes, while most of the fractures on the pebbles showed historical evidence of this weathering in the form of a patina. Small magnetic spherules were extremely abundant in the soil surrounding the depression and many of these grains had diameters up to 1cm.

The high symmetry of the structure, both as regards the size variation of the rim mounds as well as the shape and internal slope of the depression itself, suggest that the feature is not the result of either animal or human activity.

The actual site where Yardea was found is unknown. The location details as originally recorded are vague in that it is not known whether the description "6km south of Yardea Station" refers to a position 6km south of the station boundary or to one that distance from the station homestead. The direction given as south is vague, while the comment "to the north of the foot of the Gawler Ranges" is equally inexact as the Gawler Ranges are not rigorously bounded by abrupt scarps but consist in many places of low, scattered hills.

There is a possibility that this depression was produced by the terrestrial impact of Yardea - the site is some 21km from Yardea Homestead. Yardea had a mass of some 3.3kg and so it is possible that it was shifted by human agency sometime after its fall. There is also the distinct possibility that the depression was either produced by another meteorite yet to be found or by some method other than meteorite impact.

A2.5.2 The Bedford meteorites

a. The Kyancutta Museum

In June 1915, Mr. Robert Bedford and his family arrived in Australia from England and in October took up land near Kyancutta which had been allocated to them the previous year. Mr. Bedford had always been interested in museums and as a young man had set up one at home. He studied marine biology at Oxford as well as nearly completing a medical degree and after graduation a scholarship took him to Naples to further his studies in marine biology. This was followed by a period of some two years at the Berlin Museum where he also lectured to students. After his return to England, he assisted in establishing a provincial museum in South Plymouth.

On their arrival in Kyancutta, the Bedford family "share farmed" with the Peters family on their property about a kilometre from the town. In February 1922 the family moved into the town to live in the premises of the general store which Mr. Bedford had built. Soon after, he decided to establish a museum in Kyancutta and to this end he constructed a separate building next to the shop. He

imported some of the first exhibits from England. His first meteorite specimens were samples of Holbrook and San Angelo which he purchased from Ward's about 1925. He also established a library in the same building. This was not a lending library as such but rather was intended to serve as a reference collection containing such books as he considered should grace the shelves of any well-educated person's home. In the summer months early in 1928 he was appointed Postmaster and the Post Office was shifted into the Museum building where it is still located. Among other things in the years that followed, he held positions on various wheat and rural boards, as well as being secretary of the local hospital.

Mr. Bedford's interest in meteorites was heightened by the fall of Karoonda and reports of the Henbury meteorite craters. His trips to the Northern Territory and other areas are described below. This interest and the meteorite display he set up resulted in three new South Australian and two New South Wales meteorites being added to the list of known Australian recoveries. He was also responsible for the party which found the first meteorites at the Boxhole crater. Exchanges with foreign museums added specimens of nearly two hundred other meteorites to his collection.

Mr. Bedford also had palaeontological interests and during the period 1934-1939 he made several trips to the Beltana area in the Flinders Ranges, where he collected and subsequently studied, described and named many genera and species of Archaeocyatha. Because of ill-feeling generated by his incursions into the field of meteoritics he was obliged to publish the results of this palaeontological work himself and so volumes 1 to 7 of the "Memoirs of the Kyancutta Museum" were issued. These works variously co-authored with his son, William, and daughter, Joan, are still recognized as authorative references.

b. Henbury

Mr. Bedford, members of his family and friends, made several trips to the Henbury craters as described below and recovered numerous specimens. On the last trip, the party also visited Boxhole crater and investigated what was later to be called the Huckitta meteorite.

c. Cowell and Kyancutta

The history of these meteorites is complex and, in parts, defies all attempts to unravel it.

In the early 1930's, Mr. Leslie George Gardiner bought a property about 48km south east of Kyancutta and 18km north west of Caralue Siding. The property, which was traversed at intervals by NW-SE trending dune ridges, was covered with scrub. Mr. Gardiner approached his neighbour, a Mr. McDonald, for help to clear the land. Mr. McDonald offered the services of his two young sons Donald and (Robert) Jack. It was agreed that the McDonalds would clear the land and sow the first crop.

Mr. Jack McDonald told the author that early in the 1932 season, March or April, he was seeding in the south western corner of Section 44 when the drill struck something metallic. He was then about three drill widths from the western boundary fence. Thinking he had hit a hammer he stopped and picked up a small iron body a little bigger than a "pound of butter" (Figure A2.5 c). Knowing of Mr. Bedford's interest in unusual objects, he took it to Kyancutta but was told that Mr. Bedford was at Henbury. (Mr. Bedford had left for Henbury during March and returned prior to April 29 which thus fits in with Mr. McDonald's recollections.) Mr. McDonald took the specimen home and gave it to his father who later gave it to a friend to bring to Adelaide to seek information about it.

Early in June 1932, Mr. Donald McDonald while working on the same Section but across the crest of a dune some 300m away from the site described above also hit an object with a seeder. (At the time, he says, he knew nothing of the earlier find - he had apparently been at home preparing lunch when the first find was made.) Stopping in case he had damaged the seeder, he found a large mass of iron. It was so heavy (over 32kg) that he called his brother Jack to help him lift it. The interval between the two finds is explained by the method by which the clearing operations were performed. The area in one interdune corridor was cleared and seeded before work began in the next thus explaining the lapse in time between the recovery of these two fragments which were in separate interdune corridors. Some time later Mr. D. McDonald showed this mass to Mr. Gardiner who in turn subsequently showed it to the postman, Mr. Joseph Benjamin (Ben) Peters, who immediately recognized it as a meteorite and bought it for Mr. Bedford, paying a deposit of 5.

Mr. Bedford named it Kyancutta and an account of the find appeared the next morning, Saturday July 3, in the "Advertiser". The reaction in Adelaide was both vehement and unjustified. It was claimed that Mr. Bedford had "salted the

claim" with Henbury material, a story still circulated. Hodge-Smith went so far as to cast doubt on the authenticity of the find in print. He stated that he accepted the find as genuine only because Dr. L.J. Spencer of the British Museum did. Earlier when Spencer heard of the campaign of vilification he publicly defended Mr. Bedford's integrity. On Tuesday December 20, 1932 a statutory declaration as to the authenticity of the find was made before Mr. J.A. O'Loughlin, the local Justice of the Peace, and Mr. J. Emery, a bank official, by Messrs. R. and W.R. Bedford, and J.B. Peters, and a copy sent to Dr. Spencer in the British Museum.

However, none of Mr. Bedford's critics apparently knew of Mr. Jack McDonald's find. If, as they claimed, Mr. Bedford nad "planted" the Kyancutta specimen, the probability of him having put it so close to a genuine fall is too small to consider. Conversely, if he had put both pieces in the paddock, he would surely have done his best to ensure that both were discovered. In fact, Mr. Bedford died long before the true story of Jack McDonald's find was known. Even more convincing are the analytical and other results presented above in Chapter 10 which showed the dissimilarity between Henbury and Kyancutta and the similarity between Cowell and Kyancutta.

The subsequent story of Mr. Jack McDonald's meteorite is a classic example of confusion in the history of South Australia's meteorites.

On Friday March 2, 1956, an unknown man brought an iron meteorite which he wished to sell to the Geology Department of the University. A price of £15 was negotiated and an invoice detailing that the 11 pound meteorite had been found 30 miles NW of Cleve filled out. The seller received a cheque for that amount and signed the receipt in the name of R.J. McDonald. Professor Alderman was told by the man that the meteorite had been found by a Sgt. R.J. McDonald on December 12, 1955, 30 miles NW of Cleve and 11 miles NW of Darke Peak. He said that another piece weighing about 15 pounds had been found about half a mile away on an east west line in 1930 and that there was a possibility of a piece of this earlier material being in the Kyancutta Museum. As there were then considerable quantities of Henbury in circulation, no further investigations were carried out.

Unfortunately, the acquisition was not entered into the Tate Museum Catalogue until 1964 and by then the details had apparently become confused for it was stated that the meteorite had been found near Cowell and accordingly it was named Cowell. (Interestingly, in its Annual Report for 1964-1965, the S.A. Museum recorded the Cowell meteorites among their acquisitions for the year.)

The first study of this meteorite was undertaken in 1969 by Mr. B.L. Schmidt as part of an Honours thesis in this Department. He quoted the site of the find relative to Darke Peak, as given to Professor Alderman, and stated that the meteorite had been purchased in 1955 instead of 1956. He suggested that as the finding site was only some 13km west of Caralue Siding it would be appropriate if the meteorite were to be renamed Caralue. (The real site is about 17.7km N 70° W of Caralue.)

When this work was started only the scant details as recorded by Schmidt were available and so an attempt was made to clarify the situation. An appeal for information concerning Sgt. R.J. McDonald was placed in newspapers circulating on Eyre Peninsula. These elicited information from Mrs. Joan Luscombe, the daughter of Mr. Bedford, recounting that a Mr. D.H. McDonald of Caralue Siding had found the Kyancutta meteorite but that she knew nothing of a Sgt. R.J. McDonald who had found one. Up until that time Mr. Gardiner had been recorded as the finder of Kyancutta so the author travelled to Eyre Peninsula on the weekend of June 3-5, 1972, to attempt to unravel the confusion.

Mr. Don McDonald recounted the story of his find but stated that he knew nothing of another meteorite. He said he had a brother, Mr. Jack McDonald, who had lived in Adelaide for many years. When interviewed in Adelaide the following Saturday morning, Mr. Jack McDonald related the story detailed above while a subsequent letter from Mr. Gardiner confirmed the fact that he had not actually found the meteorite. Mr. Jack McDonald said that it was not he who sold the meteorite to the University but a family friend and, furthermore, he had never received the 15. This helps to explain the lack of detail in the account given to Professor Alderman, but at the same time the friend obviously knew many of the details since he commented on the other find. (Mr. McDonald was a sergeant in the Royal Australian Army Medical Corps at the time of the sale which explains the rank quoted to Professor Alderman. When the author began this work he assumed it was a police rank and spent some fruitless hour searching police records.)

On the basis of the finding site of

Cowell, in the Hundred of Caralue some 15km S 70° W of Caralue Bluff, a submission was made by the author to the International Committee on the Naming of Meteorites bringing the facts to their notice and suggesting that they adopt the recommendation of Schmidt and rename the meteorite Caralue. They refused this request on the grounds that the name Cowell had already appeared in print. On the basis of historical, chemical and mineralogical evidence presented in this work, it would seem more appropriate if neither name was to be used but rather the meteorite simply be recorded as part of Kyancutta.

d. Lake Labyrinth

The fall of the Lake Labyrinth meteorite and its subsequent find and recovery, the latter by Messrs. R. Bedford and J.B. Peters, will be described below in Section A2.6.2.

e. Kappakoola

While inspecting his crops in September 1929, Mr. Frederick W. Daniel, who lived 13km south of Kyancutta, picked up a rock from the top of a sand dune to throw at some parrots which were in the crop. On doing so he noticed that it was black and shiny and as this was unusual took the rock home. He put it in a shed where it lay for some time until it was finally lost. Subsequently Mr. Daniel described it to Mr. Bedford, who thought it might be a meteorite. On returning home Mr. Daniel searched in vain for it. Some years later the shed was burnt down and the meteorite was found lying among some wet hay while the debris was being removed after the fire. By then it was brown and cracked. Mr. Daniel used it as a paper weight until October 1935 when he took it to Kyancutta and gave it to Mr. Bedford.

Mr. Bedford sent the stone to the British Museum where it was cast and cut. He suggested the it be called the "Kyancutta Stone" but as this name would have caused confusion Spencer named it Kappakoola as it had been found in the Hundred of that name. The British Museum retained about 10% of the stone and the remainder was returned to Kyancutta along with a cast. The present whereabouts of the stone is unknown.

f. Boxhole

As described below, a Kyancutta party visited this locality in 1937 and its members were the first persons interested in meteorites to discover meteoritic material there.

A2.5.3 Cocunda

Mr. Brian Polomka bought an uncleared property south of Chandada, which is north west of Kyancutta, in 1945. While clearing the property he employed Miss Alice Mitton, a neighbour's daughter, to follow at a distance behind the tractor lest he was hit by flying debris. While doing so, she often used to pick up unusual rocks. One such rock was this meteorite, and as it differed conspicuously from the regional kunkar she took it home.

Mr. Polomka brought the meteorite to Adelaide in 1946 and gave it to the S.A. Museum, where he, rather than Miss. Mitton, was recorded as the finder. The meteorite was named Cocunda as it had been found about 1.5km west of Cocunda Rockhole.

A2.5.4 Kielpa

In 1948, Mr. Andreas Benjamin Brooks of Kielpa, who was holidaying in Adelaide attended a lecture given by Mr. A.F. Wilson of this Department (Cf. Wilson 1947). On his return to Kielpa, Mr. Brooks sent a meteorite, which he had found several years previously, to Mr. Wilson. The meteorite was delivered to the University by Messrs. French and Moore of the Government Department of Agriculture. Mr. Wilson wrote to Mr. Brooks on Saturday November 27, 1948, acknowledging receipt of the meteorite and suggested that it be named Kielpa as it had been found near that town. He requested that Mr. Brooks send him further details as to the exact location of the find and he also asked whether any other specimens had been recovered. Mr. Brooks replied on Monday December 6, giving the site of find and stating that he had recovered only one piece. The recovery site is 16km west of Kielpa. Sir Douglas Mawson subsequently wrote to Mr. Brooks thanking him for the meteorite which had been donated to the University.

Mr. W.A. (Allan) Brooks, the brother of the late Mr. A.B. Brooks, told the author in 1978 that the meteorite was seen in a paddock by a few people and after they had discussed its unusual appearance Mr. Brooks returned to the paddock and picked it up. Mr. W.A. Brooks is fairly certain that this did not occur while the land was being cleared but rather in a subequent planting season. It is possible though that the meteorite was dragged from the ground during the final preparation prior to planting the first crop. When interviewed by the author in June 1972, Mr. A.B. Brooks' recollection of the date of the find was vague; he

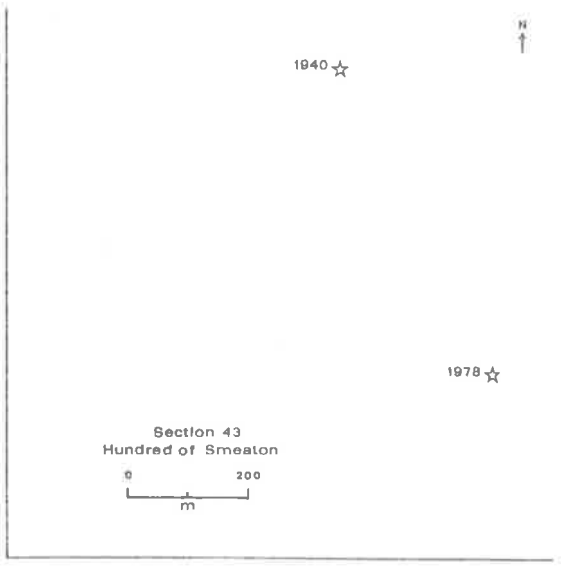
recalled that it was March or April very early in the war years and probably prior to 1942. He was certain, however, that the find coincided with a visit from Mr. Reg French, of the Department of Agriculture. When contacted, Mr. French recalled writing a report on Mr. Brooks' property in support of an application to clear part of it. He had no record of the date but thought it may have been 1940. Mr. French recalled that when he arrived at Kielpa he found that part of the land had already been cleared, probably some months before. This probably explains how the meteorite was found during Mr. French's visit if it was recovered from this earlier cleared land.

On Tuesday January 3, 1978, Messrs. Geoffrey Alan and Joseph Raymond Elleway, grandnephews of Mr. A.B. Brooks, sighted what looked like a rusted plough share some 450m away from the reputed site of the meteorite find. On stopping their vehicle to retrieve the object, they found it was a meteorite fragment similar to the earlier find. Mr. W.A. Brooks contacted the author on Thursday April 27 to inform him of the find. On Wednesday May 3, 1978, the author drove to Cleve and on the following day took possession of the 2.09kg fragment, the finders having agreed to donate the central portion of it to the University provided the end pieces were returned.

At the same time the finding site was inspected. The fragment had been recovered from the crest of a small rise in a paddock. As the soil profile consists of 10 to 15cm of quartzose sand overlying a clay-rich horizon, the fragment could not have been buried very far below the surface as the clay layer is not disturbed by cultivation techniques. The positions of both this site and that of the original find were measured relative to the paddock boundaries. It was then found that Mr. A.B. Brooks' original estimates of distance (40 and 60 chains from the western and southern fences) were somewhat in error. The new measurements were based on the location of the point which Mr. Brooks had several times pointed out as the finding site. Figure A2.6 shows the positions as accurately as could be determined. The first piece was found 550m from the western fence and 800m from the southern one, while the new find was 800 and 300m respectively from these fences.

When an attempt was made to match the new fragment to the original, a perfect fit with the base was found. The fit even extended to the matching of the edges of a scar, probably produced on impact, in the fusion crust (Figure A2.5 d). The new fragment is

Figure A2.6 : Location of the Kielpa recoveries.



far more weathered having sand grains cemented to the surface with limonite. The match of the fusion crust break suggests that the two pieces did not separate until after impact and so no conclusions can be drawn concerning the direction of the line of flight. The vegetation density prior to clearing would probably have precluded the fragments from having bounced a great distance while the finders of the new piece doubted whether normal farm equipment would have produced the separation either. It is likely that the separation was brought about during the scrub clearance when large masses of tree roots and other material were dragged around the paddock. Both pieces were probably buried during this operation.

The relative degrees of weathering of the two masses suggests that the first one had not been buried for a long time prior to its discovery but precision is not possible.

A2.5.5 Kaldoonera Hill

In June or July 1956, Dr. Brian Daily, then Curator of Minerals in the S.A. Museum, visited Eyre Peninsula to inspect a depression which had been reported as a meteorite crater but which was actually a mallee fowl's nest. The journey was not in vain, since after talking to some of the residents about the reasons for his trip, he was approached by Mr. E. Lance Beck of Poochera. He gave Dr. Daily two pieces of meteorite which had been found some years previously by Mr. E.G. Voumard on his property 9km S of Kaldoonera Hill and a few kilometres north of Poochera. Mr. Voumard had given this material to Mr. Beck because of the latter's interest in rocks and minerals. The larger piece was used as a doorstop for several years. During the

following decade or so several more pieces were discovered both by Mr. Voumard and Mr. Noel E. Gosling, the subsequent owner of the property. Some of these pieces were given to Mr. Beck and others distributed to various people.

In 1972, after attending a summer school conducted by Dr. D.W. Corbett of the University Department of Adult Education, Mr. Beck returned home and searched his shed for the pieces given to him after Dr. Daily's visit. He found two, the smaller one being covered to a great extent with pink paint. He gave the larger one to Dr. Corbett and the smaller to Mrs. Luscombe of Kyancutta. Mrs. Luscombe brought this piece to the University where the author cut it in two. One half was retained in the University and the other returned to Mrs. Luscombe in June 1972, along with a piece of Cowell, in exchange for the other half and a fragment of Kyancutta.

Early accounts (e.g. Corbett 1968) suggested, that on the basis of noises heard while ploughing, more fragments might be present in the paddock where the other material had been found. Extensive searching by the author and others on Sunday June 4, 1972, located only numerous kunkar fragments in the paddock. Enquiry revealed that the various meteorite fragments had been picked up along an east-west line over a distance of approximately one kilometre.

The Annual Report of the S.A. Museum Board for 1955-1956 suggested that the meteorite may have fallen in 1916. It was named Kaldoonera Hill because of the proximity of the discovery site to that hill.

A2.6 NULLARBOR PLAIN METEORITES

To date only two meteorites are documented as found on the South Australian section of the Nullarbor Plain. The distinct contrast with the large number found west of the border probably reflects the number of searchers.

A2.6.1 Naretha

The Kingoonya meteorite was recorded as a South Australian meteorite for some fifty years. Mr. G.W. Card, Curator of the N.S.W. Geological Survey Mining and Geological Museum in Sydney, mentioned this meteorite in letters to the British Museum on March 17 and 31, 1927. While visiting Mr. Spencer F.C. Cook, the manager of the Palace Hotel in Kalgoorlie and a keen mineral collector, he had seen three pieces of meteorite in Mr. Cook's rock and mineral collection. The material had reputedly been found near the Transcontinental Railway Line east of Kingoonya, been broken into three and given to Mr. Cook. A small piece (ca. 26g) was taken to Sydney by Mr. Cook, along with a photo of the re-assembled meteorite. The bulk of the meteorite was then apparently lost as only 87g remained in the Cook Collection when it was acquired by the S.A. Museum in 1946.

Acute "detective" work by Mr. William H. Cleverly, of the Kalgoorlie School of Mines, showed that much of this material had not been lost but rather was known under the name Naretha. (The full account of this work, mentioned by Cleverly (1976), makes intriguing reading and shows how one misunderstanding resulted in the recording of two finds.) As the meteorite was known under the name of Naretha first, Kingoonya is now recorded as a synonym. The data recorded in Chapter 14 for Naretha was determined on material labelled Kingoonya and so recorded in the cited references. Since the meteorite had been found near Naretha, a railway station in Western Australia, Kingoonya must be completely removed from the list of South Austaralian finds.

A2.6.2 Lake Labyrinth

In 1934 Mr. Bedford heard of a meteorite found on the Nullarbor Plain by an aboriginal. He and Mr. J.B. Peters, his assistant postman, set out by truck for the area late in October to find the aboriginal. This they did and according to him, Mr. Billy Austin, the meteorite had fallen to the accompaniment of a rumbling noise and lights about ten years before, possibly on the night of Tuesday February 5, 1924. About a fortnight later he had found the meteorite a small distance from a hole surrounded by freshly scattered soil and scorched bushes. One piece of the meteorite was lying between the main body and the hole and he also noticed that the meteorite was beginning to break up.

On Sunday November 11, Mr. Austin took Messrs. Bedford and Peters to the site of the fall with unerring accuracy. On their arrival, they found a saucer-shaped depression about 4m in diameter largely filled with blown sand which they dug out. This showed the hole had originally been somewhat over a metre deep. By then the meteorite was even more extensively weathered. They recovered about 26kg of fragments the largest single ones having masses of 8.4 and 4.3kg. There were 11 fragments with masses greater than 200g and approximately 70 smaller ones. Mr. Bedford estimated the original weight to have been

of the order of 34kg. Mr. Austin had previously given a piece to Mr. McBride, the owner of Wilgena Station, on which the meteorite had been found, and it was believed that other pieces might have been removed. This later prompted Mr. Bedford to suggest that "Kingoonya" as it was then known (A2.6.1 above) might have been a transported piece as the superficial description of both was similar and they had supposedly been found only 80km apart. Subsequent mineralogical, and now historical, evidence shows that they are separate.

As the meteorite was found about 32km north of Lake Labyrinth, it was given this name by Dr. Spencer, at Mr. Bedford's request, when he sent 15 specimens of it to the British Museum on Tuesday November 20, 1934.

A2.6.3 Forrest Lakes

This meteorite was found in 1948 by Mr. T. Dimer. Since that time the meteorite has had a "checkered career". It was originally called Loongana and was described as having been found in Western Australia. McCall and De Laeter (1965) stated that subsequent information from Mr. Dimer placed the find just to the east of the South Australian border and so it "became" a South Australian find. They further stated that the name Loongana was inappropriate as it was already in use and the meteorite was renamed Forrest Lakes as it had been found near a group of lakes of that name. More recent information (Binns 1974 pers. comm.) places the find back on the western side of the border and further to the south and so this meteorite must be removed from the South Australian list and returned to the Western Australian one.

A2.6.4 Muckera

With the possible exception of Binda, which recent work suggests is a eucrite, this is the first howardite to be found in Australia.

In 1951, police constable Cornelius P. Doyle was stationed in the tiny town of Cook on the Trans Australian Railway Line. On his days off, he often drove 70 or so kilometres to the northern edge of the Nullarbor Plain to an area near some small rock holes known as Muckera Rock Hole. On either Tuesday or Wednesday May 1 or 2, while walking around about 3km south west of these holes, he kicked a rock which felt different from the country rock and so he picked it up. He then noticed that it was covered with a crust and was much heavier than the normal kunkar. His attempt to remove some of the crust to identify the rock was unsucessful and he took it back to Cook. Ultimately he brought it to Adelaide and gave it to his fiancee, a Geology student at the University. She showed it to Dr. P.S. Hossfeld who thought it might be a meteorite.

The specimen was returned to Mr. Doyle who kept it until the author placed an article in the "Advertiser" of Saturday February 26, 1972, seeking information about a possible meteorite fall near Adelaide some days previously. Mr. Doyle rang the University on Monday saying that while he knew nothing of the meteor which had been seen the previous week he did have what he thought was a meteorite which he was prepared to bring to the University. This he did the next day and its meteoritic nature was confirmed by Dr. J.B. Jones. It was subsequently identified as a howardite and given the name Muckera. (This name is sufficiently different from Mukerop, a synonym for Gibeon, to avoid confusion.) Mr. Doyle generously donated the meteorite to the University.

A2.7 FAR NORTHERN AND NORTH WESTERN METEORITES

A2.7.1 Witchelina

This meteorite was found by Mr. Thomas Phillip Gourlay during the early years of the century in sandhill country on Witchelina Station south of the Witchelina homestead. Witchelina Station, lying between Lakes Eyre and Torrens is about 40km south of Maree and 23km SNW of Farina. Mr. Phillip R. Gourlay, the finder's grandson, donated the meteorite to the University in December 1966.

A2.7.2 Moorumbunna

This large iron meteorite was covered with soil with only a small portion protruding when found by an aboriginal in 1943. It was near a dam in the Horse Paddock on Anna Creek Station (reputedly the world's largest sheep station) which is at William Creek, about 65km west of Lake Eyre. The dam was near a track joining the Head Station to the William Creek railway station. As this paddock was adjacent to the Moorumbunna Paddock, the meteorite was named Moorumbunna. Mr. G.K.G. Warren of Springfield, Mount Crawford, presented the meteorite to the University on behalf of his brother, the owner of Anna Creek Station.

A2.7.3 Wingellina

This meteorite was found in 1956 by Mr. J.E. Johnson while searching for australites. Mr. Johnson was then the

resident geologist with the South Western Mining Company which was involved in a nickel search programme in the area. The meteorite was found on stony ground about a kilometre north of the mining camp at Wingellina which is some 6.5km SW of the intersection of the borders of South Australia, Western Australia and the Northern Territory. Wingellina is the native name for the yellow nickeliferous laterite beds which were being surveyed.

Mr. Johnson presented the meteorite to the S.A. Museum in 1959.

A2.7.4 Wilbia

Wilbia also was found by Mr. J.E. Johnson, but nearly a decade later in May 1965. At the time, he was a member of a S.A. Geological Survey mapping party working in the area. The group was driving across a sand dune at the end of Wilbia Hill in the Musgrave Ranges when Mr. Johnson saw and recognized the meteorite. The vehicle was stopped and he recovered the meteorite which weighed 94g. The site, which is about 32km SSW of St. Morris, is about 170km E 10° S of the Wingellina find. Mr. Johnson subsequently presented the meteorite to the S.A. Museum.

A2.7.5 Motpena

This meteorite also was found during an australite search. While searching on Motpena Station, west of Parachilna, Messrs. Norman Bartlett and Bruce Jahn found the meteorite during the weekend of August 10-11, 1968. It was seen from the back of a truck by Mr. Bartlett. It was lying in a 2cm deep depression on a clay pan but there was no sign of an impact crater. The meteorite of approximate mass 5kg was polygonal in shape and was almost completely crusted. The site of the find is on the Hundred line north west of the Motpena Homestead-Parachilna road.

An account of the find appeared in the "Advertiser" on Tuesday August 13, where it was called Parachilna. Later, further information concerning the meteorite was published under the name Motpena and as this name was the first to be used in scientific literature it has precedence over the original name even though it too has been used in scientific journals. Unfortunately, the name is then not is accord with the recommendations of Buchwald and Wasson concerning the use of homestead names.

The meteorite was purchased from the finders by the Australian National University.

A2.7.6 Kittakittaooloo

This meteorite, too, was found by a South Australian Mines Department geologist - Mr. Anthony Fyfe Williams. In August 1970, the Mines Department party was driving across the Tirari Desert when Mr. Williams saw the meteorite. He stopped his vehicle and retrieved the specimen, having recognized it as a meteorite. It was found about 750m north west of the north western tip of Lake Kittakittaooloo, a playa or salt lake, which is just south of the Warburton River and east of Lake Eyre.

The meteorite, which is a well oriented stone, not unlike a "lunar nose cone" in shape, was given to the S.A. Museum in 1970. Because of the museum staff's unwillingness to cut this meteorite, a chemical analysis is not available, and accordingly, it cannot be fully compared to Poonarunna (next section) which was found in the same general area.

A2.7.7 Poonarunna

Mr. James Dunn found this meteorite on the eastern side of a sand dune while returning from a cattle inspection in mid-1970. The dune, located on his property Kalamurina, is one of a series of north-south trending ones on the southern margin of the Simpson Desert. As Mr. Dunn was on horseback and the meteorite was too heavy to carry, he removed three small pieces and left the remainder. A subsequent search by Mr. A.F. Williams failed to locate the meteorite.

The discovery site is about 2km from the Warburton River and 15 from the Poonarunna No.1 oil well sunk by Total. The aboriginal name Poonarunna was previously used for a camp, now in ruins, that was used by a group of horse-thieves who plied their "trade" in the area. The site is about 43km north west of the Kittakittaooloo site.

A2.7.8 Brachina

Mr. Brian Martyn Eves, a Senior Inspector in the National Parks and Wildlife Service, was temporarily cut off by floodwaters in Brachina Creek in the Flinders Ranges on the morning of Wednesday May 26, 1974. At about 7:30am, while wandering near the creek, he saw what he though was an australite. When he picked the object up he realized it was not one, and, because of its strange appearance, brought it back to Adelaide. Here it was identified as an olivine achondrite by Mr. J.E. Johnson, who, at the time, held an honorary position in the S.A. Museum. The Museum authorities decided that it had to be sent to America for this

identification to be checked. Dr. B. Mason, of the Smithsonian concurred with Mr. Johnson's identification.

Brachina resembles the Chassigny olivine achondrite in several ways and for this reason it has been classified by Johnson et al (1977) as a chassignite. As pointed out in Section 6.5.1 such a classification is probably inappropriate.

The finding site is about 25km N 150° S from the region in which Motpena and Nilpena (below) were recovered. The meteorite was donated to the S.A. Museum by Mr. Eves.

A2.7.9 Nilpena

This meteorite was found about 11:00am on Wednesday June 4, 1975, by Mr. D.H. McColl, who was searching a region of NW-SE trending sand dunes and interdune corridors north west of Parachilna for australites and meteorite fragments. The meteorite was found partly buried in the sand in a blown depression. The site is about 4km NE of the location of the Motpena find. Until a detailed analysis of the meteorite is carried out, the possibility that the specimen is a fragment of the Motpena shower exists, but in case it is not, the name Nilpena has been reserved for it. This name was chosen by Mr. McColl as the meteorite was found in the north west corner of the Hundred of Nilpena in County Taunton.

The specimen was donated to the Bureau of Mineral Resources by Mr. McColl.

A2.8 NORTHERN TERRITORY METEORITES

The meteorites which have been recovered in the Northern Territory fall into two distinct groups - those found within 250km of Alice Springs and others near the northern coast.

A2.8.1 Bond Springs

The meteorite was found lying on the surface of the ground near the Overland Telegraph Line about 4.8km west of Bond Springs Station and 16km west of Mount Sir Charles.

The date of the find is uncertain. It was given to Mr. F.H. McK.Grant in August 1898 and when he donated it to the University of Melbourne Geology Department in June 1931, he stated that it had been found while Oodnadatta was a railway terminus. Since the line to Oodnadatta was not opened until 1891 this means that it was found during the period 1891 to 1898.

A2.8.2 Arltunga

When found about 3.2km south of the Government cyanide works at Arltunga by Mr. Dan Pedler, this meteorite was almost completely buried in the soil with only a small corner protruding. It had apparently cut its way obliquely into the ground to a depth of about 150cm, cutting a long groove as it did so. On the basis of the fresh nature of this groove, the finder suggested that the fall was of recent origin. The meteorite was found in September 1908 suggesting that it fell in 1907 or 1908. On the basis of the extent of weathering, however, Buchwald (1975b) suggested this was highly unlikely.

The meteorite was sold to the S.A. Museum on Thursday November 26, 1908, by Mr. J. Woodford for 30. Due possibly to a misunderstanding of the finding site, Prior (1923) originally recorded this meteorite as part of the Cranbourne (Victoria) fall.

A2.8.3 Yenberrie

Mr. John Hoare found this meteorite on Tuesday July 30, 1918, about 32km S.S.E. of Yenberrie. It was in two pieces which fitted together, both of which had been buried in the sandy soil. When found the meteorite weighed about 132 kg.

Part or all of the meteorite was sent to Sydney where a mass of about 12.7kg was acquired by a Mr. Watkin-Brown, who sent it to the United States National Museum, where it was divided into three masses of 4.5, 3.76 and 3.32kg. These masses were given to the Museums of Chicago, New York and Washington respectively. Another piece weighing 42.3kg was acquired by the Australian Museum and a further one of 33kg was placed in the official Commonwealth collection, which at that time, was housed in the Australian Museum. (The Northern Territory was not a State of Australia at that time but a Commonwealth territory hence the specimen was placed in the Commonwealth collection.) A further 500g of the meteorite was acquired by the Smithsonian some time after 1966.

The Australian Museum still holds a mass of 42.29kg while there is one of 29.33kg (weighed by the author) in the B.M.R. in Canberra. The British Museum also holds a 600g specimen which it acquired in 1963 and another mass of ca. 100g is in the N.S.W. Geological Survey Geology and Mining Museum in Sydney.

It is quite likely that the B.M.R. specimen is the remainder of the 33kg mass which was placed in the Commonwealth collection as the latter was shifted to Canberra when the B.M.R. was established, in which case the extra Washington specimen as well as the ones in the British Museum and

the Sydney Geology and Mining Museum may, have been cut from it. If this is so, then approximately 3kg of the mass is unaccounted for. Over and above this, the present location of the remaining 44kg of the original mass is unknown. It may of course, have remained in the Northern Territory when the meteorite was first found.

If the B.M.R. specimen is not the one originally placed in the Commonwealth collection, then its present location plus that of about 14kg of the original material is unknown.

A2.8.4 Roper River

Little is known of the history of this meteorite. It was found by an aboriginal in 1921 about 80km from Urapunga on the Roper River. It was acquired by the National Museum of Victoria. This meteorite is different from the other Northern Territory irons.

A2.8.5 Alikatnima

This meteorite was found about 72km N.N.E. of Alice Springs in 1931. It was purchased in January 1931 by the S.A. Museum for£ 3/10/0 from Mr. F.S. Jones of Highgate who had apparently obtained it from Mr. B. Webb of Alice Springs. It is not recorded whether Mr. Webb was the finder. The Museum purchased two masses of total weight 15.9kg at a rate of 2/0 per pound. A third specimen was retained in Alice Springs.

A2.8.6 Henbury

As a result of the fall and subsequent recovery of Karoonda, the University of Adelaide and the S.A. Museum received many letters and other communications concerning the location of other meteorites.

The most outstanding reports were those of supposed meteorite craters and meteoritic iron on Henbury Cattle Station, about 120km south west of Alice Springs. The information was supplied by, among other people, Mr. B. Bowman, the manager of nearby Tempe Downs Station, and Mr. James Max Mitchell, a prospector of Oodnadatta.

As a result of this information, the S.A. Museum commissioned Mr. (later Professor) Arthur Richard Alderman of this Department and Mr. (later Doctor) Frank Lovelock Winzor of the Chemistry Department of the University to visit the area and investigate the claims.

a. Professor Alderman's expedition

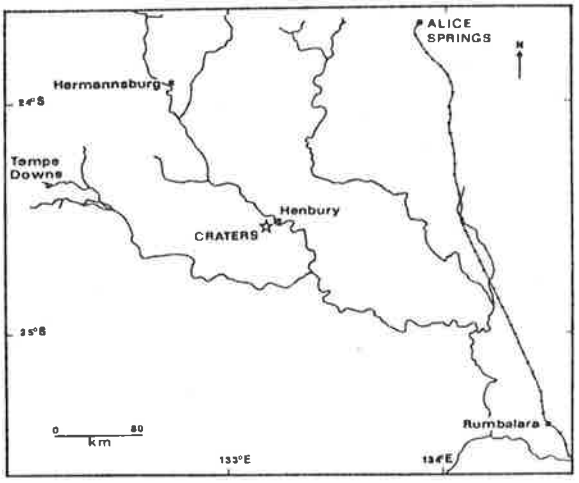
Messrs. Alderman and Winzor set out for Henbury in May 1931, travelling by rail to Rumbalara railway station and then by truck for the last 270 or so kilometres. The last part of the journey involved crossing the Finke River in four different places (Figure A2.7). They arrived at night and so saw neither the number nor the size of the craters until the next morning. When day dawned they saw thirteen craters, the largest of which was 200m in diameter and some 18m deep.

Several days were spent in the area collecting over eight hundred pieces of meteoritic iron of total weight 227kg, individual masses ranging from a few grams to 24kg. They also spent a considerable time documenting the craters. Mr. Alderman named the largest crater "The Main Crater". This crater, which had apparently been formed by the overlapping of two smaller craters, was known locally as "The Double Punchbowl". He named another crater "The Water Crater" because of the water which was in it. The other eleven craters he simply designated by numbers. The party apparently pegged part of the area under Miner's Right Number 881.

The craters are located at the northern foot of the Bacon Range where they occur in the Precambrian sandstones, shales and siltstones of the Winnall Beds. Outside the craters, most of the plain is covered with wind polished gibbers which are brown and not readily distinguished from meteorite fragments. Mr. Alderman noted the presence of a fused, glassy substance at various localities as well as sandstone "dykes" radiating from one of the craters. He commented on the resemblance of these to lunar features. (Cook (1968) claims that this is the only terrestrial example of such a ray structure.)

Because of the flooded condition of the Finke the party returned to Rumbalara by camel to meet the train a fortnight after their arrival.

Figure A2.7 : Map of the Henbury area (after Alderman 1933).



Mr. Alderman described this expedition and exhibited some of the material at a meeting of The Royal Society of South Australia on the evening of Thursday July, 9, 1931. An account of this appeared in the "Advertiser" on July 10 and in the "Chronicle" a few days later.

Virtually all of the material collected became the property of the S.A. Museum, only a minute fraction coming to the University. The S.A. Museum subsequently disposed of about 90% of the material and by the end of 1933 over 670 pieces had been sent to the Rochester University alone. This alleged destination is of interest, as Nininger (1972) pointed out that, even by 1930, the Rochester University meteorite collection had fallen into disarray and accordingly had been broken up and purchased, mainly by Ward's Natural Science Establishment, which was located in the same city. Because of this, Nininger had purchased many specimens from the Rochester collection for a nominal sum. It would thus appear that the S.A. Museum material was also sent to Ward's but in an indirect way. (A letter of Dr. L.J. Spencer of the British Museum, to Mr. R. Bedford, on Thursday July 19, 1933, stating that Ward's were offering 674 complete specimens of Henbury iron in their latest catalogue also confirms this. Dr. Spencer also commented that J.R. Gregory, of London, had several specimens for sale.) This point is of significance when attempting to estimate, from Museum holdings, the total amount of material recovered from the site and will be developed further below.

b. Mr. Bedford's expeditions

Mr. R. Bedford, of the Kyancutta Museum, visited the area three times and also organized another trip to the locality. During these visits the parties recovered material from the vicinity of the craters and also purchased specimens from Mr. P. William (Bert) Branson, the foreman in charge of Henbury Station.

Soon after the newspaper account of Mr. Alderman's expedition was published (July 10), Mr. Bedford set out for Henbury accompanied by his son William Rudolf and Mr. Gibert (Bert) James Duggin. They were not very hopeful of recovering much material, as they assumed that the area would have been visited by other parties from larger Australian Museums and also prospectors, before they arrived. However, when they finally arrived at the site, having travelled some 2,400km by truck along the then little used track, now the main road, via Kingoonya and Coober Pedy, they found that no one other than the S.A. Museum party had been there. They pegged areas not covered by the Museum's claim under Miner's Rights Numbers 969 and 970 in the name of W. Bedford, on Monday August 3, 1931. They searched the area thoroughly and a list among papers belonging to the late Mr. Bedford shows that they collected 626 specimens of reputed total weight 169.04kg. The largest of these was recorded as weighing 78.5kg. According to a letter of Mr. Bedford to Dr. Spencer on Thursday January 19, 1933, this mass, when found, was almost completely buried with only a corner showing. It was found near the junction of two creeks just before their entry into the Water Crater. (The site is marked with a cross in Figure A2.8.) They also collected samples of weathered iron shale and fused country rock. Before leaving, Mr. Bedford, arranged for Mr. Branson to continue the search and recover any material he found.

On his return to Kyancutta Mr. Bedford wrote to the Director of the British Museum on Wednesday August 26, 1931, briefly describing his and the S.A. Museum's excursions and forwarded 8.1kg of iron shale in four boxes. He went on to say that he would soon be sending a considerable quantity of meteoritic iron. He proposed that as he was sending all of this material in two duplicate sets the British Museum could choose to retain one or both sets of each lot of material and if they elected to only retain half of it he would offer the other half to an American museum. He placed an initial value of 1000 on the whole collection but said that he was prepared to accept part of this in exchange material. He wrote again on Thursday September 5, saying he had now packed up the meteoritic material and was sending it also. As the weight was less than he had originally estimated, he was reducing his valuation to 800. The consignment consisted of 540 specimens reputedly of mass 146.7kg divided into two groups of similar total weight plus the large mass described above. When weighed in London it was found that this specimen had a mass of only 77.3kg thus making a total of 145.6kg. Of this, the 16 largest weighed 112kg and so the remaining ones had an average mass of some 70g, the smallest actually weighing 3.4g. Thus 86 specimens with a combined mass of about 22.2kg were retained in Kyancutta and as the largest had a mass of 13.69kg the remaining 85 were quite small. Dr. L.J. Spencer, the Keeper of Minerals in the British Museum, replied to Mr. Bedford's letters and acknowledged receipt of five boxes of material on Sunday

October 18, and again on Tüesday November 17 saying that the three large boxes of meteorites had arrived. He stated that these last three were lying unopened awaiting instructions from the Commonwealth Government of Australia. Unbeknown to Mr. Bedford, several problems had arisen.

Possibly as the result of a request from the S.A. Museum, the Minister for Home Affairs, Mr. Arthur Blakely, was asked in Federal Parliament, on Thursday July 16, whether a request to declare the Henbury site a reserve had been received. He replied in the negative. The Deputy Administrator of the Northern Territory, Mr. Carrington, visited the site the day before Mr. Bedford arrived and again towards the end of August when he declared the site a reserve, but on what authority is unknown. He subsequently forbade Mr. Branson to remove material from the area.

Prior to this second visit, Mr. Branson and a party of twenty aborigines spent over a week searching the area and when Mr. Branson wrote to Mr. Bedford on Monday August 31, 1931, he claimed to have recovered 2000 pounds of material. (In a letter of Saturday July 1, 1933, however, he was to claim that this material was recovered during December 1930 and March 1931.) He also told Mr. Bedford of the second visit of the Deputy Administrator but said that nothing had been said of Mr. Bedford's visit.

Mr. Bedford came to Adelaide and informed the S.A. Museum of his activities in the area and subsequently attended a meeting with Sir Douglas Mawson and the Museum Board Secretary, Mr. Hately W. Marshall, on Wednesday September 16. It was agreed at this meeting that Mr. Bedford would submit a proposal to the Museum Board according to which the Museum would handle the distribution of all further Henbury material and that any profit so made would be distributed in the ratio 4:3:1, to Mr. Branson, the S.A. Museum and the Kyancutta Museum. To this end, Mr. Branson would send all of the material which he had collected to the S.A. Museum. It was also stated that this arrangement would not, however, apply to material which Mr. Bedford had already sent to the British Museum. At Sir Douglas' request, Mr. Bedford also wrote a letter to Mr. Branson outlining this proposed agreement.

At a specially convened meeting of the Museum Board on Monday September 21, 1931, the Board rejected this offer and decided to inform the British Museum that Mr. Bedford had recovered the material illegally as, according to Marshall, Mr. Bedford had not registered his mineral claim, and that furthermore, they claimed ownership of the material. Marshall wrote to the Minister for Home Affairs on Tuesday September 22, stating that they were taking steps to acquire the material collected by Mr. Bedford. Sir Douglas Mawson also wrote a letter of protest to the British Museum. The S.A. Treasurer cabled the British Museum on Wednesday September 23 stating that the ownership of the material was in dispute and that they ought to act accordingly, while on Friday September 25, the Minister for Home Affairs stated in Federal Parliament that the area had been declared a reserve and furthermore that he would take steps to circumvent the robbery which had occured. (It is not known whether the Minister was referring to the declaration made by the Deputy Administrator or to someone else, nor is it known on what authority the declaration was made. Since Mr. Bedford, like the S.A. Museum party, had collected his material from an area pegged as a mineral claim, his actions can no more be described as an act of "robbery" than theirs.)

On Wednesday December 2, Dr. Spencer wrote to Mr. Bedford saying that the three boxes of meteorites had now been opened in the presence of Professor Kerr Grant and Dr. Fenner and that the material would be placed on display in the British Museum as a loan from the Kyancutta Museum.

Mr. Branson initially agreed to the proposed arrangement with the S.A. Museum until he heard of the embargo that had been placed on the material in the British Museum when he felt he was no longer bound by this "agreement". On Saturday November 28, he sent 44.7kg of the material which he had collected to Mr. Bedford and a further 47.2kg on Saturday February 13, 1932. Some of the latter material had been purchased from other people who had also pegged claims in the area. A further 109.3kg which were dispatched on Wednesday March 9, reached Kyancutta in April. The largest mass in this consignment was one of 49.9kg. (Some of the parcels had been sent directly to Kyancutta and others to Mr. Bedford's shipping agents in Port Adelaide.)

Mr. Bedford always maintained that at least some of the Henbury material retained its outer heating zone and on Sunday January 11, 1932, he wrote to Dr. Spencer saying that he was sending him a mass of about 4 pounds which would illustrate the point.

On Thursday February 11, 1932, Mr. Bedford sent a consignment of material to the

American Museum in New York probably consisting of 37kg of meteoritic material with the largest of the 25 specimens having a mass of about 6kg. In addition, he also sent 13 specimens of iron-shale and fused glass. (Sometime after 1935 a 40kg mass was also acquired by this museum but it could not be ascertained whether this sample came directly from Mr. Bedford or from another source.)

Mr. Parkhill, the Minister for Home Affairs, wrote to Senator McLachlan, the Vice-President of the Executive Council, on Tuesday February 9, stating that current laws did not enable a reserve to be created at Henbury. A copy of this letter was sent to Mr. Bedford.

On Wednesday March 16, 1932, the Department of Home Affairs sent Miner's Right Number 57, in the name of W.R. Bedford, to Kyancutta. Mr. Bedford, his son and Mr. Ben Peters departed for Henbury on, or after, Wednesday March 23, 1932 and purchased a further 153.8kg of material from Mr. Branson on Tuesday March 29, 1932. (Mr. Branson was not actually present during this visit and the receipt was signed on his behalf by Mr. Howard Wilkinson.) The largest specimen was one of 39.5kg mass. The main aim of this excursion was not to carry out this purchase but rather to search for large meteorites which might have been buried in the craters. To this end, they dug in the floor of four of the craters - Numbers 10,11 and 13 of Alderman's list plus another not identified by him. About 2.1m below the base of Crater No.13 they found a group of four irons of total mass 200kg (132.3, 54.4, 10.9 and 2.3kg respectively) embedded in some 20kg of flaky iron shale. This latter material and the four masses had apparently been produced by the alteration of a single mass. Partial excavations in the other craters did not yield any significant results. On Sunday April 3, Mr. W.R. Bedford repegged claim Number 970, which he had pegged the previous year, and they left for Kyancutta the following day arriving there before April 14.

On Friday April 29, Mr. Bedford wrote to the S.A. Museum informing them that his offer to co-operate with them was withdrawn as, not only had they not confirmed it, but they also contested the ownership of his shipment to the British Museum and had also informed foreign museums that all the material recovered from Henbury was the property of the S.A. Government and that all dealings with individuals were illegal. On Monday May 9, Mr. Bedford wrote to the S.A. Museum concerning further excavations and requested their support, or at least no opposition, when the matter was put to the Federal authorities. Sir Douglas Mawson replied to this letter on Thursday May 12 saying that the Museum would strenuously oppose any moves made by Mr. Bedford and questioned both his integrity and educational qualifications. On Wednesday May 24, Mr. Bedford wrote to Mr. Branson acknowledging receipt of the material sent in March and informing him of the letter sent to the S.A. Museum repudiating the agreement with them.

On Tuesday May 3, Mr. Bedford sent a case containing 53.75kg of specimens to the British Museum and another two cases on Tuesday May 31. He wrote to the British Museum on Thursday May 5 saying that he was sending this material and that he had returned with about 200kg of specimens. He further stated that he would send the larger masses in a few weeks. He wrote again on Tuesday May 31, saying that he was now sending the larger masses plus 60 smaller ones found around crater No.13. The boxes of shale etc. arrived in London on June 7, 10 and 12 and another box containing 34 meteorite samples on Friday June 24. The two boxes containing the three largest masses from crater No.13 and the slugs arrived on Friday July 22. (The smallest mass from this crater had been included in the May 3 shipment.)

Dr. Spencer wrote to Mr. Bedford on Saturday July 20 acknowledging receipt of this material and stating that to that date Mr. Bedford had then sent about 404kg of material.

On Thursday July 21, Mr. Bedford wrote to the S.A. Treasurer pointing out the fact that no law existed which enabled Henbury to be declared a reserve and requesting that the Goverment embargo on the material in London be lifted. Unbeknown to Mr. Bedford, some three weeks previously, the Agent General for South Australia in London, at the request of the British Museum, had sent the following cable to the Treasury in Adelaide: "Referring to your telegram of 23 September 1931. British Museum asking whether dispute ownership meteorites settled as they desire to remunerate Bedford" and the reply received on July 12, which was sent on the advice of the S.A. Museum was: "Referring to your telegram of 29 June advise British Museum make their arrangements meteorites Federal Government delay prevents Public Library action".

Dr. Spencer wrote to Mr. Bedford on Saturday July 30, telling him of these telegrams and requesting that an arrangement

be made. Mr. Bedford replied on Friday September 9, suggesting that the British Museum retain 600 pounds of material in exchange for 250 (sterling) and 350 worth of exchange material (minerals, fossils etc.). On October 14, Dr. Spencer drew up a detailed inventory of the material which Mr. Bedford had sent to the Museum, selecting 599 5/8 pounds of material for purchase and listing a separate 291 1/2 pounds. This list was presented to the Museum Trustees at their meeting on Saturday October 22, 1932 and the payment of 250 was cabled to Mr. Bedford on Monday October 24. The first three cases of exchange minerals (342lb) were sent soon after.

Dr. Spencer's inventory showed that the Museum had recieved 642 specimens of total weight 404.2kg to that data which means that 102 specimens with a mass of 258.6kg were sent after the first consignment.

The Commonwealth Gazette for Thursday August 18, 1932, contained the following notice:

"Notice temporarily reserving certain crown lands in the Northern Territory from being taken up and occupied by the holder of a miner's right or business licence.

In pursuance of the powers conferred upon me by Section 3 of the Mining Ordinance 1932, I, Robert Archdale Parkhill, Minister of State for the Interior do hereby temporarily reserve the Crown Lands set out in the Schedule hereto from being taken up and occupied by the holder of a miner's right or business licence.

Dated this fifth day of August, 1932.

Archdale Parkhill.

Minister of State for the Interior.

Schedule referred to.

All that piece or parcel of land in the Northern Territory, containing an area of 640 acres, being part of Northern Territory Pastoral Lease No. 1677, commencing at a point forty chains true north from the centre of the principal meteorite crater of the Meteorite occurence situated approximately seven mile west-south-west from Henbury Head Station; thence true east for forty chains; thence true south for eighty chains; thence true west for eighty chains; thence true north for eighty chains; thence true east for forty chains to the point of commencement."

On Tuesday August 23, Mr. Bedford sent a 400g fragment of the newly found Kyancutta meteorite to London. Dr. Spencer replied on Friday October 14 acknowledging receipt of it. On Thursday November 10, Mr. Bedford sent a further Kyancutta specimen to London as well as some specimens of Henbury "glass" and other terrestrial material from the craters. As further evidence of his claim that some of the specimens still exhibited their original outer surface Mr. Bedford dispatched 5 specimens of weight 28.32kg to London on December 13, 1932. When they arrived in London on Thursday March 12, they brought the total material received to 647 specimens having a mass of 427.23kg.

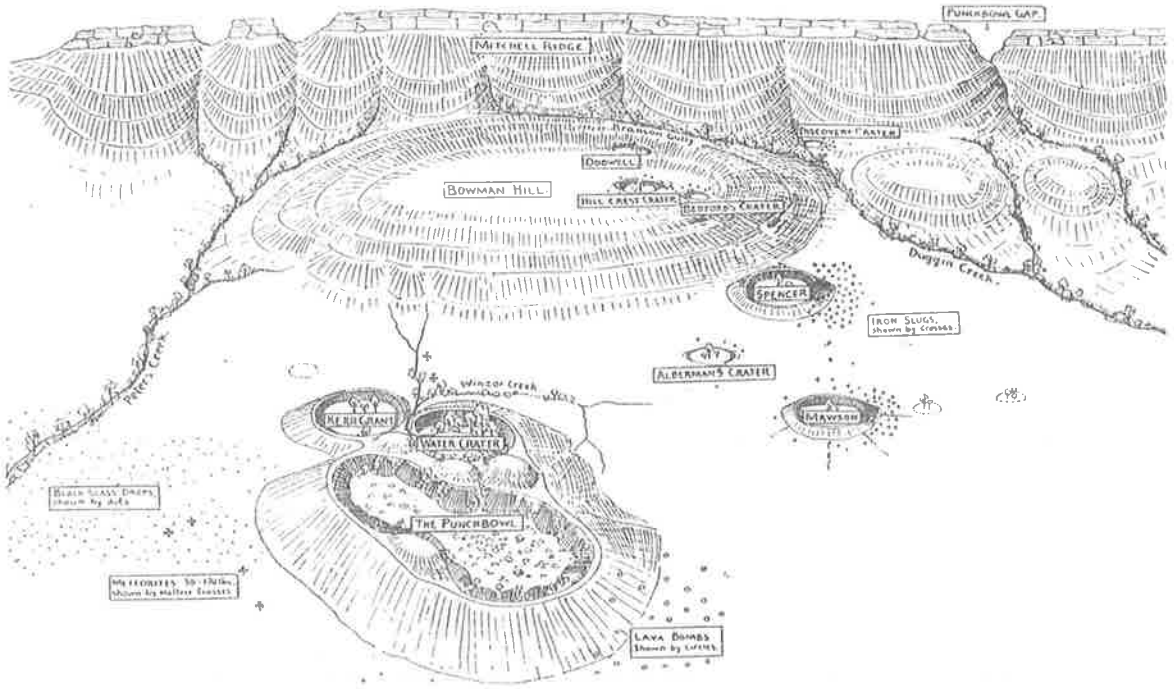
Mr. Bedford wrote a brief account of his first two trips to Henbury for the "Sunday Mail" of November 19, 1932. (This article was also published in the "Sydney Mail".) In this he included a sketch map of the area showing the thirteen craters identified by Mr. Alderman. He named the ten largest ones as follows (See also Figure A2.8):

Mr. Alderman	*Mr. Bedford*
1	*Un-named*
2	*Un-named*
3	*Mawson*
4	*Spencer*
5	*Alderman*
6 (Water Crater)	*Water Crater*
7 (Main Crater)	*The Punch Bowl*
8	*Kerr Grant*
9	*Un-named*
10	*Hill Crest*
11	*Bedford*
12	*Dodwell*
13	*Discovery*

The people so commemorated were connected with either the Karoonda or Henbury finds. Other people associated with the discoveries were commemorated by way of Duggin, Peters and Winzor Creeks, Bowman Hill, Mitchell Ridge and Branson Gully.

Mr. Bedford wrote to the British Museum on Monday December 19, 1932, stating that he would like to give the large 77.5kg mass from his first trip to them. The trustees sent an official letter of thanks, acknowledging this donation, on Tuesday February 14, 1933. This specimen, plus the second one of Kyancutta and the Henbury glass etc. sent in November 1932, were the only specimens from Kyancutta which were catalogued in the British Museum in 1933. The first Kyancutta specimen was catalogued in 1932 almost immediately after the 600

Figure A2.8 : The Henbury craters as drawn by Mr. Bedford. (Reproduced by courtesy of "The Sunday Mail".)



pounds of material purchased in October of that year.

Mr. Bedford exported another consignment of material weighing 101kg to an unknown destination on Monday January 1933. This definitely did not go to London but an examination of present museum holdings did not result in the identification of the destination.

Mr. Branson wrote to Mr. Bedford on Thursday July 1, 1933 saying that he still had about 1500 pounds of material for sale, including masses claimed to weigh about 500 and 350 pounds. (He had first written to Mr. Bedford concerning the larger mass in January 1932.)

The Silverton meteorite, which had been rediscovered a few weeks earlier by Mr. Bedford and his daughter (A2.2.1 above), was sent to London on Wednesday August 23, 1933, where it was received on Tuesday October 17. They were given permission to cut it and retain a portion for their collection. This, plus the specimen of Murnpeowie given to the British Museum by the S.A. School of Mines, were catalogued early in 1934.

On Tuesday September 19, 1933, Mr. Bedford, his daughter Joan and Messrs. Ben Peters and Albert C. Schondorf, the blacksmith's son, set out from Kyancutta for Henbury, the temporary reservation around the area having expired on Friday August 18, 1933. On Thursday October 12, they purchased the material still in Mr. Branson's possession, although as Mr. Branson had already sent the smaller of the two large masses to Mr. Bedford the latter did not receive it until he arrived back in Kyancutta. While at Henbury the party collected several brick-sized specimens as well as 80 or so small fragments, the total weight of all the material being about 100kg. They arrived back in Kyancutta in the middle of November and a brief account of this trip was written by Mr. Bedford for the "South Australian Wheatgrower" for the Monday January 15, 1934, issue.

In a letter on Tuesday January 9, Mr. Bedford told Dr. Spencer of this trip and commented that no reserve had been pegged in the area. While there, he said, they had examined two craters, one of which they had not identified before. They located about 1cwt of rust and shale in this new one at a depth of about 7 feet and some shale balls in the other. However, they removed nothing from either. In this same letter, Mr. Bedford said that the British Museum should retain the remainder of the material then in London against further exchanges. Dr. Spencer replied as follows on Friday February 23: "The remaining Henbury irons here include masses of 46lb 5oz, 25 1/4lb, 24 1/4lb and 471 slugs with an aggregate weight of 69 1/2lb - (total 165 1/2lb). I much appreciate your kindness in letting us keep this lot. This will be weighed up in detail and registered and the exhibition series extended." Accession numbers given by Hey show that this was done quite soon after Silverton and Murnpeowie were catalogued.

On Monday April 9, 1934, Mr. Bedford sent a small mass of 64g to Dr. Spencer which still clearly showed an original heating

zone thus proving the point of his letter published in Nature the previous week. This arrived in London on June 4, 1934, bringing the total number of specimens sent to London to 648 with a total mass of 426.3kg. Two of these had been cut and a mass of 227g returned to Kyancutta. Both pieces of the other mass were catalogued separately and thus 649 specimens of total weight of 426.1kg were recorded as having come from Mr. Bedford. Some 370kg of this material was contained in 24 specimens the other 56kg being distributed between 624 specimens. In a comment published with Mr. Bedford's letter to Nature, but written on February 15, 1934, Dr. Spencer stated that the British Museum had received 10001b of material from Mr. Bedford - this must have been an approximation to the actual weight of 940 pounds mentioned above as Hey's catalogue shows that no further Henbury material was given by Mr. Bedford.

On Friday June 1, 1934, Mr. Bedford wrote to Mr. Branson concerning the problems he was having disposing of the material and stating that the two large masses actually had weights of 118 and 180kg respectively. The larger of these two mases he offered to the British Museum for £300 (sterling) in a letter of Tuesday November 6, 1934. In this letter he commented that he had obtained it from Henbury during his trip the previous year. The British Museum apparently were not able to meet the cost and the meteorite was ultimately bought by the Smithsonian in 1935. The smaller of these two masses was offered for sale on a "hand bill" dated March 1, 1934, which Mr. Bedford had printed. A price of £200 (sterling) was requested for this mass.

It is likely that much of the other 45kg of material in the Washington collection also came from Mr. Bedford. Over the years he also sent material to Chicago (at least 18 specimens), and many other foreign museums. Not all of the material was sent overseas as a more than representative collection was retained in Kyancutta.

The 118kg mass was actually purchased early in 1959 by Dr. Nininger, from Mrs. E. Bedford, after the death of her husband. Dr. Nininger took this and several smaller specimens back to America with the stated intention of cutting the larger mass and selling the resulting sections. The Nininger Collection was finally dispersed in 1960 the first part having gone to the British Museum in October 1958. The remainder, about 80%, was purchased by the University of Arizona, Tempe, in July 1960. Hey's 1953 catalogue recorded 60kg of Henbury material in the Nininger Collection, at least part of which, according to Nininger (1972), had been obtained directly from Mr.Bedford. The fact that Nininger also purchased specimens from Ward's suggests that some of this material may have come from the original S.A. Museum collection. Hey's 1966 catalogue shows the University of Arizona then held 174kg of Henbury material, much, if not all, of this presumably coming from the Nininger Collection, being made up of part of the 60kg recorded by Hey in 1953 and part or all of the material purchased in Australia in 1959. Hey did not record any addition of Henbury material to the British Museum after 1950 and so it would appear that no Henbury material was acquired with the Nininger material by the British Museum. The 1976 Catalogue of the University of Arizona Collection shows that the large mass of 117.9kg was not cut by Dr. Nininger before it was acquired by the University of Arizona.

At least one other large Henbury specimen was acquired by Mr. Bedford, but no details are extant concerning either the time or location of the find. It is currently located in the Australian National University Collection and its mass is estimated to be 200kg - if this estimate is accurate then it is the largest known single mass of Henbury iron. Mrs. Joan Luscombe, however, told the author that she estimates its weight to be only 380 pounds (172kg) which would make it smaller than the large Washington mass. Unfortunately, location data are unavailable for most of the large Henbury masses. Buchwald and Graff-Petersen (1976) stated that the largest mass recovered was one of 225kg but they did not give any details concerning it.

As described in Section A2.6.2, Messrs. R. Bedford and J.B. Peters recovered Lake Labyrinth in November 1934.

In August 1937, Mr. W.R Bedford (Mr. Bedford's son), his sister Miss Brunhild Bedford, along with Mr. Ben Peters and Mr. Max O'Brien, a family friend from Kyancutta, returned to Henbury and collected a few more specimens. They then travelled north eastwards to the Boxhole crater where they collected several specimens. From there they travelled to Huckitta Station to investigate reports they had heard concerning a meteorite found there. Since arrangements had already been made between the station manager and Dr. Madigan for the sale of the meteorite no details were given to the Kyancutta party concerning its whereabouts. (Dr. Madigan, of Adelaide University, had been shown and recognized the meteorite some

weeks before - Section A2.8.8 b below.) This was the final Bedford expedition which resulted in the recovery of meteoritic material.

During the years following the Henbury trips, Mr. Bedford pursued an active programme of exchange with foreign museums, gradually building up an amazing collection of the then known meteorites. This he was able to do by exchanging specimens from the Henbury field as well as Flinders Ranges fossil specimens. The second World War effectively brought a halt to this programme. Some of the exchanges were never completed, while others, such as one with a Russian museum, were not concluded until after the war. The following list of museums, culled from the Kyancutta Museum catalogue, shows the extent of this exchange programme - Adelaide, Batavia, Brazil, Braunau, Calcutta, Chicago, Dorpat, Egypt, Geneva, Gottenburg, Helsinki, Lieden, London, Melbourne, Mexico, Minnesota, Tubingen, Paris, Perth, Rome, Sarajevo, Smithsonian, Stockholm, Sydney, Upsala, Utrecht, Wanganui and Wurzburg. Exchanges were also carried out with Dr. Nininger and Ward's.

After his death in 1951, Mr. Bedford's family was not able to devote extensive time to the maintenance of the Museum, and so it was finally decided that its contents should be dispersed among other museums. The material was not disposed of in Adelaide. In 1961, Dr. J.F. Lovering, of the Australian National University, visited Kyancutta to pursue enquiries about the Coolac meteorite, which had been sold to Mr. Bedford many years before. During this visit, it was suggested that A.N.U. would purchase much of the meteorite collection. Accordingly, Dr. Lovering took virtually all of the stony meteorites with him on his return. About a year later, he returned to Kyancutta and collected most of the remaining Henbury material and several other iron meteorites. These purchases resulted in A.N.U.'s fine collection of foreign meteorites. Most of the mineral and fossil specimens were purchased by Professor D. Brown, also from the Australian National University. In 1971, Mr. T. Darragh, of the National Museum of Victoria, visited Kyancutta and purchased the remainder of the meteorite collection, mainly irons, and some fossils for his institution. This material left Kyancutta on Wednesday February 16, 1972.

Catalogues of the National Museum of Victoria for 1967 and 1972 show that they received 11 specimens of Henbury material, with a total mass of some 138kg, from the dispersal of the Kyancutta Museum, while it would appear that A.N.U. acquired some 268kg, made up of two masses of ca. 200 and 40kg, plus 17 others of total weight 31 kg. Hodge-Smith (1939) in his listing of Henbury material made no mention of this largest mass. Likewise, he listed a 40kg mass as being in either New York or the Smithsonian but neither of these institutions lists such a mass among their current holdings. Most of the large masses mentioned by Hodge-Smith were either recovered or purchased by Mr. Bedford during 1932.

In his catalogue in 1939, Hodge-Smith listed a minimum of 2028 specimens as having been recovered from Henbury by the end of 1937. Eliminating the 800 recovered by the S.A. Museum party, this implies that the Kyancutta Museum received at least 1228 specimens. This figure is a minimum as the maximum weights of specimens listed by him are less than some of the larger specimens listed above. Hodge-Smith also estimated that some 1200kg of material had been recovered. In the light of data available to the author, this figure must be increased. Mr. Bedford purchased at least 1065kg of material from Mr. Branson and collected at least a further 850kg. Together with the 227kg collected by the S.A. Museum party, this represents a minimum of 2100kg. Other material subsequently collected (small slugs are still being sold in shops in Alice Springs at present) suggests a minimum of at least 2.5 tonne from the field which agrees with the 2 ton suggested by Mr. Bedford in his museum catalogue.

Recent large discoveries in the area include one of 45.5kg in 1974 by Mr. Reg Smith, the present manager of Henbury station. This specimen was completely buried prior to its find.

c. Subsequent expeditions

Since these early trips, the area has been visited by several groups of scientists. Some of these parties include:

1937 - a magnetic survey carried out by a party led by Mr. J.M. Rayner. They concluded that no large meteorite lay under the surface, except at improbably great depths.

1962 - Dr. C.H. Chao visited the area to search for shatter cones.

1963 - Drs. E.P. Henderson and B. Mason of the Smithsonian and Mr. O. Chalmers of the Australian Museum, visited and searched the area for further fragments. They located, with the help of a mine detector, over 600 specimens, the largest being about

1kg in weight while most weighed no more than 100g. Many of these specimens were found on the sides and top of Bacons Range.

- Drs. D.J. Milton and F.C. Michel carried out a detailed mapping survey and described a possible fourteenth crater.
- Dr. P.W. Hodge visited the area to investigate the soil in and surrounding the craters.

Numerous other parties have visited the area including a recent survey carried out by NASA personel.

d. Age of the fall

Various evidence has been put forward by different authors in an attempt to date the terrestrial age of the meteorite. The Oodnadatta prospector, Mr. J.M. Mitchell, told Mr. Bedford that the aborigines of the region referred to the area as "chindu chinna waru chingi yabu" - "sun walk fire devil rock". According to an old aboriginal interviewed by Mr. Mithchell, his father's father had seen the fire devil come from the sun. Furthermore, the aborigines were not permitted to drink water from the crater lest the fire devil fill them with iron.

Mr. Alderman commented on the mulga trees growing in the craters, as well as the remains of dead ones. This suggested to him that the fall was not of recent origin as these treees are slow growing. Another indicator of the antiquity of the fall was the presence of considerable quantities of iron shale, formed by the weathering of meteorite fragments. His conclusion was that the age of the fall ought to be reckoned in thousands of years, while Kohman and Goel (1962) suggested an age of less than 5000 years. On the other hand, the presence of original heat affected zones discovered by Mr. Bedford on several of the specimens ought not to be forgotten, although the rate of weathering will be reduced in the arid climate of the region.

In a letter to the "Advertiser" on Thursday January 11, 1934, Mr. Mitchell claimed that he had seen iron from Henbury as early as 1916, and that others had known of the existence of the craters prior to this. The Nuleri meteorite which has recently been shown to be most probably a piece of Henbury material (Buchwald 1975b, p.1408) was found about 1902 thus making the discovery date of meteorite specimens as early as this.

In the light of these facts, no date has been recorded either for the fall or finding of Henbury. A recognition date is likewise uncertain as the early letters to the University implied that their authors had recognized the meteoritic nature of the craters and the material that surrounded them. Similarly, the identification in about 1906 of Nuleri, even though its relationship to Henbury was unknown, in a strict sense implies that a recognition date of at least as early as 1906 must be stated for Henbury material.

A2.8.7 Boxhole

On Sunday June 20, 1937, Dr. Cecil Thomas Madigan, while on a geological expedition in Central Australia was shown a large crater by Mr. Joseph Webb, a shearer and uncle of the owners of Boxhole station. (This station, which was named after a well call Box Hole, is now known as Dneiper Station while a neighbouring one is called Boxhole.) The crater, which is almost 175m in diameter and averages about 12m in depth, lies on the side of a small quartzose ridge of pre-Cambrian metamorphic rock about 10m high. Dr. Madigan spent only one afternoon at the site and during that time surveyed the crater and found two iron-shale balls similar to those which had been found at Henbury. No meteorite specimens were recovered.

As mentioned above, a Kyancutta Museum party visited the area in August. They found two large meteorite masses of 82 and 50kg plus eight smaller ones and numerous small fragments. Nine of the larger masses were found on the ridge to the north of the crater and the tenth north of the ridge. Most of the slugs were also found to the north but some were recovered inside the crater near the eastern wall. The smaller of the two large masses, which was found by Miss. Brunhild Bedford, was cut, with difficulty, by Mr. Bedford. Subsequently an end slice (1.3kg), some filings and 3 small fragments as well as the large mass and two shale balls were sent to London by Mr. Bedford on Thursday September 2, 1937. Another slice (2.1kg) of this, as well as one of the smaller ones (3.7kg) and 40 or so fragments (700g) were sent to the Smithsonian while another individual (7.6kg) and at least two fragments of mass 1.1kg were sent to the American Museun in New York. The 2.55kg individual and the four fragments in the Nininger Collection probably came from Mr. Bedford as probably did the seven individuals, of total mass 45.26kg, in the A.N.U. collection. It is difficult to ascertain the present whereabouts of the remainder of the 50kg mass, but judging from the number of slabs

distributed in various museums, it is likely that the whole of this mass was cut up by Mr. Bedford. In all, it seems that the Kyancutta party recovered at least 150kg of meteoritic material.

Subsequently, three smaller masses having a total weight of about 19.4kg were found by Mr. Webb and sold to the S.A. Museum, while other fragments were subsequently acquired from other sources. In 1949, the S.A. Museum acquired a single mass of 167kg from the Webb brothers of Mount Riddock Station, in the Northern Territory. These men were, possibly, the owners of Boxhole Station.

It has been suggested that this crater also is about 5000 years old.

A2.8.8 The Huckitta meteorites

a. Alice Springs

In 1924, Dr. Herbert Basedow led a Vice Regal Expedition to Central Australia. During this expedition he picked up a meteorite about 16km north of Alice Springs on the Alice Springs - Huckitta road. The meteorite was lying partly buried in the ferruginous sand on the Burt Plain, north of the MacDonnell Ranges. The mass remained among other specimens until he went to England in 1931 when he presented the 1.08kg mass to the British Museum in November. Examination revealed its pallasitic nature and it was called "Alice Springs".

b. Huckitta

About three days after leaving Boxhole Station on Sunday June 20, 1937, Dr. Madigan arrived at Huckitta Station en route to the Tarlton Range at the northern edge of the Simpson Dessert. While at the station, he was shown a flat, rusty mass by an aboriginal, Mr. Michael Laughton. Examination "by hammer" showed that it was composed, at least in part, of iron which suggested a meteorite. Dr. Madigan was told that the specimen had come from a large stone standing "several feet" out of the ground. This report was greeted with some scepticism, but it was agreed that the party would return in a fortnight and inspect the "rock". Meanwhile, Mr. Laughton and the station manager, Mr. William Madrill, would peg the area as a mineral claim to establish some sort of ownership of the body.

When they returned on Tuesday July 6, the meteorite was found to the north of the station, on the far side of the Dulcie Range, in an area used by station employees as a camp site during mustering. Mr. Laughton had noticed that aboriginal stockmen always kept as far away from the stone as possible thus indicating that they feared it, perhaps alluding to a legend concerning its origin. This was the cause of Mr. Laughton' interest. (It should be pointed out that Mr. Laughton was not a full-blooded aboriginal which explains his dispassionate view of the meteorite.)

The meteorite was the only large boulder in the vicinity and at first glance Madigan thought that it was only a large boulder of conglomerate but close "hammer examination" revealed the iron and its silicate inclusions. The meteorite was in a depression from which it took no little effort to move it as it weighed nearly 1.5 tonnes. Once it was moved a large deposit of iron shale was seen beneath it.

Madigan made arrangements to purchase the meteorite and to have it transported to Adelaide. On his return to Adelaide, Madigan arranged for the University to pay the transport costs of the meteorite from the finding site. However, little of the meteorite was finally placed in the University collection. Mr. W. Burdett, of Basket Range, gave £200 for its purchase and then presented the meteorite to the S.A. Museum. The task of transporting the body took several weeks due to difficulties experienced in loading the meteorite onto a truck and then shifting it to Alice Springs. The transport to Alice Springs was carried out by Mr. Charles Symonds, an Alice Springs carrier. The meteorite was ultimately sent to Adelaide in September 1937 and was unloaded at Mile End Railway Station on Wednesday September 22, 1937.

The iron shale, which lay under the meteorite, was also excavated after Madigan left the site, as he had requested that it all be sent to Adelaide. After this excavation the dimensions of the resulting crater were measured and they too were sent to Madigan. Comparison of the size of the crater with the volume of the shale received caused Madigan to suspect that not all of the excavated shale had been sent to Adelaide. Taking this into account he suggested that the meteorite probably weighed over ten tonnes originally. The degree of weathering points to the antiquity of the fall.

After its arrival in Adelaide, the meteorite was sectioned in the Islington Railway workshops with a saw blade specifically designed and made for the purpose at a cost of £74. (This blade was later used to cut Pinnaroo.) After sectioning and polishing, a slab of the meteorite, named Huckitta from the station on which it was discovered, was placed on display in the S.A. Museum where it still

forms an impresive sight in the main foyer.

Chemical and mineralogical as well as physical appearance, suggest that "Alice Springs" is a small piece of this material. Even though the two masses were over 160km apart, the weight of the smaller mass (1.08kg) would not preclude its transport. This contention is further supported by the rarity of pallasites of which only forty or so are known. Accordingly "Alice Springs" is listed only as a synonym for Huckitta.

In his account of "Alice Springs", Spencer listed other Australian pallasites known at the time and discussed one which had been named "Australia". This meteorite had reputedly been found in 1880, but no details of the location of the find were known. He stated that it had been discredited by Prior in 1927. Hodge-Smith (1939) also listed this meteorite as being doubtful. Both of these authors, however, acknowledged that specimens were still extant in the museums of Harvard and New York, as did Reeds (1935). The Harvard specimen was recorded by Huntington (1888), who stated that it had been acquired with the J. Lawrence Smith collection, and also by Palache (1926). The find was again reported, along with eleven other meteorites, to the Society for Research on Meteorites by Mr. Bedford in 1940 (Nininger 1940). Mason (1964) and Frondel (1965) both recorded the specimens as still being in their respective institutions. The obvious great terrestrial age of Huckitta, plus the fact that "Alice Springs" may have been removed from it, is consistent with "Australia" being another fragment. Prior's 1927 suggestion that it might be a fragment of the Mount Dyrring pallasite from near Singleton in New South Wales is equally likely as this meteorite consisted of several masses. Trace element analyses may solve this problem.

A2.8.9 Tawallah Valley

This meteorite was acquired in April 1939, by the Australian Museum from a Mr. Heathcock, the constable in charge of the Borroloola Police Station in the Northern Territory. Mr. Heathcock stated that the meteorite had been in the police station for about 18 months since its find by a Mr. Condon. It had been found in the Tawallah Valley, about 78km north west of Borroloola. It was somewhat unusually shaped in that it was almost flat without any pronounced regmaglypts or other surface markings. When the meteorite was received by the Museum, it weighed 75.75kg, a small piece, probably less than 200g, having been removed.

A2.8.10 Mount Sir Charles

Mr. T. Williams found this meteorite in 1942 about 11.3km east of the Bond Springs Station, north east of Alice Springs. It was subsequently acquired by Mr. N.C. Bell of that city from whom the S.A. Museum obtained it later in the year.

It was initially named "Bond Springs" until it was discovered that this name had been in use since 1931 for a stone found 15km to the west. Accordingly, it was renamed Mount Sir Charles as it had been found close to a hill of that name.

When found, the meteorite had an unusual shape. It appeared to be part of the "outer shell" of a meteorite with the inner part missing. This was probably partly a result of weathering. A mass of about 550g had been broken from the meteorite prior to its acquisition by the Museum.

A2.8.11 Glen Helen

While pasing through Alice Springs in 1963 on their Henbury expedition, Drs. Henderson and Mason and Mr. Chalmers were given this meteorite by Mr. P.D. Boerner, an Alice Springs resident. They were told that it had been found by an aboriginal in the Glen Helen area of the MacDonnell Ranges. Very little is known about it except that it is an iron. It is in the Australian Museum at present. It is possible, especially in the light of Section A2.9.2 below, that it is a transported piece of Henbury.

A2.8.12 Rabbit Flat

This meteorite was found in 1974 by a road gang working on the road between The Granites and Rabbit Flat. Little is known of its present whereabouts but it may be in the possession of Mr. D.P. Boener of Alice Springs. Like Bond Springs, this second find of a stony meteorite in the Northern Territory is an olivine bronzite chondrite.

A2.9 DISCREDITED OR PAIRED METEORITES

A2.9.1 South Australia

a. Glen Osborne

Prior (1929) said that, according to Mr. Card of Sydney, this meteorite was in the possession of Sir Douglas Mawson, while Alderman (1936) suggested that although it had been listed in various catalogues and papers he could find no information about it and therefore it should be discredited. Hodge-Smith (1939) stated that it originated in a manuscript of Mr. Card where it was listed as "awaiting verification". Hodge-Smith stated that since such verification had not been forthcoming he had not included

it in his list of Australian meteorites.

It may be that the name was a corruption of Glenormiston, an unusual meteorite found in northern Queensland in 1926.

b. Monte Colina

As pointed out above, the probability of this meteorite having an independent existence is extremely small. The case for it being a part of the outer surface of Carraweena has been put and analytical and other evidence quoted above support this contention.

c. Clare, Gawler or S.A. Beta

This meteorite is a medium octahedrite with an uncertain terrestrial history.

About fifteen years ago, Mr. Arthur Shepherd reportedly picked up two or more pieces of material from the side of the Gawler to Clare road in the vicinity of Gawler. After his death, one of his sons found two pieces of meteorite in his father's shed which may be the material Mr. Shepherd picked up from the roadside. One of the pieces was taken to Broken Hill where it was cut into four. A second piece (3.174kg) was brought to the University where the author cast it and cut it initially into five. One of these pieces was later quartered.

The material in Broken Hill has been referred to variously as the Clare or Gawler meteorite while in Adelaide the piece that came to the University was called "S.A. Beta" because of the paucity of detail concerning the location of its find. (The poorly located Adelaide meteorite, Section A2.4.5 above, had initially been called S.A. Alpha for similar reasons.)

Analytical results suggested a very close affinity to Henbury. Accordingly, a piece was sent to Germany to Dr. Vagn F. Buchwald, who examined it and reported that he had no hesitation in concluding that it was a transported Henbury sample. Unfortunately, by this stage, samples of the material had been distributed throughout the country and at least three museums in the eastern States are now in possession of samples of this "new" meteorite.

d. Kingoonya

It was shown in Section A2.6.1 that "Kingoonya" and "Naretha" are different names for the same meteorite and as Naretha accurately identifies the place where the meteorite was recovered the alternative "Kingoonya" ought not to be used any more.

A2.9.2 Northern Territory

a. Basedow Range

Sometime prior to 1957 this meteorite was found about 6.4km from Wilbia Wells along the south side of the Basedow Range, about 100km from the Henbury craters. For many years Hodge-Smith considered it to be a transported piece of Henbury and Scott et al (1973) came to a similar conclusion.

b. Hart Range

A 608g meteorite fragment reportedly found in the Hart Range area was placed in the Western Australian meteorite collection. (The Hart Range is west of Alice Springs.) McCall (1972) and De Later (1973) concluded that this sample is probably identical with material from the Boxhole crater.

c. Nutwood Downs

This meteorite was sold to Mr. David New, a New York mineral dealer, by a Surfer's Paradise mineral dealer who claimed that it had been found on Nutwood Downs Station. Scott et al (1972) report that it is a piece of Henbury, while Mason (1974) reported that the manager of Nutwood Downs Station denied that the meteorite had been found on the property.

d. Gallipoli Station

This meteorite of about 6kg was also acquired by Mr. New from the same Surfer's Paradise mineral dealer. It had reportedly been found on Gallipoli Station. This material has also been examined by Buchwald (Buchwald 1975b) who concluded that it also is a piece of Henbury material. On the other hand, Hutchison et al (1977) stated that on the basis of nickel contents, Dr. C.B. Moore disagrees.

A2.9.3 Western Australia

a. Nuleri

As was the case with Nutwood Downs, Buchwald (1975b, p.1408) concluded that this meteorite is a transported fragment from the central Australian crater fields, probably from Henbury. The meteorite, which was reportedly found in 1902, was picked up almost in the centre of Western Australia, near Lake Throssell, by a prospector. As its mass was only some 120g it could easily have been carried the 950 or so kilometres from Henbury to where it was found. Its recognition in 1906, or earlier, makes it the first known piece of Henbury material to be recognized as a meteorite and recorded as such.

This ubiquity of Henbury material underlines the care that must be taken in assessing the authenticity of new Group IIIA finds in Australia.

A2.9.4 Australia

a. Australia

This pallasitic meteorite was discussed in Section A2.8.8. At present, no unambiguous conclusions can be drawn concerning the site of its find nor its relationship to any other known Australian meteorite.

Chapter A3

Bibliographic Survey

A3.1 INTRODUCTION

This chapter summarizes the results obtained in this work and all other known published ones at least to July 1978. As these latter are widely dispersed through many journals under various guises there are undoubtedly some omissions but hopefully the number is minimal.

The meteorites are treated in alphabetical order and the available information recorded using a standard format, the headings of which are generally self explanatory. The box at the head contains the meteorite's name classification and "fall" or "find" status. The numbers listed on the right hand side of the page refer to references, so marked in the Bibliography, which carry relevant information. Data marked by an asterisk (*) are part of the results of this study and are generally unpublished. Such results may, or may not, be duplicated in earlier chapters.

The coordinates of latitude and longitude have been checked wherever possible, and in several cases, values differing from ones previously recorded are given as it is believed that they more accurately represent the location of the site of the finds. As stressed by Buchwald and Wasson (1972) the exact location of the discovery site is given by the geographical coordinates and not by the adopted name. Despite this, in a few instances marked #, the coordinates are those of the place from which the meteorite takes its name as the site of the find is unknown. The majority of these new coordinates, which constitute part of this study, were sent to Dr. B. Mason by the S.A. Museum and were cited by him in 1974 without acknowledgement. It is believed that he was not informed of their author.

The figures quoted in the specimen distribution sections are only as accurate as the latest available references permit and accordingly ought to be treated with caution.

The following abbreviations are used for various museums:

A.M.	Australian Museum, Sydney
A.N.U.	Australian National University, Canberra
A.S.U.	Arizona State University, Tempe
B.M.	British Museum (Natural History), London
B.M.R.	Bureau of Mineral Resources, Canberra
F.M.C.	Field Museum of Natural History, Chicago
G.L.W.A.	Government Laboratories of Western Australia, Perth
G.S.C.	Geological Survey of Canada, Ottawa
G.S.I.	Geological Survey of India, Calcutta
G.S.N.S.W.	Geological Survey of New South Wales, Sydney
G.S.S.A.	Geological Survey of South Australia, Adelaide
N.M.V.	National Museum of Victoria, Melbourne
N.Y.	American Museum of Natural History, New York
S.A.M.	South Australian Museum, Adelaide
U.A.	Tate Museum, Department of Geology and Mineralogy, University of Adelaide
U.C.	University of California, Los Angeles
U.M.	Department of Geology, University of Melbourne
U.S.N.M.	United States National Museum, Smithsonian Institution, Washington
W.A.M.	Western Australian Museum, Perth.

The entry under which the meteorite's classification is given is simply headed "Chemical Group" for reasons of simplicity. In the case of the chondrites the terminology of Van Schmus and Wood (1967), Van Schmus and Hayes (1974) and Fitzgerald and Jones (1977) is used. In the case of the iron meteorites this general heading has been considered adequate to include the Ga-Ge groups of Wasson and co-workers, for, as pointed out by Wasson (1974) himself, other elements will give rise to similar groupings and so the specification of the gallium and

germanium is unnecessary. Little information additional to that already given in the main heading is provided for the other achondrites.

Generally little attempt has been made to discuss conflicting results but all references are quoted in each instance. In all cases precedence has been given to the results of this work, otherwise, the result which appears more appropriate is quoted where necessary, without comment.

A3.2 ALPAHABETICAL LISTING OF METEORITES

ACCALANA

L chondrite

Find

FIND	In January 1914 or earlier by Thomas Flinders Gill.	*, 141, 143, 144, 267, 268, 269, 272, 284, 329, 376, 438, 584, 586
LOCATION	Near Accalana Well which is 9.6km south of the Carraweena Head Station ruins on Strzelecki Creek and about 13km east of Lake Blanche. 29° 15'S 139° 58'E	6, 143, 268, 269, 284, 309, 329, 336, 383, 388, 586, 640
IDENTIFIED	Early 1914.	*
MASS	2.83kg	141, 143, 267, 268, 269, 272
DESCRIPTION	The meteorite has a well developed chondritic texture with barred, radiating and glassy chondrules present, the latter showing varying degrees of devitrification. The chondrules which generally vary in size from about 0.5mm to 1.5mm are set in a matrix of chondrule fragments and opaque minerals. Porphyritic inclusions are common. Polysynthetically twinned clinopyroxene is common. Many of the barred chondrules and porphyritic inclusions contain a pale pink, isotropic glass which shows no evidence of devitrification. Rare gas analysis suggests that Accalana and Carraweena both belong to the same shower. Chemical, mineralogical and textural evidence reported here and elsewhere support this contention.	*, 270, 272, 294, 383, 388

DISTRIBUTION

Main mass	2.5kg	S.A.M.	143, 267, 268, 269, 284
Others	14g	U.S.N.M.	384
	12.5g	U.A.	*
	1.4g	N.Y.	376

ELEMENTAL COMPOSITION

F	246, 269	V	246, 269, 325
Na	*	Cr	*, 246, 269
Mg	*	Mn	*, 246, 269
Al	*	Fe	*, 246
Si	*	Co	246, 269
P	*, 246	Ni	*, 246
S	*	Cu	246, 269
Cl	246, 269	Zn	246, 269, 655
K	*	Ge	246, 269, 289
Ca	*	Sr	246, 269
Sc	246, 269	Ba	246, 269, 484
Ti	*, 246, 269		

SILICATES		
Olivine	X.R.D. : $Fa_{24.9}$	*, 374, 376
CHEM. GROUP	L3	376, 383, 384, 421
OTHER STUDIES		
Age		272
Inert gases		270, 272
Shock history		272

ADELAIDE

C chondrite

Find

FIND	Prior to 1972.	153
LOCATION	"Found" in the offices of the Geological Survey of South Australia. Find site unknown but possibly from the south east of South Australia.	152, 153
IDENTIFIED	The meteorite was identified at the AMDEL (Adelaide) laboratories in September 1972. It was named by the author acting on the advice of Dr. R.A. Binns.	*, 152, 153, 203
MASS	2.03+kg	152, 153
DESCRIPTION	The meteorite was originally polyhedral in shape with nine faces, the largest dimension being about 9cm. A weathering rim of some 4-5mm is present. About 65% of the meteorite is composed of chondrules, inclusions and mineral fragments, most of which range in size from 0.02 to 0.5 mm though a few have diameters of about 1mm. Most are irregular in shape, the majority being composed of olivine, however, pyroxene is also present. The silicate compositions are variable. The matrix is very fine both troilite and pentlandite being present, as well as magnetite as spherical grains with diameters of about 1 micron but very little free Ni-Fe. Feldspar was not detected optically.	*, 152, 153, 203
DISTRIBUTION		
Main mass	1.931kg G.S.S.A.	152, 153
Others	0.038kg U.A.	*
DENSITY	3.2	152, 153

ELEMENTAL COMPOSITION	Li	152, 153	
	C	152, 153	
	Na	*, 152, 153, 203	
	Mg	*, 152, 153, 203	
	Al	*, 152, 153, 203	
	Si	*, 152, 153, 203	
	P	*, 152, 153, 203	
	S	*, 152, 153, 203	
	K	*, 152, 153, 203	
	Ca	*, 152, 153, 203	
	Ti	*, 152, 153, 203	
	Cr	*, 152, 153, 203	
	Mn	*, 152, 153, 203	
	Fe	*, 152, 153, 203	
	Co	152, 153	
	Ni	*, 152, 153, 203	
	Cu	152, 153	
	Zn	152, 153	
	Ga	152, 153	
	Ge	152, 153	
	La	*	
	Ce	*	
	Nd	*	
	Sm	*	
	Eu	*	
	Gd	*	
	Dy	*	
	Er	*	
	Yb	*	
	Cd	522	
	Sn	152, 153	
	Te	562	
	Ba	156	
	Pb	152, 153	
SILICATES			
Olivine	Variable - X.R.D. peaks at Fa_1 and Fa_{42}		*, 152, 153, 203
Pyroxene	Variable - Probe average Fs_2		152, 153
CHEM GROUP	C2K		*, 151, 153, 202, 203, 364, 367, 421

ALIKATNIMA

Ataxite

Find

FIND	In 1931 or earlier.	143, 294, 435
LOCATION	About 72km NNE of Alice Springs. 23° 20'S 134° 07'E	6, 143, 267, 268, 269, 284, 330
IDENTIFIED	Possibly when acquired by the S.A. Museum from B. Webb, an Alice Springs resident, via F.S. Jones, of Highgate, South Australia, in January 1931.	*, 143
MASS	15.87+kg	6, 141, 143, 267, 268, 269, 284, 294, 435
DESCRIPTION	The meteorite has an ataxitic texture. Small crystals of daubreelite and schreibersite are present as well as fine blebs of the latter. A fusion crust is absent but there is a 2mm wide heat-affected zone present.	83

Main mass	9.07kg	S.A.M.	83, 143, 284
Others	5.78kg	S.A.M.	83, 143, 284
	241g	U.A.	*
	145g	S.A.M.	143
	32g	U.S.N.M.	294, 384
	31g	A.N.U.	38

ELEMENTAL COMPOSITION: Ni 83, 294, 383, 506, 649 Ge 294, 383, 506, 649 Ga 294, 506, 649

CHEM. GROUP: Anomalous — 83, 143, 224, 294, 383, 384, 506, 551, 649

ARLTUNGA

Ataxite

Find

FIND: In September 1908 by Daniel Pedler. — 11, 35, 83, 141, 143, 267, 268, 269, 391, 438, 483, 573, 694

LOCATION: About 3km south of the Government cyanide works near the Arltunga goldfields, north east of Alice Springs. 23° 28'S 134° 40'E — 6, 11, 83, 143, 269, 330, 391, 483, 563

IDENTIFIED: Probably when purchased by the S.A. Museum from J. Woodford in 1908. — *, 6, 11, 83, 141, 143

MASS: 18.14kg — 11, 13, 35, 83, 143, 268, 269, 438, 483, 563, 694

DESCRIPTION: The meteorite was polygonal in shape with flat surfaces and little evidence of regmaglypts. The meteorite has an ataxitic structure with a dense grid of plates of kamacite aligned octahedrally in a matrix of plessite. No Neumann bands are present. Troilite nodules are present but no daubreelite. Calculations show that Arltunga cooled more rapidly than most other meteorites. — 40, 83, 143, 286, 391

DISTRIBUTION

Main mass	12.70kg	S.A.M.	83, 143, 269, 286
Others	979g	U.S.N.M.	83, 294, 384
	828g	S.A.M.	83, 143
	369g	B.M.	83, 267, 268, 269
	260g	A.N.U.	38, 83
	120g	A.M.	35, 269, 286
	47g	U.A.	*
	24g	A.S.U.	294
	2g	N.M.V.	427

DENSITY	7.848		284, 391
ELEMENTAL COMPOSITION	P 52, 83, 284, 286, 391 S 391 Cr 52, 83, 269, 284, 286, 348, 391 Fe 52, 284, 286, 391 Co 52, 83, 269, 284, 286, 348, 391 Ni 52, 83, 235, 269, 284, 286, 294, 346, 348, 383, 389, 391, 506, 552, 649, 688	Cu 83, 269, 348 Ga 83, 269, 294, 348, 506, 552, 649 Ge 83, 235, 269, 294, 348, 383, 506, 552, 649 Ir 83, 294, 552, 649 W 688	
Ni-Fe ALLOYS			
Bandwidth			83, 235, 550, 552
Cooling Rate			83, 550
Hardness			83
CHEM. GROUP	IID - Anomalous		35, 83, 172, 224, 235, 267, 268, 269, 294, 304, 384, 409, 550, 551, 552, 649, 665, 688, 694
OTHER STUDIES			
Magnetic Properties			234, 235

ARTRACOONA

L chondrite

Find

FIND	About 1914 by William George Amesbury.	35, 141, 143, 144, 267, 268, 269, 272, 284, 309, 329, 376, 388, 438, 573
LOCATION	On the side of a sandhill, 3.2km east of Nott's Hill, 9.5km west of Artracoona Hill and 13km NW of the Carraweena Head Station ruins on Strzelecki Creek, east of Lake Blanche. 29° 04'S 139° 55'E	*, 6, 35, 143, 268, 269, 284, 294, 309, 336, 383, 388, 483
MASS	20.81kg	6, 111, 143, 267, 268, 269, 272, 284, 309, 388

DESCRIPTION

A well oriented stone with a height of about 20cm and a base of 30. Nickel-iron and troilite are present as well as a large quantity of limonite. The kamacite is strongly corroded. The silicates have been strongly recrystallized with little evidence, in plain polarized light, of a chondritic texture, however it is more obvious in the crossed polar configuration. The fracture planes of most of the olivine grains are stained with limonite. The sharp extinction exhibited by most of the silicates points to the general absence of shock effects. Glass is absent having been devitrified to granular aggregates. Rare gas analysis shows that it is distinct from Accalana and Carraweena.

*, 270, 272, 309, 388

DISTRIBUTION

Main mass	14.75kg	U.A.	*, 143, 268, 269, 483
Others	1122g	U.A.	*
	502g	S.A.M.	143
	375g	U.S.N.M.	384
	358g	A.N.U.	*
	154g	A.M.	35
	137g	B.M.R.	*
	89g	B.M.	294
	5.7g	N.Y.	376

DENSITY 3.52 — 309

ELEMENTAL COMPOSITION

H	309, 623	Ca	*, 309
C	309, 623	Ti	*
Na	*, 309	Cr	*, 309
Mg	*, 309	Mn	*
Al	*, 309	Fe	*, 309, 623
Si	*, 309	Ni	*, 309
P	*, 309	Zr	555
S	*, 309	Hf	555
K	*, 309		

SILICATES

Olivine	X.R.D.	: $Fa_{25.2}$	*, 374
	Probe	: $Fa_{25.6}$	294, 383, 649
Pyroxene	Probe	: $Fs_{20.4}$	383

CHEM. GROUP L6 — 35, 143, 224, 268, 269, 284, 376, 383, 384, 421, 628, 649

OTHER STUDIES

Age	272
Inert Gases	270, 272, 671
Shock History	272
Ultra Violet Reflectance	526

BASEDOW RANGE

Medium octahedrite

Find

FIND	Prior to 1957	35, 349
LOCATION	6.4km from Wilbia Wells along the south side of the Basedow Range SW of Alice Springs. The Basedow Range is about 85km SW of the Henbury craters. 25° 06'S 132° 33'E	35, 83, 269
MASS	A few kilograms	83
DESCRIPTION	The specimen displays a medium Widmanstatten structure with long, straight kamacite lamellae. Neumann bands are present. Schreibersite occurs only as rare veinlets. Occasional elongated nodules of troilite are present. Abundant plates of carlsbergite are present. Hodge-Smith, Buchwald and others have concluded that this is a transported fragment of Henbury.	83, 383, 551, 553, 649

DISTRIBUTION

Main mass	1.244kg	A.M.	35
Others	858g	A.M.	35
	246g	U.S.N.M.	83
	91g	A.N.U.	38

ELEMENTAL COMPOSITION

P	83	Cu	83, 269, 348
Cr	83, 269, 348	Ga	83, 269, 348
Co	83, 269, 348	Ge	83, 269, 348
Ni	83, 235, 269, 348	Ir	83

Ni-Fe ALLOYS

Bandwidth		83, 235, 553
Cooling Rate		235
Hardness		83
CHEM. GROUP	IIIA	35, 83, 235, 269, 297, 348, 551, 553, 649

OTHER STUDIES

Magnetic Properties		235
Shock History		296, 297

BOND SPRINGS

H chondrite

FIND

FIND	During the period 1891 to 1898 by an unknown person.	50, 268, 269
LOCATION	Near the Overland Telegraph Line, 5km west of Bond Springs Station and about 16km west of Mount Sir Charles. 23° 33'S 133° 54'E	*, 268, 269, 383
IDENTIFIED	Possibly 1898	50
MASS	6.18g	50, 141, 268, 269
DESCRIPTION	The outer skin is smooth and free of significant depressions, the crust being dark brown and less than 0.25mm thick. There are numerous chondrules of olivine and pyroxene which are frequently partly outlined by nickel-iron and troilite grains. These latter minerals also occur scattered through out the matrix.	50
DISTRIBUTION		
Main mass	2.03g U.M.	50
Others		
DENSITY	3.53	50
CHEM. GROUP	H6	50, 224, 383, 421

BOOLKA

Chondrite

Find

FIND	July 1968 by Lindsay H. Russell	294, 359
LOCATION	5km NNW of Boolka Bore, on Moorabie Station, County Evelyn, New South Wales. This point is about 6.3km east of the State border. 30° 04'S 141° 03'E	*, 294, 359
IDENTIFIED	July 1968 by D.H. McColl	359
MASS	2-3kg	294, 359

DESCRIPTION	The specimen was originally approximately pyramidal in shape the base being about 15x20cm with a height of about 10cm. About 30% of the meteorite is missing. The remainder is traversed by numerous fractures filled with alteration products and has broken along one of these fractures. The surface is dark brown where the crust is intact and is marked by several shallow depressions.	*
DISTRIBUTION		
Main mass	2-3kg Finder	*
Others		
CHEM. GROUP	Chondrite	*, 294, 359

BOXHOLE

Medium octahedrite

Find

FIND	Cecil Thomas Madigan found two shale ball when he was shown and identified the crater on Sunday June 20, 1937. The first unweathered material was found by a party of four from the Kyancutta Museum in August 1937. Other material was found subsequently up to a kilometre from the crater which is about 175m in diameter and varies in depth from 9 to 16m and is on the southern side of a small quartzose ridge which is about 10m high. The crater, which is thought to be about 5000 years old has been classified as an "Intermediate, Large" one and is an explosion one. No shatter cones have so far been located.	*, 8, 35, 55, 82, 83, 112, 126, 141, 143, 160, 161, 231, 255, 267, 268, 269, 278, 284, 290, 310, 316, 317, 334, 357, 368, 370, 372, 376, 381, 694
LOCATION	The crater is about 1.2km north of Boxhole (now Dneiper) Homestead and 290km NE of Alice Springs. 22° 37'S 135° 12'E	35, 83, 85, 126, 143, 160, 267, 268, 269, 330, 331, 333, 357, 368, 436
MASS	Unknown, but over 360kg have been recovered to date.	*, 83, 85, 143, 231, 310, 694
DESCRIPTION	Some masses are part of a large body which exploded on impact with the earth while others apparently passed through the atmosphere independently. The former are therefore generally deformed. The undeformed material has a well developed Widmanstatten pattern. Schreibersite, troilite and daubreelite are present. Some of the independent masses retain a heat affected zone. In the distorted material the Widmanstatten lamellae are bent and stretched out into long stringers with the kamacite often being recrystallized. On the basis of chemistry and mineralogy it would appear that Boxhole and Henbury, although similar, represent separate falls.	83, 155, 255, 279, 284, 354, 389, 665

DISTRIBUTION			
Main mass	166.9kg	S.A.M.	83, 143, 294
Others	83.5kg	B.M.	83, 267, 268, 269, 370, 592
	45.96kg	A.N.U.	38, 83, 333
	8.7kg	N.Y.	83, 294, 376, 389,
	6.5kg	U.S.N.M.	83, 294, 384
	3.6+kg	A.M.	35, 83, 269, 284
	3.184kg	A.S.U.	83, 269, 294, 694
	2.396kg	N.M.V.	357
	1.046kg	W.A.M.	427
	1.003kg	U.A.	*
	1kg	Tubingen	83, 294
	0.417kg	Copenhagen	83, 85
	0.267kg	U.C.	333, 652
	Another large mass is in the possession of the present owners of Dneiper Station.		*
DENSITY	7.80		370

ELEMENTAL COMPOSITION

C	83, 155, 310, 337, 370	Cu	83, 155, 269, 348
Si	370	Zn	155, 521
P	83, 85, 155, 173, 337, 370, 505	Ga	83, 84, 155, 269, 294, 348, 354, 553, 649, 650, 708
S	173, 370	Ge	83, 85, 155, 269, 294, 348, 354, 383, 553, 649, 650, 708
Cl	173, 231, 310	Cd	155, 521
Cr	83, 155, 269, 348	Ir	83, 85, 155, 294, 553, 649, 650
Fe	173, 370		
Co	83, 155, 269, 337, 348, 354, 370		
Ni	83, 85, 155, 173, 235, 269, 294, 310, 337, 348, 354, 370, 383, 389, 553, 649, 650, 665, 708		

Ni-Fe ALLOYS

Bandwidth	83
Composition	505
Cooling Rate	235
Hardness	83, 235
CHEM.GROUP IIIA	35, 83, 85, 143, 224, 235, 261, 267, 268, 269, 333, 357, 376, 383, 384, 551, 553, 649, 652, 694

OTHER STUDIES

Age	229, 310
Magnetic Properties	261
Shock history	83, 296, 297
Soil Study	280, 282

BRACHINA

Anomalous chondrite

Find

FIND	7:30am on Wednesday May 26, 1974, by Brian Martyn Eves	32, 300, 513, 571, 703
LOCATION	On the flood plain of Brachina Creek, west of Brachina Gorge in the Flinders Ranges, in the Hundred of Bunyeroo, County Taunton. 31° 18'S 138° 23'E	*, 300, 513, 703
IDENTIFIED	Identified as a chassignite by J.E. Johnson soon after the find. Another classification is suggested in this work.	
MASS	202.85g	32, 300, 513, 703
DESCRIPTION	The anterior domed surface of the mass, which is approximately hemispherical in shape with a diameter of about 5cm, is covered with a smooth fusion crust while the posterior surface carries a more scoriaceous crust. The shape suggests the meteorite fragmented early in flight. It is composed predominantly of olivine with minor amounts of diopside and plagioclase. The brown, sub-hedral olivine is unshocked. The meteorite is somewhat friable but there is no evidence of chondrules, the texture being dominated by triple point grain boundaries. It has been suggested that the meteorite is a fine grained cumulate.	32, 300, 513

DISTRIBUTION

Main mass	195.30g	S.A.M.	300
Others	7.0+g	S.A.M.	300

ELEMENTAL COMPOSITION

C	300	Nb	300
Na	300, 693	Cs	300
Mg	300, 693	Ba	300
Al	300, 693	La	300
Si	300, 693	Ce	300
P	300, 693	Pr	300
S	300	Nd	300
K	300, 693	Sm	300
Ca	300, 693	Eu	300
Sc	300	Gd	300
Ti	300, 693	Tb	300
V	300	Dy	300
Cr	300, 693	Ho	300
Mn	300, 693	Er	300
Fe	300, 693	Yb	300
Co	300	Lu	300
Ni	300	Tr	300
Rb	300	Au	300
Sr	300	Pb	300
Zr	300	Th	300
Y	300		

SILICATES		
Olivine	Probe : Fa_{33}	300, 693
Pyroxene	Probe : Fs_{14} Wo_{40}	300, 693
Feldspar	Probe : An_{22}	300, 693
SULFIDES	Accessory troilite and pentlandite present	300
CHEM. GROUP	Anomalous chondrite	*, 32, 207, 300, 513, 693, 703

CADELL

L chondrite

Find

FIND	On Thursday April 14, 1910, by Charles H. Bannear	21, 35, 141, 143, 268, 269, 284, 376, 438, 481, 573, 586
LOCATION	Almost completely buried in a sandhill on the eastern side of the Murray River about 4.8km from Morgan in the Hundred of Cadell, County Albert. 34° 04'S 139° 45'E	6, 11, 35, 143, 268, 269, 284, 336, 383, 438, 481, 586
IDENTIFIED	Possibly on Monday May 2, 1910 when presented to the S.A. Museum	
MASS	3.29kg	6, 11, 141, 1423, 268, 284, 481
DESCRIPTION	There is little evidence of a chondritic texture and many of the silicates are stained with limonite. Large anhedral grains of olivine and orthopyroxene are present with many of the former having limonitic stained fracture planes. These grains also frequently enclose small pyroxene grains and many show an undulatory extinction with some possessing a mosaic texture. Exsolution lamellae can be seen in some of the orthopyroxene grains.	*

DISTRIBUTION			
Main mass	2.27kg	S.A.M.	11, 143, 284
Others	128g	S.A.M.	143
	71g	U.S.N.M.	269, 384
	66g	U.A.	*
	18g	A.M.	35
	2g	N.Y.	376

ELEMENTAL COMPOSITION	F 246, 311	V 246, 269, 325	
	Na *	Cr *, 246, 269	
	Mg *	Mn *, 246, 269	
	Al *	Fe *, 246, 269	
	Si *	Co 246, 269	
	P *, 246	Ni *, 246	
	S *	Cu 246, 269	
	Cl 246, 269	Zn 246, 269, 655	
	K *	Ge 246, 269, 289	
	Ca *	Sr 246, 269	
	Sc 246, 269	Ba 246, 269, 484	
	Ti *, 246, 269		
SILICATES			
Olivine	X.R.D. : $Fa_{25.7}$		*, 374
	Probe : $Fa_{25.5}$		383, 649
Pyroxene	Probe : $Fs_{20.9}$		383
CHEM. GROUP	L6		35, 143, 224, 284, 294, 376, 383, 384, 421, 573, 649

CAROLINE

H chondrite

Find

FIND	About 1930 by Stuart Keith McEarchern	50, 141, 268, 269, 376, 602
LOCATION	About 1km NE of Dry Creek Homestead (now in ruins) which was south east of Mount Gambier and about 100m from the South Australia-Victorian border. The meteorite was thus found about 500m on the Victorian side of the border. 37° 58'S 140° 58'E	*, 143, 269, 294, 336, 383
IDENTIFIED	Possibly by R.A. Keble about 1940	*, 602
MASS	800g	143, 268, 269, 602
DESCRIPTION	The meteorite was approximately rectangular in shape with dimensions of approximately 8, 8 and 6cm. Regmaglypts are present on one surface. Numerous olivine and pyroxene chondrules are present in a matrix of the same minerals. Recrystallization has obliterated some of the chondrule boundaries. Both barred and radiating chondrules are present. Nickel-iron and a sulfide, claimed to be pyrrhotite, are present. On the basis of mineral content Edwards and Baker (1941) suggested a relationship to Koraleigh but this is untenable as the latter is an L chondrite.	50, 174, 602

DISTRIBUTION			
Main mass	645g	N.M.V.	294, 427
Others	33.5g	S.A.M.	143, 294
	17.3g	A.N.U.	38
	13 g	U.S.N.M.	384
	7.2g	A.M.	35
	0.9g	N.Y.	376
DENSITY	3.40		602
SILICATES			
Olivine	X.R.D. :	Fa_{19}	374
	Probe :	$Fa_{20.9}$	383, 649
Pyroxene	Probe :	$Fs_{18.0}$	383
CHEM. GROUP	H5		35, 143, 224, 376, 383, 384, 421, 602, 649

CARRAWEENA

L chondrite

Find

FIND	In late 1913 or early 1914 by William George Amesbury and Thomas Flinders Gill	*, 35, 119, 143, 267, 268, 269, 284, 329, 376, 388, 438, 573, 584, 586, 640, 694
LOCATION	About 9.7km SW of the Carraweena Head Station which was on the Stzelecki Track east of Lake Blanche 29° 10'S 139° 56'E	*, 6, 35, 119, 143, 268, 269, 284, 294, 336, 383, 388, 586, 640
IDENTIFIED	By W.S. Chapman on Friday February 6, 1914	*, 119
MASS	28.8kg	6, 141, 143, 266, 267, 268, 269, 272, 284, 388, 438, 483, 694
DESCRIPTION	The meteorite was somewhat triangular in shape and the surface is marked with numerous regmaglypts. Numerous light chondrules are set in a dark grey to black matrix as are numerous metal and troilite grains with the outer portions being more weathered than the inner. The bulk of the meteorite is comprised of chondrules and rounded inclusions. Many of the chondrules contain glass exhibiting varying degrees of devitrification. Polysynthetically twinned clinopyroxene is common, particularly in porphyritic material. Undulatory extinction, and in many grains, a pronounced mosaic texture, are indicative of shock. There is minimal evidence of recrystallization. Rare gas analysis suggests that Accalana and Carraweena belong to the same shower.	*, 6, 108, 170, 269, 270, 272, 284, 292, 294, 388, 486, 488, 671

DISTRIBUTION

Main mass	21.77kg	S.A.M.	143, 284, 481
Others	1.47kg	S.A.M.	143
	858g	A.N.U.	38
	703g	U.A.	*
	521g	B.M.	267, 268, 269
	386g	N.Y.	294, 376
	369g	S.A.M.	143
	99g	N.M.V.	427
	44g	U.S.N.M.	294, 384
	21g	A.S.U.	294, 694
	12g	A.M.	35

DENSITY 3.43 — 6, 388

ELEMENTAL COMPOSITION

H	6, 388, 659	Co	119, 388, 659
C	119, 388, 407, 630, 659, 675	Ni	*, 6, 65, 119, 166, 388, 659
Na	*, 6, 119, 166, 388, 623, 659	Cu	65
Mg	*, 2, 6, 119, 166, 388, 659	Zn	65, 659
Al	*, 2, 6, 119, 166, 266, 388, 623, 659	Ga	65
Si	*, 2, 6, 119, 388, 659	As	65
P	*, 6, 119, 166, 388, 659	Se	65
S	*, 6, 119, 388, 659	Cd	65
K	*, 6, 119, 388, 659	In	65
Ti	*, 119, 166, 388, 659	Sb	65
Cr	*, 6, 119, 166, 388, 659	Te	65
Mn	*, 6, 119, 166, 388, 659	Ba	65
Fe	*, 6, 119, 164, 166, 294, 388, 659	Au	65
		Tl	65
		Bi	65

SILICATES

Olivine	X.R.D. : $Fa_{24.9}$		*, 374, 388
	Probe : $Fa_{25.3}$		*, 65, 162, 163, 164, 165, 166, 383, 649
Pyroxene	Probe : $Fs_{20.5}$	$Wo_{2.0}$	*, 65, 164, 383, 626
	Optical : Fs_{22}		388

CHEM. GROUP L3 — 6, 35, 108, 143, 170, 224, 266, 284, 376, 383, 384, 388, 407, 421, 624, 628, 649, 671, 675, 694

OTHER STUDIES

Age	272
Inert Gases	266, 270, 272, 671, 673, 675
Shock History	108, 272

CARTOONKANA

L chondrite

Find

FIND	By Thomas Flinders Gill during the decade 1914-1924	*, 6, 143, 144, 267, 268, 269, 329, 376, 573
LOCATION	On the "Big Plain", Yandama Station, in County Evelyn, New South Wales. 29° 21'S 141° 10'E	*, 6, 143, 267, 268, 269, 284, 294, 330, 336, 381, 383, 421
MASS	ca. 340g	6, 143, 267, 268, 269
DESCRIPTION	A small almost complete mass of 8x5x5cm. A small portion is missing from what otherwise appears to be a complete mass. Extensive recrystallization has completely obliterated the chondritic texture and removed most of the glass. The silicates have a granular texture in places while in others large grains of olivine and pyroxene can be seen. Abundant limonite is present and in general the silicates show little evidence of shock. This meteorite may be related to Yandama.	*, 6, 294, 383

DISTRIBUTION

Main mass	290g	S.A.M.	143, 267, 268, 269, 483
Others	2.0g	U.A.	*
	1.2g	N.Y.	376, 394
	Section	U.S.N.M.	294, 384

DENSITY	3.33	6

ELEMENTAL COMPOSITION

Na	*	Ca	*
Mg	*	Ti	*
Al	*	Cr	*
Si	*	Mn	*
P	*	Fe	*
S	*	Ni	*
K	*		

SILICATES

Olivine	X.R.D.	: $Fa_{24.0}$	*, 374, 376
	Probe	: $Fa_{25.7}$	294, 383, 649
Pyroxene	Probe	: $Fs_{21.6}$	294, 383

CHEM. GROUP	L6	6, 143, 284, 374, 376, 383, 384, 421, 438, 573, 649

COCKBURN No.1

L chondrite

Find

FIND	In 1946 by James Eric Johnson	123, 299
LOCATION	On an aboriginal campsite on Thackaringa Station, south east of Cockburn. About 300m north west of Ophara Hut ruins in County Yancowinna, New South Wales and so about 8km east of the State Border. 32° 07'S 141° 05'E	*, 123, 294, 299
IDENTIFIED	When found	299
MASS	10.13g (estimated original weight ca.12g)	123, 294, 299
DESCRIPTION	The meteorite was bipyramidal in shape and much of the surface was covered with a fusion crust. The silicates have been extensively recrystallized and little chondritic texture is evident. Many irregular metal grains up to 1mm in diameter and smaller ones of troilite are present. Limonitic staining is associated with most of the metal.	*, 299
DISTRIBUTION		
Main mass	4.8g U.A.	*
Others	1.9g U.A.	*
DENSITY	3.47	299
SILICATES		
Olivine	X.R.D. : Fa_{25}	299, 649
	Probe : $Fa_{26.2}$	*
Pyroxene	Probe : $Fs_{22.8}$ $Wo_{1.5}$	*
CHEM. GROUP	L6	*, 299, 649

COCKBURN No.2

L chondrite

Find

FIND October 1967 by Lois E. McColl *

LOCATION	About 1km NW of the Ophara hut ruins on Thackaringa Station, south east of Cockburn in County Yancowinna, New South Wales and about 8km east of the State border. 32° 07'S 141° 05'E	*
IDENTIFIED	By D.H. McColl when found	*
MASS	5.0g	*, 359
DESCRIPTION	The meteorite is pyramidal in shape with flow lines radiating from the vertex. Extensive recrystallization has obliterated any chondritic texture although some evidence of it can be seen in the configuration of metal and troilite grains. Limonitic staining is associated with the metal grains.	*
DISTRIBUTION		
Main mass	2.9g U.A.	*
Others	1.3g U.A.	*
SILICATES		
Olivine	Probe : $Fa_{26.4}$	*
Pyroxene	Probe : $Fs_{22.8}$ $Wo_{1.5}$	*
CHEM. GROUP	L6	*

COCKBURN No.3

L chondrite

Find

FIND	2:45pm on Thursday June 8, 1972, by James Eric Johnson	*
LOCATION	On Thackaringa Station, south east of Cockburn. About 1km north of the Ophara hut ruins in County Yancowinna, New South Wales and about 8km east of the State border. 32° 07'S 141° 05'E	*
IDENTIFIED	When found	*
MASS	83.0g	*
DESCRIPTION	This meteorite is approximately rhombohedral in shape. It has a smooth anterior surface and a rougher posterior one, which may be an earlier fracture surface, marked with many shallow regmaglypts. Small grains of metal and troilite are evenly disseminated throughout the specimen. A colour zonation produced by sulfide weathering can be seen. Recrystallization has obliterated most of the chondritic texture, but, in some places, it is quite clear and more marked than in any of the other Cockburn specimens. Limonitic staining is ubiquitous.	*

DISTRIBUTION

Main mass	68g	U.A.	*
Others	1g	U.A.	*

ELEMENTAL COMPOSITION

Na	*	Ca	*
Mg	*	Ti	*
Al	*	Cr	*
Si	*	Mn	*
P	*	Fe	*
S	*	Ni	*
K	*		

SILICATES

Olivine X.R.D. : $Fa_{24.7}$ *

CHEM. GROUP L6 *

COCKBURN No.4

L chondrite

Find

FIND At 9:50am on Sunday July 2, 1972, by James Eric Johnson *

LOCATION On Thackaringa Station, south east of Cockburn. About 600m north west of the Ophara Hut ruins in County Yancowinna, New South Wales, and about 8km east of the State border. *
32° 07'S 141° 05'E

IDENTIFIED When found *

MASS 75.0g *

DESCRIPTION The meteorite is approximately tetrahedral in shape with a height of about 3.5cm. Three of the surfaces are quite smooth while the other has shallow indentations in it. Limonitic staining is generally confined to the vicinity of metal particles, the unstained material being white to grey. Except for isolated instances, recrystallization has removed all traces of a chondritic structure. *

DISTRIBUTION

Main mass	48g	U.A.	*
Others	4.3g	U.A.	*

ELEMENTAL COMPOSITION	Na *	Ca *	
	Mg *	Ti *	
	Al *	Cr *	
	Si *	Mn *	
	P *	Fe *	
	S *	Ni *	
	K *		
SILICATES			
Olivine	X.R.D. : $Fa_{25.4}$		*
CHEM. GROUP	L6		*

COCKBURN No.5

L chondrite

Find

FIND At 2:30pm on Sunday July 2, 1972 by Roderick Jeffery Hill *

LOCATION On Thackaringa Station, south east of Cockburn, about 8km east of the State border. About 100m west of the ruins of Ophara Hut in County Yancowinna, New South Wales. *
32^{o} 07'S 141^{o} 05'E

IDENTIFIED When found *

MASS 31.0g *

DESCRIPTION The specimen is elongated. One surface shows evidence of pock marking while the other three are quite smooth with evidence of flow structures on them. The specimen probably broke on impact and about 15% is missing. There are numerous small metal grains present, many associated with oxidative staining. Recrystallization has obliterated most of the chondritic texture. *

DISTRIBUTION

Main mass	16.25g	U.A.	*
Others	16.3g	U.A.	*

ELEMENTAL COMPOSITION	Na *	Ca *	
	Mg *	Ti *	
	Al *	Cr *	
	Si *	Mn *	
	P *	Fe *	
	S *	Ni *	
	K *		
SILICATES			
Olivine	X.R.D. : $Fa_{26.1}$		*
CHEM. GROUP	L6		*

COCKBURN No.6

L chondrite

Find

FIND	Sunday July 22, 1973, by Brian Harold Mason	*, 123, 383
LOCATION	On Thackaringa Station, south east of Cockburn. About 600m north west of the Ophara Hut ruins in County Yancowinna, New South Wales, some 8km east of the State border. 32° 07'S 141° 05'E	*, 123, 294, 383
IDENTIFIED	When found	383
MASS	2.207kg	123, 294, 383
DESCRIPTION	This meteorite is heavily altered and in places weathering has taken place along a series of fractures which are approximately paralllel to the outer surface. Small grains of metal and troilite are widely distributed. Extensive replacement of opaque minerals has occured. Recrystallization has erased most of the chondrule boundaries. The fusion crust on part of the specimen has been removed by sandblasting.	*

DISTRIBUTION

Main mass	1.807kg	U.S.N.M.	*, 384
Others	87g	U.S.N.M	*, 384
	66g	U.A.	*
	34g	A.N.U.	38
	32g	B.M.R.	360

ELEMENTAL COMPOSITION

Na	*	Ca	*
Mg	*	Ti	*
Al	*	Cr	*
Si	*	Mn	*
P	*	Fe	*
S	*	Ni	*
K	*		

SILICATES

Olivine	X.R.D.	: $Fa_{25.5}$	*
	Probe	: $Fa_{25.1}$	383
Pyroxene	Probe	: $Fs_{21.4}$	383

CHEM. GROUP	L6	123, 224, 294, 383, 384, 421

COCKBURN No.7

L chondrite

Find

FIND	Sunday July 22, 1973, by Brian Harold Mason	*, 123, 383
LOCATION	On Thackaringa Station, south east of Cockburn. About 600m north west of the Ophara Hut ruins in County Yancowinna, New South Wales some 8km east of the State border. 32° 07'S 141° 05'E	*, 123, 383
IDENTIFIED	When found	*
MASS	53g	*, 383
DESCRIPTION	This small brown specimen has no evidence of a fusion crust and may be a fragment of Cockburn No.6 as it was found only a metre away from it.	*
DISTRIBUTION		
Main mass	53g U.S.N.M.	*
CHEM. GROUP	?L6	*, 123, 383

COCUNDA

L chondrite

Find

FIND	In 1945 by Alice Mitton	*, 141, 143, 269, 374, 376, 566
LOCATION	In the centre of the western edge of Section 33 of the Hundred of Inkster, County Robinson on Eyre Peninsula. This location is about 1.5km from Cocunda Rockhole on a bearing of 245°. 32° 49'S 134° 44'E	*, 143, 294, 374, 383
IDENTIFIED	Probably when presented to the S.A. Museum in 1946	
MASS	482g	141, 143, 376

DESCRIPTION The silicates of this meteorite have been completely recrystallized and little trace of chondrules remain. There are areas of olivine megacrysts set in a fine granular matrix which were probably once inclusions of porphyritic material. The amount of limonitic staining is variable. Large anhedral grains of olivine are present and those in areas stained with limonite have limonitic stains on their fracture planes. Many of the olivine grains contain small bubble trains, while fibrous pyroxenes, which are possibly devitrified glasses, contain numerous opaques. *

DISTRIBUTION

Main mass	367g	S.A.M.	143, 269
Others	1g	N.Y.	294, 376
	1g	U.A.	*
	Slide	U.S.N.M.	294, 384

ELEMENTAL COMPOSITION

F	246	V	246, 325
Na	*	Cr	*
Mg	*	Mn	*
Al	*	Fe	*
Si	*	Co	246
P	*, 246	Ni	*
S	*	Cu	246
Cl	246	Zn	246, 655
K	*	Ge	246
Ca	*	Sr	246
Sc	246	Ba	246, 484
Ti	*, 246		

SILICATES

Olivine	X.R.D. : $Fa_{25.2}$		*, 374
	Probe : $Fa_{25.8}$		294, 383, 649
Pyroxene	Probe : $Fs_{21.1}$		383

CHEM. GROUP L6 — 143, 224, 294, 374, 376, 383, 384, 421, 649

COOMANDOOK No.1

H chondrite

Find

FIND In 1939 by G. Ninnis — 141, 143, 269, 294, 374, 376, 570

LOCATION In a paddock 13km east of the town of Coomandook. In Section 21 of the Hundred of Roby, County Buccleuch
35° 29'S 139° 50'E — 143, 269, 294, 374

IDENTIFIED	Probably when presented to the S.A.M. in 1940	143
MASS	1.05kg	141, 143, 294, 374
DESCRIPTION	There is little evidence of a chondritic texture in this meteorite, fragments of pyroxene and olivine being set in an opaque matrix. The olivine grains which are extensively fractured have limonitic stains on their fracture planes. Occasional fragments consisting of anhedral mineral grains set in a devitrified matrix are present.	*
DISTRIBUTION		
Main mass	843g S.A.M.	*, 143, 294
Others	15g U.A.	*
	1.2g N.Y.	376
ELEMENTAL COMPOSITION	Na *, Mg *, Al *, Si *, P *, S *, K *, Ca *, Ti *, Cr *, Mn *, Fe *, Ni *	
SILICATES		
Olivine	X.R.D. : $Fa_{19.0}$	*, 374
	Probe : $Fa_{18.8}$	383, 649
Pyroxene	Probe : $Fs_{17.0}$	383
CHEM. GROUP	H6	224, 269, 376, 383, 384, 421, 649

COOMANDOOK No.2

H chondrite

Find

FIND	In January 1967 by Rex Arnold Goodall	*, 143, 294, 570
LOCATION	In a paddock 7.6km east of the town of Ki Ki. In the SE corner of Section 18 of the Hundred of Livingston in County Buccleuch. This place is less than 16km from the place where Coomandook No.1 was found. 35° 32'S 139° 52'E	143, 570
MASS	ca. 4.54kg	*
DESCRIPTION	This meteorite is similar in external appearance, mineralogy and composition to Coomandook No.1.	143

DISTRIBUTION			
Main mass	4.192kg	S.A.M.	*, 143, 294
Others	250g	S.A.M.	*
SILICATES			
Olivine	X.R.D. : Fa_{19}		374
CHEM. GROUP	?H6		143, 374

COONANA

H chondrite

Find

FIND	On Thursday June 7, 1962 by John Rattus	141, 143, 269, 376, 568
LOCATION	5.5km west of Coonana Bore which is on Yandama Creek east of Lakes Blanche and Callabonna 29° 51's 140° 42'E	*, 143, 269, 294, 383
IDENTIFIED	When found	*
MASS	6.8 kg - about one fifth was broken off after the meteorite was found	*, 141, 143
DESCRIPTION	The meteorite is heavily weathering suggesting an old fall. The most abundant mineral is olivine; feldspar, pyroxene and glass occur in minor amounts. Troilite and nickel-iron are present. Fractures are filled with goethite. Numerous chondrules are present and in general they show less limonitic staining than the matrix. Barred olivine ones are present, some of the olivine bars being skeletal. Porphyritic material commonly consists of olivine megacrysts set in a partly devitrified glass.	*, 39, 143

DISTRIBUTION			
Main mass	4.36kg	S.A.M.	143, 294
Others	479g	S.A.M.	143
	209g	N.M.V.	427
	22.3g	U.A.	*
	20.5g	B.M.	294
	18g	N.Y.	294, 376
	Slide	U.S.N.M.	384

ELEMENTAL COMPOSITION	Na *	Ca *
	Mg *	Ti *
	Al *	Cr *
	Si *	Mn *
	P *	Fe *
	S *	Ni *
	K *	

SILICATES			
Olivine	X.R.D.	: $Fa_{18.9}$	*, 378
	Probe	: $Fa_{19.2}$	294, 383, 649
Pyroxene	Probe	: $Fs_{16.3}$	383
CHEM. GROUP	H4		143, 224, 269, 376, 383, 384, 421, 649

COWELL

Medium octahedrite

Find

FIND	In March or April 1932 by Robert Jack McDonald	*, 35, 294, 530, 569
LOCATION	In the SW corner of Section 44 of the Hundred of Caralue, County Buxton. About 19km from the Caralue railway siding on a bearing of 292°. This meteorite was found about 300m west of the recovery site of Kyancutta. 33° 18'S 136° 01'E	*, 35, 141, 143, 269, 294, 530
IDENTIFIED	Probably when sold to Adelaide University in March 1956	*, 530
MASS	5.717kg	294, 359, 530
DESCRIPTION	The meteorite has a Widmanstatten pattern typical of medium octahedrites with 60-90% being composed of kamacite lamellae. There is only one orientation present in the lamellae implying crystallization from a single crystal. Scattered large troilite nodules are present. The meteorite was originally rectangular in shape to a first approximation with most of the surface marked with large regmaglypts, at least one of whoch intersects a large troilite nodule.	*, 530

DISTRIBUTION			
Main mass	1.874kg	U.A.	*, 269, 530
Others	2.348g	U.A. (three masses)	*
	269g	Kyancutta	*
	221g	S.A.M.	*, 143
	219g	N.M.V.	427
	127g	A.M.	35
	96.5g	B.M.	294
	Section	A.N.U.	38
DENSITY	7.64		359

ELEMENTAL COMPOSITION	C 530	Co 530	
	P 530	Ni *, 506, 530	
	S 530	Cu 530	
	Cl 530	Zn 530	
	Cr 530	Ga 294, 506, 649	
	Mn 530	Ge 294, 383, 506, 649	
	Fe 530		
Ni-Fe ALLOYS			
Bandwidth	1.15mm		*
Cooling rate			*
CHEM. GROUP	IIIA		35, 83, 143, 224, 269, 294, 383, 506, 530, 551, 649

CROCKER'S WELL

Chondrite

Find

FIND	In 1956 by James Eric Johnson	124, 141, 143, 294
LOCATION	On a granite hill 450m north of the East Crocker uranium prospect near Crocker Well Camp and north west of Plumbago Homestead in County Lytton. 32° 01'S 139° 47'E	124, 143, 383
IDENTIFIED	When found	
MASS	3.8g	124, 141, 143
DESCRIPTION	A chondrite which may be related to Ethiudna	*
DISTRIBUTION		
Main mass	3.8g S.A.M.	143
Others		
CHEM. GROUP	Unclassified	124, 143, 224, 294, 383, 421

ETHIUDNA

?L chondrite

Find

FIND Morning of Sunday February 20, 1977, by Michael James William Larrett *

LOCATION Laying on a very flat, red-brown, loamy plain 6.8km NNW of Ethiudna Hill and NW of Plumbago Station, County Lytton. *
31° 59'S 139° 46'E

IDENTIFIED When found *

MASS 74.318kg *

DESCRIPTION The meteorite is approximately cubic in shape although one of the faces is comprised of three slightly pyramidal faces. Most of the meteorite is crusted. In one place there is a 20cm long piece missing but the scar has been crusted over. One surface has numerous regmaglypts on it while the others are much smoother. It has a chondritic texture and is the largest recovered South Australian chondrite. There is a small piece missing from one corner and the mass be related to Crocker's Well, South Australia's smallest find, which was recovered only 6.5km away. Preliminary investigations at AMDEL suggest the meteorite is an L chondrite. *

DISTRIBUTION

Main mass 74.318kg Finder *

FORREST LAKES

LL chondrite

Find

FIND In 1948 or earlier by T. Dimer 29, 268, 269, 357

LOCATION About 75km from the Reid railway station on the Trans Australian Railway line on a bearing of 35° 64, 269, 357
30° 15'S 128° 55'E

MASS 500g 294, 357

DESCRIPTION	The meteorite is covered with a rough dark brown fusion crust and the shape of the fragment recovered suggests that the mass was small and perhaps cone shaped. The chondrules are enclosed in a dark opaque matrix with little metal being visible.		357
DISTRIBUTION			
Main mass	208.5g	G.L.W.A.	350, 357
Others	38g	W.A.M.	357
	33g	N.Y.	294, 376
	Slide	U.S.N.M.	294, 384
DENSITY	4		357
ELEMENTAL COMPOSITION	F 246, 269	Fe 246	
	P 246	Co 246, 269	
	Cl 246, 269	Ni 246	
	Sc 246, 269	Cu 246, 269	
	Ti 246, 269	Zn 246, 269	
	V 246, 269	Ge 246, 269	
	Cr 246, 269	Sr 246, 269	
	Mn 246, 269	Ba 246, 269, 484	
SILICATES			
Olivine	X.R.D. : Fa_{26}		378, 649
	Probe : $Fa_{27.5}$		294, 383
Pyroxene	Probe : $Fs_{20.7}$		383
CHEM. GROUP	LL5		224, 268, 269, 294, 350, 357, 421, 484, 649

GALLIPOLI STATION

Medium octahedrite

Find

FIND	Supposedly on Gallipoli Station in 1970 but the station manager denies all knowledge of this.	83, 294
MASS	6kg	294
DESCRIPTION	Buchwald maintains that this is a piece of Henbury while Moore suggests it may be distinct.	83, 85, 294
ELEMENTAL COMPOSITION	Ni 294	
CHEM. GROUP	IIIA	85

GLEN HELEN

Iron

Find

FIND	Believed to have been found by an aboriginal	*
LOCATION	The meteorite was given to Drs. Henderson and Mason and Mr. Chalmers from the Australian Museum in 1963 by P.D. Boerner, an Alice Springs resident, who claimed that it had been found in the Glen Helen area in the MacDonnell Ranges, west of Alice Springs #23° 41'S 132° 40'E	*, 35
MASS	727g	35
DESCRIPTION	It is possibly a Henbury fragment.	*
DISTRIBUTION Main mass	727g A.M.	35
CHEM. GROUP	Iron	35

HART RANGE

Medium octahedrite

Find

FIND	Unknown	357
LOCATION	Unknown - reputedly in the Hart Range area of the Northern Territory #23°S 131°E	83, 155, 269, 357
MASS	Unknown	357
DESCRIPTION	On the basis of analytical data and an examination of the Widmanstatten pattern it has been concluded that this meteorite is identical to Boxhole but different from Henbury.	123, 155, 294, 354, 383
DISTRIBUTION Main mass	608g W.A.M.	155, 357
ELEMENTAL COMPOSITION	Co 155, 354 Ga 155, 354 Ni 155, 354 Ge 155, 354	
CHEM. GROUP	Medium octahedrite	83, 155, 357

HENBURY

Medium octahedrite

Find

LOCATION	The presence of meteoritic material at Henbury was reported to Adelaide University early in 1931; the material was reputedly known locally as early as 1916. The first scientific party to visit the area arrived in May 1931 when they found 13 craters, the largest of which, actually a double crater, was some 200m in diameter. Some are explosion craters while others are impact ones. They were produced by a shower of a large number of masses up to 5000 years ago. Two of the craters have ejecta rays radiating from them similar to lunar features. The first and subsequent parties collected a large number of specimens from around the craters, which are about 11km WSW of Henbury Station on the Finke River in Northern Territory. The locality is SW of Alice Springs. Material was also subsequently excavated from some of the craters. 24° 35'S 133° 08'E	*, 3, 4, 5, 6, 8, 11, 16, 17, 18, 19, 20, 21, 24, 25, 26, 27, 28, 31, 35, 44, 45, 55, 57, 59, 82, 83, 85, 112, 114, 115, 126, 137, 141, 143, 147, 149, 150, 159, 160, 196, 197, 210, 211, 231, 248, 253, 254, 255, 267, 268, 269, 277, 278, 284, 290, 308, 310, 315, 316, 317, 330, 333, 334, 335, 352, 357, 368, 372, 376, 381, 397, 399, 400, 401, 403, 420, 435, 441, 442, 448, 468, 494, 495, 496, 509, 573, 574, 576, 582, 585, 588, 611, 620, 654, 679, 682, 684, 685, 694, 710
MASS	ca. 2.5 tonne recovered to date	*, 83, 85, 143, 231, 284, 632, 694
DESCRIPTION	Both distorted and undistorted material is known. The former was probably produced by fragmentation on impact while the latter had an independent passage through the atmosphere. Regmaglypts and heat-affected zones are present on many of the undistorted specimens. These have an octahedral etch pattern showing normal Neumann lines. Schreibersite and nitrides such as carlsbergite are present as are troilite and daubreelite. Reichenbach lamellae can be seen. The presence of native copper has been reported. In the distorted material, the Widmanstatten pattern is distorted and partly resorbed. Surface markings on various specimens give an indication of their history as do internal fractures. Various lines of evidence point to the independence of the Henbury and Boxhole falls although the meteorites both belong to the same chemical group. Shale balls similar to those found at Boxhole crater were found at Henbury. The metallic spherules found in the soil around the craters represent material vapourized on impact.	4, 41, 43, 58, 75, 83, 84, 88, 143, 155, 255, 308, 354, 368, 370, 430, 440, 441, 462, 488, 525, 575, 576, 583, 697, 699
DISTRIBUTION	The largest known, accurately weighed single mass is one of 180.9kg U.S.N.M.	83, 85, 141, 284, 420
Others	408kg B.M.	3, 5, 83, 267, 268, 269, 284, 420
	ca.270kg A.N.U.	38, 83
	227kg U.S.N.M.	83, 267, 268, 269, 384
	175kg A.S.U.	83, 268, 269, 443, 694

159kg	N.M.V.	427
133kg	S.A.M.	83, 143, 267, 268, 269, 284
72kg	N.Y.	83, 267, 268, 269, 376, 509
57+kg	A.M.	35, 83, 267, 268, 269, 284
36kg	Idar-Oberstein Heimatmuseum	83
24kg	Tubingen	83
19kg	F.M.C.	83, 269
7.5kg	Paris	83, 269
7.4kg	Budapest	83, 268, 269
6.9kg	U.A.	*
6.7kg	B.M.R.	*
5.7kg	Calcutta	83
5.0kg	G.L.W.A.	269, 357
4.8kg	Oslo	83
4.6kg	Dorpat	83
2.5kg	U.C.	83, 269, 331, 333, 652
2.1kg	W.A.M.	83, 357
2.1kg	Yale	83, 269
2.0kg	Harvard	83, 212
1.6kg	Ann Arbor	83
1.5kg	Michigan	268, 269
1.4kg	G.S.C	83, 223, 269
1.1kg	Amherst	83
950g	Moscow	83
530g	Stockholm	83
500g	Prague	83
440g	Copenhagen	83, 85
353g	Jena	209
212g	G.S.N.S.W.	136
200g	Belgrade	83

DENSITY 7.53 — 4, 495

ELEMENTAL COMPOSITION

Be	101, 113, 310, 343, 525
C	4, 83, 155, 173, 229, 230, 284, 310, 337, 431, 462, 496
Al	525
Si	4, 260, 496
P	4, 83, 85, 155, 173, 260, 284, 337, 462, 496, 504
S	4, 83, 173, 260, 284, 462, 496, 575
Cl	113, 173, 231, 310, 462, 525, 632
K	257
Sc	260
V	325, 343, 431
Cr	83, 155, 171, 260, 269, 343, 348, 428, 431, 462, 560
Mn	343
Ge	83, 85, 155, 171, 188, 189, 233, 269, 289, 343, 348, 354, 383, 428, 506, 520, 553, 559, 560, 619, 649, 650, 708
As	134, 249, 260, 269, 340, 431, 453, 455, 456, 560, 561
Se	260
Zr	269, 395
Nb	99
Mo	260, 322, 560
Ru	146, 252, 260, 269, 430, 554, 721
Rh	146, 269, 430, 554
Pd	146, 233, 250, 269, 430, 554, 559, 560, 721, 730
Ag	100, 321, 560, 633
Cd	155, 521
In	260, 560

Fe	4, 173, 260, 284, 316, 393, 431, 462, 494, 495, 496, 575, 658	Sn	102, 157, 158, 260, 269, 457, 556, 662
Co	4, 83, 134, 155, 171, 173, 233, 260, 269, 284, 316, 337, 343, 348, 354, 393, 431, 462, 469, 496, 575, 658	Sb	249, 260, 269, 454, 456, 560, 561
		Lu	361
		Hf	269, 372, 395
		Ta	34, 177, 178, 269, 729
		W	34, 179, 313, 688, 690, 724
Ni	*, 4, 33, 75, 83, 85, 134, 155, 158, 171, 173, 189, 233, 235, 260, 269, 284, 316, 337, 343, 346, 348, 354, 383, 389, 393, 428, 430, 431, 469, 476, 494, 495, 496, 503, 504, 506, 520, 553, 575, 619, 649, 650, 662, 665, 666, 688, 697, 704, 708	Re	9, 79, 232, 260, 264, 265, 269, 411, 419, 560, 721, 731
		Os	9, 146, 260, 264, 265, 269, 412, 554, 721, 731
		Ir	83, 85, 134, 146, 155, 233, 250, 260, 269, 307, 348, 430, 553, 554, 649, 650, 721, 730
Cu	83, 134, 155, 171, 269, 284, 343, 348, 428, 431, 446, 462, 560, 575	Pt	146, 250, 269, 430, 462, 554, 721, 730
		Au	134, 232, 233, 260, 269, 560
Zn	83, 155, 251, 260, 269, 431, 445, 446, 520, 521, 559, 560, 655, 689	Hg	260, 463
		Pb	9, 200, 269, 287, 423, 424, 460, 461, 465, 466, 601, 656
Ga	83, 85, 134, 154, 155, 171, 233, 269, 348, 354, 428, 446, 506, 520, 553, 559, 560, 619, 649, 650, 708	Th	146
		U	146, 269, 414, 423, 502

It has been suggested that some of these analyses have been carried out on mislabelled specimens. 520, 544, 650

Ni-Fe ALLOYS

Alpha parameter 462

Bandwidth 0.92mm *, 83, 213, 235, 476, 520, 544, 553, 650, 665

Composition 476, 504, 505

Cooling rate *, 235, 476

OTHERS Schreibersite 503

CHEM. GROUP IIIA 4, 6, 9, 35, 83, 85, 143, 224, 235, 260, 261, 267, 268, 269, 308, 333, 343, 348, 357, 376, 383, 384, 420, 430, 446, 476, 551, 553, 575, 594, 633, 649, 652, 665, 666, 688, 694

OTHER STUDIES

Age 9, 33, 148, 195, 200, 222, 231, 287, 310, 312, 323, 324, 424, 465, 525, 528, 631, 632, 637

Henbury Glass	49, 51, 110, 114, 169, 175, 176, 198, 314, 325, 381, 478, 479, 510, 515, 555, 575, 577, 578, 579, 580, 587, 589, 591, 603, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 686, 722, 723
Inert Gases	9, 33, 109, 113, 148, 222, 464, 502, 622, 631, 632
Magnetic Properties	261, 346, 471
Shock History	297, 298, 469, 512
Soil Study	225, 279, 280, 281, 494, 495, 496, 697
Terrestrial Age	3, 5, 9, 83, 126, 229, 230, 231, 310, 492, 525

HOLLMAYER No.5

H chondrite

Find

FIND	Between 1969 and 1975 by Werner Hollmayer	*
LOCATION	About 135km south of Broken Hill in the Popio Lakes area	*
IDENTIFIED	April 1975 by D.H. McColl and M.J. Fitzgerald	*
MASS	72.2g	*
DESCRIPTION	This meteorite has a clear chondritic texture with many of the chondrules containing skeletal crystals. Former glassy material is commonly devitrified giving "feathery" and "wheatsheaf" structures.	*

DISTRIBUTION

Main mass		Finder	*
Others	16.7g	B.M.R.	*
	3.8g	U.A.	*

ELEMENTAL COMPOSITION	Na *		Ca *	
	Mg *		Ti *	
	Al *		Cr *	
	Si *		Mn *	
	P *		Fe *	
	S *		Ni *	
	K *			

SILICATES				
Olivine	X.R.D.	: $Fa_{18.9}$		*
	Probe	: $Fa_{19.8}$		*
Pyroxene	Probe	: $Fs_{17.5}$	$Wo_{1.0}$	

CHEM. GROUP H5

HOLLMAYER No.6

H chondrite

Find

FIND Between 1969 and 1975 by Werner Hollmayer *

LOCATION About 135km south of Broken Hill in the Popio Lakes area. *

IDENTIFIED April 1975 by D.H. McColl and M.J. Fitzgerald *

MASS 68.2g *

DESCRIPTION This meteorite has a well defined chondritic texture, both barred and radiating chondrules being present in addition to glassy ones. *

DISTRIBUTION			
Main mass			
Others	12.9g	B.M.R.	*
	3.0g	U.A.	*

ELEMENTAL COMPOSITION	Na *		Ca *	
	Mg *		Ti *	
	Al *		Cr *	
	Si *		Mn *	
	P *		Fe *	
	S *		Ni *	
	K *			

SILICATES				
Olivine	X.R.D.	: $Fa_{15.1}$		*
	Probe	: $Fa_{18.0}$		*
Pyroxene	Probe	: $Fs_{16.7}$	$Wo_{1.2}$	*

CHEM. GROUP H5 *

HUCKITTA

Pallasite

Find

FIND	Prior to June 1937 by Michael Laughton. A small fragment initially called Alice Springs and believed to be a fragment of the larger mass was found in 1924 by Herbert Basedow.	141, 143, 267, 268, 269, 284, 315, 369, 375, 376, 435, 573, 694
LOCATION	On the northern side of the Dulcie Range in the Northern Territory, 32km NE of Huckitta Station. (The small piece was found about 16km north of Alice Springs) 22° 22'S 135° 46'E	143, 267, 268, 269, 284, 330, 369, 437, 573, 683
IDENTIFIED	The smaller piece was probably identified when found while the larger mass was identified by C.T. Madigan on Tuesday July 6, 1937.	368, 369, 573
MASS	1415+kg	55, 143, 267, 268, 269, 294, 355, 368, 372, 694
DESCRIPTION	The meteorite was shaped somewhat like a flat iron with a length of about 130cm and a maximum girth of about 220cm. About 60% by volume of the mass is a brown to green olivine while troilite and schreibersite make up about 1%. The olivine, which is fresh, is of constant composition throughout the mass and occurs as anhedral single grains. Rounded grains of kamacite surround areas of plessite, generally edged with taenite. A Widmanstatten pattern can be seen in the plessite.	103, 104, 344, 368, 375, 546, 651

DISTRIBUTION

Main mass	916kg	S.A.M.	143
Others	225.3kg	S.A.M.	143
	4.23kg	U.A.	*
	3.76kg	N.Y.	376
	2.1 kg	A.S.U.	269, 694
	1.04kg	B.M.	267, 268, 269
	403g	U.S.N.M.	294, 384
	7.6g	A.N.U.	38
	877kg	S.A.M. (shale)	143

DENSITY	5.073	103, 284, 368, 546

ELEMENTAL COMPOSITION

C	369, 375	Co	145, 284, 369, 375, 545, 546, 573
Na	284	Ni	145, 284, 369, 375, 383, 545, 546, 573
Mg	145, 284, 375, 546, 573	Ga	545
Si	145, 284, 369, 375, 546, 573	Ge	545
P	369, 546	As	545
S	284, 369, 375, 546, 573	W	545
Ca	284, 375, 573	Ir	545
Cr	546	Au	545
Mn	284	Th	413, 418
Fe	145, 284, 369, 375, 546, 573	U	414, 418

SILICATES		
Olivine	Probe : $Fa_{12.5}$	104, 294, 375, 546
Pyroxene	Probe : $Fs_{11.8}$	546
Ni-Fe ALLOYS		
Cooling Rate		104, 639, 649, 651
OTHERS	Phosphate minerals	105
CHEM. GROUP	Pallasite (metal composition is similar to IIE irons)	104, 141, 143, 151, 224, 267, 268, 269, 372, 376, 383, 384, 435, 545, 639, 649. 694

KALDOONERA HILL

H chondrite

Find

FALL	Possibly during 1916	567
FIND	During a period of some ten to twelve years beginning three or four years prior to 1956 by E.G. Voumard and Noel Everard Gosling	*, 141, 143, 269, 374, 376, 694
LOCATION	Dispersed along an east-west trending line approximately 1km in length in a paddock 8.8km south of Kaldoonera Hill, Section 2 of the Hundred of Kaldoonera, County Robinson. 32° 37'S 134° 51'E	*, 143, 269, 294, 374, 383
IDENTIFIED	First samples by B. Daily in 1956, subsequent ones when found	*
MASS	12+kg	*, 141, 143, 374, 694
DESCRIPTION	The meteorite is extensively weathered. Nickel-iron and troilite can be seen on a polished surface as well as some evidence of a chondritic texture. The meteorite has been extensively recrystallized, nonetheless, several partly rounded grains, which are possibly chondrule fragments, are present. These commonly consist of subhedral to anhedral megacrysts of olivine set in a granular pyroxenic groundmass, but in some cases the groundmass has a radiating texture. In both instances the groundmass is probably a devitrified glass. The fracture planes of many of the olivine grains are stained with limonite.	*

DISTRIBUTION			
Main mass	4.54kg	S.A.M.	143
Others	3.585kg	S.A.M.	*
	1.86kg	S.A.M.	143
	752g	Kyancutta	*
	675g	U.A.	*
	478g	N.Y.	269, 294, 376
	40g	A.S.U.	694
	1.4g	U.S.N.M.	384
	Other masses are also held in the Streaky Bay School and by relatives of Mr. Voumard and Mr. Beck		*

ELEMENTAL COMPOSITION	F 246, 269, 311	V 246, 269, 325	
	Na *	Cr *, 246, 269	
	Mg *	Mn *, 246, 269	
	Al *	Fe *, 246	
	Si *	Co 246, 269	
	P *, 246	Ni *, 246	
	S *	Cu 246, 269	
	Cl 246, 269	Zn 246, 269, 655	
	K *	Ge 246, 269, 289	
	Ca *	Sr 246, 269	
	Sc 246, 269	Ba 246, 484	
	Ti *, 246, 269		

SILICATES		
Olivine	X.R.D. : $Fa_{18.1}$	*, 374
	Probe : $Fa_{18.7}$	294, 383, 649
Pyroxene	Probe : $Fs_{16.8}$	383
CHEM. GROUP	H6	224, 294, 376, 383, 384, 421, 649, 694

KAPPAKOOLA

H chondrite

Find

FIND	In September 1929 by Frederick W. Daniel	35, 141, 144, 267, 268, 269, 284, 435, 586
LOCATION	On a sand dune 13km south of Kyancutta in Section 11 of the Hundred of Kappakoola, County Le Hunte 33° 15'S 135° 32'E	*, 6, 35, 267, 268, 269, 284, 294, 336, 383, 586, 649
IDENTIFIED	In October 1935 by R. Bedford	586
MASS	392.5g	6, 141, 284, 435, 586

DESCRIPTION	When found this meteorite was complete, being in the shape of a right triangular prism with a slightly concave base and domed apex. The surface was even with no conspicuous regmaglypts. The interior was not extensively weathered as shown by its grey colour. Troilite and nickel iron could be seen on a cut surface as could rare chondrules, most of which had been recrystallized.		315, 586
DISTRIBUTION			
Main mass	?331g	Unknown	143, 571, 586
Others	45g	B.M.	267, 268, 269, 586
	9g	S.A.M.	294
	1.3g	A.M.	35
	0.7g	U.S.N.M.	384
DENSITY	3.59		586
SILICATES			
Olivine	X.R.D. : Fa_{17}		374, 649
	Probe : $Fa_{19.6}$		383
Pyroxene	Probe : $Fs_{17.2}$		383
CHEM. GROUP	H6		35, 224, 374, 383, 421, 628, 649

KAPUNDA

Medium octahedrite

Find

FIND	About 1965 by Ann Marie Peters and Heather Shakes	*, 294
LOCATION	Near a creeek bridge on a back road some 2km south east of Allandale North and about 4km from Kapunda on a bearing of 15°. Probably in one of Sections 1463, 1505, 1552 or 1553 of the Hundred of Kapunda in County Light #34° 19'S 138° 56'E	*, 294
IDENTIFIED	On Sunday June 11, 1972, by J.B. Peters and M.J. Fitzgerald	*
MASS	541.5g	*, 294
DESCRIPTION	A small shield-like body similar in shape to Murnpeowie. The flatter of its two main surfaces is marked with numerous regmaglypts while the other surface is irregular with several protrusions and shallow pits. Several small troilite nodules can be seen on a cut and etched surface.	*
DISTRIBUTION		
Main mass	382g U.A.	*, 294
Others	136.8g U.A.	*

ELEMENTAL COMPOSITION Ni-Fe ALLOYS	Fe *	Ni *	
Bandwidth	0.93mm		*
CHEM. GROUP	IIIA		*, 294

KAROONDA

C chondrite

Fall

FALL	10:53pm on Tuesday November 25, 1930	3, 5, 12, 22, 35, 141, 143, 218, 242, 243, 244, 267, 268, 269, 284, 317, 334, 371, 376, 386, 391, 421, 425, 573, 586, 634, 680, 684, 694
FIND	By Kerr Grant and George Frederick Dodwell on the morning of Tuesday December 9, 1930. The fragmented meteorite was lying within a circle of about 1m radius. A further amount of material was found about 20m away some 2 to 3 weeks later by Paul Benno Sontagg and his brother.	*, 12, 14, 15, 16, 23, 141, 143, 224, 242, 243, 244, 267, 268, 269, 386, 391, 573, 681, 710, 711
LOCATION	The meteorite was found 400m west of the eastern corner of Section 48 of the Hundred of Marmon Jabuk, County Buccleuch. This location is approximately 2km east of the town of Karoonda. A column to commemorate the fall and finding of the meteorite was erected in the main street of this town about 18 months later. 35° 05'S 139° 55'E	*, 6, 35, 123, 141, 143, 242, 243, 244, 267, 268, 269, 284, 294, 329, 383, 391, 421, 438, 586, 686, 694
IDENTIFIED	When found	
MASS	41.73+kg	*, 6, 125, 141, 143, 242, 243, 244, 267, 268, 269, 284, 362, 371, 386, 694
DESCRIPTION	The meteorite consists predominantly of olivine. In section granular olivine chondrules and anhedral olivine fragments are seen set in a fine grained, opaque matrix, much of which is olivine. Other material in the matrix includes layer structure silicates. Nickel-iron is absent, most of the nickel being present as pentlandite and the iron as ferromagnesian silicates. Both pigeonite and plagioclase are present as are pyrite and chalcopyrite in small amounts. Magnetite, which may contain some chromite, is present. The colour density of the matrix is variable giving the meteorite a brecciated appearance. It is very fresh and has been extensively recrystallized.	*, 10, 60, 70, 71, 127, 143, 144, 145, 152, 153, 202, 214, 262, 284, 303, 305, 306, 308, 355, 362, 364, 365, 371, 372, 373, 383, 386, 391, 422, 458, 475, 486, 488, 510, 516, 517, 524, 597, 625, 626, 628, 660, 677, 705, 706

DISTRIBUTION

Main mass	3.51kg S.A.M.	143, 294
Others	2.9 kg S.A.M.	143
	1.314kg N.Y.	269, 376
	514g Karoonda Council	*
	492g A.N.U.	38
	490g U.A.	*
	477g Private collection	*
	307g B.M.	268, 269, 294
	149g A.M.	35, 269
	123g U.S.N.M.	269, 294, 384
	41g A.S.U.	269, 294, 444, 694
	28g F.M.C.	294
	24g Harvard	212
	6g Calcutta	50
	5g U.C.	652

DENSITY 3.5 — 50, 386, 391

ELEMENTAL COMPOSITION

H	284, 386, 391, 659
Li	433, 485
B	485
C	60, 125, 228, 284, 319, 386, 391, 406, 630, 659, 675
N	228, 320, 386, 404, 405, 659, 664
O	128, 130, 458, 663
F	246, 311, 497, 696
Na	*, 80, 153, 202, 256, 284, 366, 367, 386, 391, 432, 433, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 659
Mg	*, 1, 80, 125, 153, 202, 284, 366, 367, 382, 386, 391, 533, 659
Al	*, 80, 153, 199, 202, 284, 341, 366, 367, 386, 391, 432, 623, 638
Si	*, 1, 80, 125, 146, 153, 202, 284, 366, 382, 386, 391, 539, 542, 634, 659, 663, 721
P	*, 80, 153, 202, 246, 284, 386, 391, 659
S	*, 80, 153, 202, 284, 293, 302, 366, 367, 386, 391, 629, 659
Cl	8, 246, 485, 498, 500, 696
K	*, 80, 153, 202, 256, 257, 284, 366, 367, 386, 391, 432, 433, 540, 659
Ca	*, 80, 153, 202, 246, 284, 366, 367, 386, 391, 432, 434, 659
Sc	246, 269, 532, 533, 534, 535, 538, 539, 540, 541, 542
Co	80, 153, 246, 269, 362, 386, 390, 434, 459, 532, 533, 534, 535, 537, 538, 539, 541, 659
Ni	*, 50, 80, 153, 202, 246, 284, 362, 366, 367, 386, 391, 434, 623, 628, 659, 709
Cu	202, 246, 269, 386, 429, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 659
Zn	220, 245, 246, 269, 390, 655, 659, 709
Ga	362, 390, 511
Ge	220, 245, 246, 269, 289, 362, 511, 709
Se	390, 709
Br	216, 339, 500, 696, 709
Rb	709
Sr	246, 269, 470
Zr	180, 183, 218, 269, 470, 636
Pd	709
Ag	390, 709
Cd	390, 604, 709
In	390, 511
Sb	184, 362, 604, 605, 709
Te	362, 390, 500, 709
I	217, 474, 497, 500, 696
Cs	390, 709
Ba	246, 269, 484
La	692
Ce	692
Nd	692
Sm	692
Eu	692
Gd	692
Dy	692
Er	692
Yb	692

Ti *, 80, 153, 202, 246, 269, 366, 367, 386, 659
V 153, 246, 269, 325, 386, 429, 659
Cr *, 80, 153, 202, 245, 269, 284, 366, 367, 386, 391, 434, 531, 532, 533, 534, 535, 538, 539, 540, 541, 542, 659, 669
Mn *, 80, 153, 202, 245, 246, 266, 269, 386, 391, 434, 511, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 659, 669
Fe *, 1, 50, 80, 153, 202, 245, 246, 284, 366, 367, 382, 386, 391, 434, 517, 531, 532, 533, 534, 535, 538, 539, 540, 541, 542, 623, 628, 658, 659
Hf 180, 183, 722
Re 362, 411, 415, 416, 709
Os 146, 410, 412, 415, 416, 425, 709, 721
Ir 185, 362, 709
Pt 181
Au 181, 362, 511, 604, 709
Hg 182, 362, 499, 501, 621, 728
Tl 390, 709
Bi 362, 390, 527, 709
Th 345, 413, 417, 425, 518, 726
U 345, 414, 417, 425, 519, 709, 727

SILICATES

Olivine — X.R.D. : $Fa_{32.2}$ — *, 10, 374, 386, 475
Probe : $Fa_{34.2}$ — *, 202, 294, 362, 383, 625, 649
Optical : Fa_{32} — 371, 516

Pyroxene — X.R.D. : Fs_{46} — 386

Feldspar — Optical : An_{30} — 202, 386

SULFIDES

Others — Pentlandite, pyrite and chalcopyrite — 247, 372, 386, 425, 486, 705, 706

OTHERS — Magnetite — 202, 386, 677, 702, 706

CHEM. GROUP — C5V — *, 10, 35, 72, 118, 125, 127, 129, 141, 143, 145, 181, 202, 224, 262, 267, 268, 269, 275, 284, 294, 302, 305, 306, 320, 341, 358, 362, 363, 367, 376, 378, 382, 383, 384, 390, 391, 422, 628, 652, 667, 692, 694, 695, 698, 702, 705, 707, 709

OTHER STUDIES

Age — 10, 276, 338, 392, 472, 473, 474, 672

Inert Gases — 168, 273, 274, 276, 306, 362, 392, 467, 474, 595, 596, 670, 671, 673, 675

Magnetic Properties — 70, 71, 72, 262

Metamorphism Temperature		127, 130, 202, 390, 677, 705, 707, 709
Organic Compounds		80, 303, 425, 447, 452
Spectral Studies		116, 117, 118, 220, 308, 523, 524, 660, 671, 676, 677, 678, 698, 702

KIELPA

H chondrite

Find

FIND	The larger piece was possibly found in March or April of 1940 by Andreas Benjamin Brooks, while a smaller piece was found on Tuesday January 3, 1978 by Geoffrey Alan Elleway and Joseph Raymond Elleway.	*, 53, 54, 122, 294
LOCATION	16km west of Kielpa in a paddock in Section 43 of the Hundred of Smeaton in County Jervois 33° 36'E 136° 06'S	*, 53, 54, 122, 294, 383
IDENTIFIED	The first mass by A.D. Wilson in 1948 and the second when found	*
MASS	13.6kg and 2.090kg	*, 53, 54, 122, 294
DESCRIPTION	The meteorite was apparently conical shape originally. About one third has been recovered to date. It was probably oriented during flight. The meteorite is deeply weathered. Recrystallization has occured but a chondritic texture can still be seen. Glass bars and chondrules have been at least partly devitrified. There is abundant opaque matrix present and the chondrules have generally been fragmented with most exhibiting broken edges. Many of the silicate grains are stained with limonite as are the fracture planes of the olivine grains. The latter mineral is generally present in the form of subhedral grains most of which exhibit a sharp extinction. The smaller piece is much more heavily weathered than the larger one possibly suggesting that the fall is relatively recent.	*, 53, 54, 122

DISTRIBUTION

Main mass	8.40kg	U.A.	*, 294
Others	2.020kg	S.A.M.	*
	351g	U.S.N.M.	294, 384
	275g	B.M.	294
	14g	A.N.U.	38
	4.1g	U.A.	*
	1.843kg	Finders (2nd mass)	*
	212g	U.A. (2nd mass)	*

DENSITY	3.46		53, 54
ELEMENTAL COMPOSITION	Na *, 53, 54	Ca *, 53, 54	
	Mg *, 53, 54	Ti *, 53, 54	
	Al *, 53, 54	Cr *, 53, 54	
	Si *, 53, 54	Mn *, 53, 54	
	P *, 53, 54	Fe *, 53, 54	
	S *	Co 53, 54	
	Cl 53, 54	Ni *, 53, 54	
	K *, 53, 54		
SILICATES			
Olivine	X.R.D. : $Fa_{18.3}$		*, 53, 54, 649
	Probe : $Fa_{18.9}$		294, 383
Pyroxene	Probe : $Fs_{17.0}$		383
	X.R.D. : Fs_{21}		53, 54
CHEM. GROUP	H5		53, 54, 122, 224, 294, 383, 384, 421, 649

KINGOONYA

See NARETHA

KITTAKITTAOOLOO

H chondrite

Find

FIND	August 1970 by Anthony Fyfe Williams	123, 294, 661
LOCATION	750m north of the north western tip of Lake Kittakittaooloo in the Tirari Desert and 16 km from the Warburton River 28° 02'S 138°08'E	*, 123, 383, 661
IDENTIFIED	When found	661
MASS	3.6kg	123, 294, 661

DESCRIPTION	The meteorite has a conical shape but is incomplete. It is about 12cm high and 20cm across the base. The apex of the meteorite is smooth but there is a series of ridges and furrows radiating from the centre of the apex. Metal can be seen in the matrix which has a chondritic texture.	661
DISTRIBUTION		
Main mass	S.A.M.	*
Others	10g U.S.N.M.	294, 384
DENSITY	ca.3.3	661
SILICATES		
Olivine	Probe : $Fa_{18.9}$	294, 383
Pyroxene	Probe : $Fs_{16.8}$	383
CHEM. GROUP	H4	123, 224, 294, 383, 384, 421, 661

KYANCUTTA

Medium octahedrite

Find

FIND	Early in June 1932 by Donald Henry McDonald	*, 35, 83, 85, 141, 143, 144, 267, 268, 269, 284, 357, 435, 577, 586, 694
LOCATION	In the SW corner of Section 44 of the Hundred of Caralue, in County Buxton on Eyre Peninsula. About 300m from the site of the Cowell find and some 48km SE of Kyancutta. 33° 18'S 136° 01'E	*, 35, 83, 143, 267, 268, 269, 284, 336, 577, 586, 694
IDENTIFIED	By J.B. Peters on Friday July 1, 1932	*, 37
MASS	32.6kg	23, 83, 85, 141, 143, 267, 268, 269, 284, 357, 435, 577, 586, 694
DESCRIPTION	The meteorite was approximately 35cm long being triangular in section. The surface is covered with terrestrial oxides, the outer heat-affected zone having been removed by weathering. Numerous ablation regmaglypts of 2-3cm diameter are present. A well developed Widmanstatten pattern is present. Schreibersite, daubreelite and troilite are present, the latter sometimes occuring as large nodules. Reichenbach lamellae are also present.	75, 83, 234, 235, 284, 577

DISTRIBUTION

Main mass	16.8kg	S.A.M.	*, 143, 294
Others	6.745kg	A.N.U.	38
	1.41 kg	F.M.C.	83, 269
	1.241kg	A.M.	35, 83, 269
	1.090kg	Kyancutta	*
	845g	S.A.M.	83, 143
	754g	U.S.N.M.	83, 268, 269, 384
	750g	Calcutta	83, 144
	750g	W.A.M.	83, 269, 357
	464g	A.S.U.	83, 269, 294, 493, 694
	398g	B.M.	83, 267, 268, 269
	346g	N.M.V.	427
	323g	U.A.	*
	200g	Copenhagen	83, 85
	80g	Ann Arbor	83

DENSITY 7.73 — 173, 269, 577

ELEMENTAL COMPOSITION

C	83, 173, 284, 408, 577	Cu	83, 269, 284, 348, 408, 577
N	226		
P	83, 85, 173, 284, 408, 577	Ga	83, 85, 269, 294, 348, 506, 553, 649
S	83, 173, 284, 408, 577	Ge	83, 85, 269, 294, 348, 383, 506, 553, 649
Cl	173, 284, 577	Nb	99, 493
Cr	83, 269, 348	Ir	83, 85, 294, 553, 649
Fe	*, 173, 577		
Co	83, 173, 269, 284, 348, 408, 577		
Ni	*, 75, 83, 85, 173, 235, 269, 284, 294, 346, 348, 383, 389, 408, 506, 553, 577, 649		

Ni-Fe ALLOYS

Bandwidth	0.98mm	*, 83, 85, 235, 553
Cooling Rate		*, 235
Hardness		83, 85
CHEM. GROUP	IIIA	35, 75, 83, 85, 143, 224, 226, 234, 235, 267, 268, 269, 284, 336, 357, 383, 384, 408, 506, 544, 551, 553, 577, 649, 694

OTHER STUDIES

Thermo-magnetic Analysis	346

KYBUNGA No.1

?L chondrite

?Fall

FALL	Thought to be from the fall of 4:30pm of Sunday September 7, 1941	167, 398
FIND	In 1963 by Glen Charles Wiech	123, 294, 359, 398
LOCATION	In the SW corner of Section 153 of the Hundred of Blyth in County Stanley and a matching fragment in the SE corner of Section 161. The recovery area is about 3km NNW of Kybunga railway siding. 33° 54'S 138° 30'E	*, 123, 294, 359, 398
IDENTIFIED	Saturday February 15, 1969 in the S.A. Museum	398
MASS	2.76kg (total of two pieces)	294, 359
DESCRIPTION	The meteorite has a well developed chondritic texture with barred and radiating chondrules being present plus numerous rounded and sub-rounded porphyritic inclusions. There are also granular aggregates present and rare grains of clinopyroxene. In contrast to Kybunga No.3, nearly every larger grain in the section examined displayed a mosaic texture.	*
DISTRIBUTION		
Main mass	S.A.M.	*
Others	Finder	*
CHEM. GROUP	?L5	167, 398

KYBUNGA No.2

?L chondrite

?Fall

FIND	In 1971 by Glen Charles Wiech	123, 294, 359
LOCATION	The NW corner of Section 159 in the Hundred of Blyth in County Stanley. North west of the Kybunga railway siding. 33° 53'S 138° 29'E	*, 123, 294, 359
IDENTIFIED	When found	*

MASS	2.37kg		294, 359
DISTRIBUTION			
Main mass		Finder	*
Others	90g	S.A.M.	*
CHEM. GROUP	?L5		167, 398

KYBUNGA No.3

L chondrite

?Fall

FIND	In 1971 by Ian David Schumacher		35, 123, 359
LOCATION	In the NW corner of Section 122 in the Hundred of Blyth, County Stanley, NW of the Kybunga railway siding. 33° 53'S 138° 28'E		*, 123, 294, 359, 383
MASS	2.86kg		35, 359
DESCRIPTION	The specimen was completely covered with a fusion crust and on one surface lines can be seen radiating from the centre of one edge. The opposite surface is lined and patterned with regmaglypts. Much of the material is greenish-grey and unweathered however many of the numerous metal and troilite grains are surrounded by limonitic staining. An overall chondritic texture is readily seen and numerous barred and radiating chondrules are present as well as devitrified glassy ones. In some areas recrystallization has obliterated the chondritic texture. Occasional grains, particularly large ones, show evidence of shock in the form of undulatory extinction and mosaic textures.		*
DISTRIBUTION			
Main mass	1.233kg	U.A.	*
Others	1.202kg	U.A.	*
	94 g	U.S.N.M.	384
	88.2g	B.M.R.	*
	76.4g	Finder	*
	35.7g	A.N.U.	38
	20.1g	A.M.	35

ELEMENTAL COMPOSITION	Na *	Ca *
	Mg *	Ti *
	Al *	Cr *
	Si *	Mn *
	P *	Fe *
	S *	Ni *
	K *	

SILICATES		
Olivine	X.R.D. : $Fa_{25.2}$	*
	Probe : $Fa_{25.0}$	383, 649
Pyroxene	Probe : $Fs_{21.4}$	383
CHEM. GROUP	L5	123, 294, 383, 384, 421, 649
OTHER STUDIES		
Orbit Parameters		326

LAKE BONNEY

L chondrite

Find

FIND	Saturday October 21, 1961 and later by Bertha Grace McDonald	*, 140, 141, 142, 143, 269, 294, 376
LOCATION	About 21km SSW of Millicent on Jacky Peninsula in the Hundred of Mayura in County Grey. 37° 45'S 140° 18'E	140, 141, 142, 143, 269, 294, 383
IDENTIFIED	The first specimen was identified after its discovery by D.W. Corbett, the other three were identified by him and B.G. McDonald when found the following year.	*, 140, 142
MASS	2.768kg (Total weight)	140, 141, 142, 143, 269
DESCRIPTION	Four stones bearing a brownish black fusion crust. All are fairly heavily oxidised suggesting an old fall. The meteorite is strongly recrystallized with only a trace of a chondritic structure. Pronounced mosaicism in the olivine grains is indicative of shock. The texture is now one of olivine megacrysts which are commonly anhedral, set in a granular groundmass. Fracture planes in the olivine are stained with limonite.	*, 140, 141, 142

DISTRIBUTION			
Main mass	1.96kg	S.A.M.	140, 141, 142, 143, 269
Others	517g	S.A.M.	143
	206g	Finder	*
	77g	U.A.	*
	57g	S.A.M.	143
	40g	N.Y.	376
	Slide	U.S.N.M.	294

ELEMENTAL COMPOSITION	Na *	Ca *	
	Mg *	Ti *	
	Al *	Cr *	
	Si *	Mn *	
	P *	Fe *	
	S *	Ni *	
	K *		
SILICATES			
Olivine	X.R.D. : $Fa_{25.7}$		*, 140, 378, 649
	Probe : $Fa_{24.5}$		383
Pyroxene	Probe : $Fs_{21.1}$		383
CHEM. GROUP	L6		140, 142, 143, 224, 269, 376, 378, 383, 384, 421, 649

LAKE LABYRINTH

LL chondrite

?Fall

FALL	Possibly during the night of Tuesday February 5, 1924	35, 143, 267, 268, 269, 329, 357, 435, 509, 586
FIND	About a fortnight later by Billy Austin	135, 141, 143, 144, 284, 294, 586
LOCATION	32km north of Lake Labyrinth and about 13km north of Peela Rockhole and Well on Wilgena Station on the Nullarbor Plain. 30° 33'S 134° 45'E	6, 33, 35, 143, 223, 267, 268, 269, 284, 294, 336, 357, 383, 586
IDENTIFIED	When recovered by R. Bedford and J.B. Peters in October 1934 some 30m from a crater of about 4m diameter.	85, 135, 141, 143, 144, 267, 268, 269, 284, 294, 357, 376, 435, 586, 634, 635, 694
MASS	25.85kg recovered but it was estimated that about 8kg were missing	6, 85, 135, 141, 143, 267, 268, 269, 284, 357, 435, 586, 694
DESCRIPTION	The meteorite was originally elipsoidal in shape with axes of about 24, 22 and 19cm. The surface had both shallow and deep regmaglypts on it. The unoxidised material is greenish-grey. Chondrules are readily seen on the surface. The meteorite has been completely recrystallized and no chondrule boundaries can be seen the meteorite now consisting of anhedral grains of olivine set in a fine-grained, granular ground mass. The olivine grains are heavily fractured and almost without exception exhibit a well developed and pervasive mosaicism. As the meteorite is quite fresh the olivine fracture planes are generally not stained with limonite.	*, 108, 220, 221, 328, 387, 475, 483, 486, 488, 586

DISTRIBUTION

Main mass	3.75kg	B.M.	267, 268, 269, 586
Others	6.966kg	A.N.U. (21+ pieces)	38
	3.629kg	A.S.U.	268, 269, 294, 440, 694
	1.515kg	S.A.M.	143, 294
	1.085kg	U.S.N.M.	268, 269, 384
	767g	N.Y.	268, 269, 376, 509
	652g	N.M.V.	427
	475g	G.S.I.	144
	286g	U.A.	*
	284g	B.M.	267, 268, 269, 586
	255g	A.M.	35, 268, 269
	77g	G.S.C.	223
	27g	U.C.	331, 333, 652
	18g	Copenhagen	85

DENSITY 3.45 — 586

ELEMENTAL COMPOSITION

C	407, 675	Fe	*, 246, 394, 434, 488, 541, 719, 720
N	227	Co	246, 269, 434, 488, 541
O	190, 635	Ni	*, 246, 434, 719, 720
F	246, 269	Cu	246, 269, 429, 488, 537, 538, 541
Na	*, 531, 537, 538, 572, 719, 720	Zn	246, 269, 655
Mg	*, 327, 533, 719, 720	Ga	120
Al	*, 327, 341, 541, 572, 719, 720	Ge	120, 135, 246, 269, 289
Si	*, 146, 634, 719, 720, 721	Rb	237, 238
P	*, 246, 719, 720	Sr	238, 246, 269
S	*, 719, 720	Zr	269
Cl	246, 269	Nb	99, 493
K	*, 238, 719, 720	Cd	521, 522
Ca	*, 434, 719, 720	Sb	184, 605
Sc	246, 269, 531, 541	Te	562
Ti	*, 246, 269, 719, 720	Ba	246, 269, 484
V	246, 269, 325, 429	Hf	269, 555, 722
Cr	*, 246, 269, 434, 488, 541, 719, 720	Ir	48, 146, 185, 269, 721
Mn	*, 246, 269, 434, 488, 537, 538, 541, 719, 720	U	201

SILICATES

Olivine	X.R.D. : $Fa_{29.5}$	*, 63, 371, 374, 376, 475
	Probe : $Fa_{29.4}$	294, 383, 649
Pyroxene	Probe : $Fs_{23.6}$ $Wo_{2.1}$ - opx	93, 383
	Probe : $Fs_{10.2}$ $Wo_{44.3}$ - cpx	93
	Optical : Fs_{23}	371
Silicate Structures		63, 489

Ni-Fe ALLOYS

Composition	606
Cooling Rate	606

CHEM. GROUP	LL6	108, 143, 186, 201, 223, 224, 227, 261, 267, 268, 269, 284, 305, 327, 333, 341, 371, 376, 383, 384, 407, 421, 628, 649, 652, 675, 678, 694, 712
OTHER STUDIES		
Age		108, 238, 269, 271, 572
Equilibration Temperature		93
Inert Gases		271, 301, 671, 675
Luminescence Spectra		220, 221, 678
Magnetic Properties		261
Orbit Parameters		327
Shock History		108

MONTE COLINA

L chondrite

Find

FIND	All available evidence suggests that this is a fragment of Carraweena which was found late in 1913 or early in 1914 by Thomas Flinders Gill and William George Amesbury	*, 383, 388
LOCATION	Carraweena was found 9.7km SW of Carraweena Head Station on Montecollina Station near Strzelecki Creek east of Lake Blanche 29° 10'S 139° 56'E	*, 6, 35, 119, 143, 268, 269, 294, 336, 383, 388, 586, 640
IDENTIFIED	By W.S. Chapman on Friday February 6, 1914 and rediscovered in the 1960's by J.E. Johnson	*, 119
MASS	116.8g	141, 143, 388
DESCRIPTION	The small specimen is well weathered but shows an excellent chondritic texture. Representatives of most chondrule types are present being set in a dark matrix. Many of them contain glass which has not been devitrified. Many of the olivine grains show evidence of shock in the form of undulatory extinction and mosaic features. Polysynthetically twinned clinopyroxene is common in porphyritic inclusions.	*

DISTRIBUTION			
Main mass	72g	G.S.S.A.	*, 294, 388
Others	12g	G.S.S.A.	*
	10g	S.A.M.	143, 294
	5g	N.Y.	294

ELEMENTAL COMPOSITION	C 119	Ca *, 119	
	Na *, 119	Ti *, 119	
	Mg *, 119	Cr *, 119	
	Al *, 119	Mn *, 119	
	Si *, 119	Fe *, 119	
	P *, 119	Co 119	
	S *, 119	Ni *, 119	
	K *, 119,		

SILICATES		
Olivine	X.R.D. : $Fa_{25.2}$	*, 378, 649
CHEM. GROUP	L3	294, 378, 383, 388, 421, 649

MOORABIE

L chondrite

Find

FIND	Prior to 1965 by Lindsay H. Russell	123, 294, 359
LOCATION	2km NW of Boolka Bore on Moorabie Station, County Evelyn, New South Wales. About 6.3km east of the State border. 30° 06'S 141° 04'E	*, 123, 294, 359
IDENTIFIED	Possibly by J.E. Johnson on Tuesday October 10, 1967	359
MASS	14.05kg	359
DESCRIPTION	The meteorite was approximately tetrahedral in shape and much of the surface is covered with a fusion crust penetrated by chondrules. Metal and troilite grains are common and often surround chondrules. The meteorite is not extensively weathered. The lack of equilibration of the silicates is shown by their compositional variability. Many of the silicate grains are stained with limonite. Glassy regions have undergone little devitrification and polysynthetically twinned clinopyroxene is common in the porphyritic inclusions. Many of the larger olivine grains are skeletal in form.	*

DISTRIBUTION			
Main mass		Finder	*
Others	2.0kg	U.A.	*

DENSITY	3.46		359
ELEMENTAL COMPOSITION	Na *	Ca *	
	Mg *	Ti *	
	Al *	Cr *	
	Si *	Mn *	
	P *	Fe *	
	S *	Ni *	
	K *		
SILICATES			
Olivine	X.R.D. : $Fa_{15.6}$		*
	Probe : $Fa_{15.7}$		*
Pyroxene	Probe : $Fs_{12.4}$ $Wo_{0.8}$		*
CHEM. GROUP	L3		*, 123, 224, 421

MOORUMBUNNA

Medium octahedrite

Find

FIND	In 1943 by an aboriginal	35, 83, 141, 143, 173, 268, 269
LOCATION	Near a dam on the track leading from the Anna Creek Head Station to the William Creek railway station some 65km west of Lake Eyre 28° 55'S 136° 14'E	*, 35, 83, 143, 173, 268, 269
MASS	76.75kg	141, 143, 173, 268, 269
DESCRIPTION	The meteorite is elongated in form with dimensions of about 50, 31 and 19cm. The surface is marked with deep regmaglypts of depth of about 5cm and there is an external limonite skin less than 0.5mm thick. A section shows a well developed Widmanstatten pattern with individual lamellae ranging in width from 0.5 to 1.5mm and in length from about 1 to 2cm. Irregular veinlets of schreibersite, swathed with kamacite, are present. "Reichenbach lamellae" of thin troilite blades encased in kamacite are also present. Occasional nodules of troilite are present and also evidence of lawrencite.	*, 75, 83, 173, 259

DISTRIBUTION			
Main mass	66.30kg	U.A.	*, 143, 294
Others	3.037kg	S.A.M.	*
	1.34 kg	A.M.	35
	584g	S.A.M.	143, 294
	400g	U.A.	*
	46g	U.C.	294, 652

ELEMENTAL COMPOSITION	P 83, 173, 259 S 83, 173, 259 Cl 173 Fe 173, 259 Co 83, 173, 259 Ni 83, 173, 259, 294, 383, 553, 649	Cu 259 Ga 83, 294, 553, 649 Ge 83, 294, 383, 553, 649 Ir 83, 294, 553, 649	
Ni-Fe ALLOYS			
Bandwidth	0.90mm		*, 83, 553
Cooling Rate			*
CHEM. GROUP	IIIA		35, 83, 173, 224, 268, 269, 383, 526, 551, 553, 649, 652
OTHER STUDIES			
Spectral Studies			526

MOTPENA

L-chondrite

Find

FIND	On the weekend of August 10-11, 1968, by Bruce A. Jahn and Norman A. Bartlett	30, 123, 294, 508
LOCATION	On a clay pan NW of the Motpena Homestead - Parachilna road. On the Hundred line of the Hundred of Nilpena in County Taunton. 31° 06'S 138° 16'E	123, 383, 421, 508
IDENTIFIED	When found	
MASS	8.82kg	30, 123, 294, 508
DESCRIPTION	The meteorite is polygonal in shape with regmaglypts on some faces. The body is finely cracked and is pervaded by brown limonitic staining. It has been recrystallized and only a few chondrules can be seen in thin section. Limonitic staining is ubiquitous. Most of the meteorite consists of granular material having an average grainsize of 0.02mm, anhedral grains of both olivine and pyroxene are present. Many of the pyroxene grains show an undulatory extinction although in some cases it is quite sharp. Some of the olivine grains exhibit shock lamellae while others have a mosaic texture.	*, 508

DISTRIBUTION			
Main mass	4.712kg	A.N.U.	38, 508
Others	443g	B.M.	294, 508
	300g	F.M.C.	508
	158g	U.A.	*
	98g	U.S.N.M.	384, 508
	93g	A.M.	35, 508
	48g	B.M.R.	294, 508
	35g	A.N.U.	*, 38, 508

ELEMENTAL COMPOSITION	Na *		Ca *	
	Mg *		Ti *	
	Al *		Cr *	
	Si *		Mn *	
	P *		Fe *	
	S *		Ni *	
	K *			

SILICATES			
Olivine	X.R.D.	: $Fa_{25.3}$	*
	Probe	: $Fa_{25.9}$	*, 294, 383, 508, 649
Pyroxene	Probe	: $Fs_{21.9}$ $Wo_{1.4}$	*, 383, 508
Feldspar	Probe	: Ab_{83} An_{10}	508
CHEM. GROUP	L6		123, 224, 294, 383, 384, 421, 508, 649

MOUNT BROWNE

H chondrite

Fall

FALL AND FIND	The meteorite fell at 9:30 on the morning of Thursday July 17, 1902, and was picked up about five minutes later by Mr. W. Jordan.	35, 81, 106, 107, 194, 206, 224, 267, 268, 269, 284, 357, 376, 394, 421, 438, 481, 634
LOCATION	At Mount Browne (now recorded as Mount Brown) gold diggings, 9km SW of Milparinka in County Evelyn, New South Wales 29° 47'S 141° 46'E	*, 35, 81, 106, 107, 194, 206, 224, 267, 268, 269, 284, 294, 330, 333, 357, 383, 394, 421, 438, 480, 481
MASS	11.45kg (It is thought that the finder removed about 500g)	35, 81, 106, 107, 194, 206, 224, 267, 268, 269, 284, 357, 394, 421, 438, 481

DESCRIPTION — The meteorite was pyramidal in shape standing on a base of about 19x19cm. The outer surface was covered with a black fusion crust and some ablation regmaglypts were present. The light grey interior is fine grained and troilite and nickel iron can be seen on a broken surface. — 106, 107

DISTRIBUTION

Main mass	6.246kg	A.M.	35, 284
Others	486g	U.S.N.M.	269, 384, 394
	380g	F.M.C.	194, 269
	359g	Prague	269
	245g	G.S.N.S.W.	136
	81g	Vienna	77
	76g	A.M.	35
	55g	N.Y.	294, 376
	37g	A.N.U.	38
	11g	U.C.	331, 333, 652
	Section	G.S.W.A.	357

ELEMENTAL COMPOSITION

Li	394	Ga	121, 560
C	394, 623, 657	Ge	121, 246, 269, 560, 645
F	246	As	560
Na	80, 394, 426, 623, 657	Rb	269
Mg	80, 394, 426, 623, 657	Sr	246, 269, 394
Al	80, 394, 623, 657	Zr	394
Si	80, 146, 394, 623, 634, 657, 721	Ru	269
		Pd	560
P	80, 246, 394, 623, 657	Sb	560
S	394, 623, 657	Ba	246, 269, 394, 426
Cl	246, 394	La	426
K	80, 394, 426, 623, 657	Ce	426
Ca	80, 394, 426, 623, 657	Nd	426
Sc	246, 269, 657	Sm	426
Ti	80, 246, 269, 394, 623	Eu	426
V	246, 269, 394	Gd	426
Cr	80, 246, 269, 394, 623, 657	Dy	426
		Er	426
Mn	80, 246, 269, 394, 623	Yb	426
Fe	80, 246, 394, 516, 623, 657	Lu	426
		Re	560
Co	80, 246, 269, 623, 657	Os	146, 416, 721
Ni	80, 121, 246, 480, 516, 623, 657	Hf	183, 722
		Ir	121, 185
Cu	246, 269	Au	185, 560
Zn	246, 269	U	201

SILICATES

Olivine	X.R.D.	: $Fa_{17.0}$	377, 378, 516
	Probe	: $Fa_{18.8}$	*, 294, 383, 649
Pyroxene	Probe	: $Fs_{17.0}$ $Wo_{1.3}$	*, 80, 383, 516, 649
Feldspar			396

Ni-Fe ALLOYS

Composition	516
Volume	80, 121

CHEM. GROUP	H6	10, 35, 93, 224, 267, 268, 269, 333, 376, 383, 384, 396, 421, 481, 623, 628, 649, 652, 715
OTHER STUDIES		
Age		715
Inert Gases		715
Magnetic Properties		10, 73, 598, 599, 600, 700

MOUNT SIR CHARLES

Fine octahedrite

Find

FIND	In 1942 by T. Williams	123, 141, 143, 294
LOCATION	11km east of Bond Springs Station, Northern Territory, near Mount Sir Charles 23° 50'S 134° 02'E	123, 141, 143, 294
MASS	22.91kg	123, 141, 143, 294
DESCRIPTION	An unusual shaped iron as most of the material has apparently weathered away leaving part of a spherical shell. An etched section reveals a very fine, wavy, Widmanstatten pattern. No obvious troilite or other nodules can be seen.	*
DISTRIBUTION		
Main mass	22.23kg S.A.M.	143, 294
Others	120g U.A.	*
	21g U.S.N.M.	294, 384
	1.2g A.N.U.	38
ELEMENTAL COMPOSITION	Fe * Ni *, 83, 294, 383, 506, 507, 649 Ga 83, 294, 506, 507, 649 Ge 83, 294, 506, 507, 649	
Ni-Fe ALLOYS		
Bandwidth	0.22mm	*
Cooling rate		*
CHEM. GROUP	Anomalous	*, 83, 123, 143, 224, 294, 384, 506, 507, 551, 649

MUCKERA

Howardite

Find

FIND	On Tuesday or Wednesday May 1 or 2, 1951 by Cornelius Patrick Doyle	*, 294
LOCATION	About 5km SW of Muckera Rock Hole on the extreme northern edge of the Nullarbor Plain, 70km from the Cook railway station on a bearing of 333° 30° 05'S 130° 02'E	*, 294
IDENTIFIED	Tentatively identified as a meteorite by P.S. Hossfeld in 1951. Identification confirmed by J.B. Jones in 1972.	*
MASS	513g (estimate about 100g removed when found)	*, 294
DESCRIPTION	A somewhat elongated, elipsoidal mass measuring about 10x8x5cm. Much of the brown fusion crust is missing but there is some evidence of regmaglypts. Rounded and sub-rounded white to grey clasts set in a black matrix can be seen on a cut surface. Small grains of nickel-iron and sulfide, generally surrounded by limonitic staining, can also be seen. The brecciated texture is readily seen in thin section. The clasts range from mineral fragments through monomineralic aggregates to polymineralic ones. These include pyroxene and plagioclase grains. Lithic fragments include rock types such as basalt and gabbro. Deformation is shown by crushed but non-disaggregated clasts as well as undulatory extinction and mosaic textures. The clast to matrix ratio is about 5:1.	*

DISTRIBUTION

Main mass	144.8g	U.A.	*, 294
Others	129.0g	S.A.M.	*
	106.4g	U.A.	*
	30g	Finder	*

ELEMENTAL COMPOSITION

Na	*, 718	Ca	*, 718
Mg	*, 718	Ti	*, 718
Al	*, 718	Cr	*, 718
Si	*, 718	Mn	*, 718
P	*, 718	Fe	*, 718
S	*, 718	Ni	*, 718
K	*, 718		

SILICATES

Olivine	Probe	: $Fa_{27.4}$	*
Pyroxene	Probe	: $Fs_{\text{Wide range}}$	*
Feldspar	Probe	: $An_{88.0}\ Ab_{11.3}$	*

CHEM. GROUP	Howardite	*, 294, 701

MURNPEOWIE

Anomalous iron

Find

FALL	Probably between 1904 and August 1909	11, 143, 284, 563, 584
FIND	August 1909 by A. Hamblin and others	6, 11, 21, 35, 83, 111, 141, 143, 144, 267, 268, 269, 284, 285, 438, 481, 563, 573, 584, 586
LOCATION	On Murnpeowie Station about 8km west of Lake Callabonna and 26km NE by E of Mount Hopeless and 85km from the homestead 29°35'S 139° 54'E	6, 11, 35, 46, 47, 83, 143, 267, 268, 269, 284, 330, 336, 563, 564, 584, 586
IDENTIFIED	At the S.A. School of Mines in 1909	563, 564
MASS	1145.4kg	6, 11, 13, 83, 141, 143, 267, 268, 269, 284, 285, 291, 315, 332, 355, 372, 438, 481, 563, 564, 573, 584, 710, 711
DESCRIPTION	This is the largest known South Australian meteorite. It measures 89x120x48cm being roughly triangular in shape. There are shallow regmaglypts on one surface and deep ones on the other. Several cracks are present in the mass. Both the fusion crust and the heat affected zone are present, the latter being about 3mm thick below projecting surfaces but only about 1mm thick below the regmaglypts. An etched face shows a fine granular surface being a mixture of large and small, partly oriented, recrystallized kamacite grains, none of them being greater than 0.5cm in length. Taenite and schreibersite are absent. Troilite, cohenite and daubreelite are present. The metal grains show well developed Neumann lines. Its nickel content places it between the hexahedrites and the octahedrites but its trace element content is characteristic of neither. It is structurally and chemically anomalous and resembles no other known meteorite. It is apparently a mechanically deformed meteorite which has been imperfectly recrystallized.	15, 40, 83, 234, 259, 267, 268, 269, 284, 291, 505, 563, 564, 565, 584, 593

DISTRIBUTION

Main mass	1143.1kg	S.A.M. (Property of S.A. School of Mines)	83, 143, 294
Others	802g	B.M.	83, 267, 268, 269
	766g	A.M.	35, 83, 268, 269, 285
	191g	U.S.N.M.	83, 294, 384
	66g	N.M.V.	427

DENSITY	7.78	284, 462, 584

ELEMENTAL COMPOSITION	P 284, 409, 505	Ge 83, 234, 269, 284, 289, 294, 348, 383, 409, 462, 505, 552, 559, 584, 649	
	S 83, 284, 462, 584		
	Cr 83, 269, 284, 348, 559		
	Fe 284, 462, 584		
	Co 83, 269, 284, 348, 462, 547, 584	As 547	
		Mo 559	
	Ni 33, 40, 83, 234, 269, 284, 348, 383, 389, 409, 462, 505, 547, 552, 584, 649	Pd 146, 559, 721	
		Ag 100, 559, 633	
		In 559	
		Sb 559	
		W 547	
	Cu 83, 269, 284, 348, 462, 559, 584	Re 208, 411	
		Ir 83, 294, 547, 552, 649	
	Zn 83, 559, 655	Pt 83, 284, 409, 462, 584	
	Ga 83, 234, 269, 348, 409, 505, 552, 559, 649	Au 208, 547	
Ni-Fe ALLOYS			
Alpha Parameter			83, 462
Bandwidth			409, 552
Cooling Rate			83, 547
Hardness			83, 409
CHEM. GROUP	Anomalous		35, 40, 74, 83, 143, 208, 224, 267, 268, 269, 304, 383, 384, 409, 505, 544, 551, 552, 584, 633
OTHER STUDIES			
Age			33, 56
Inert Gases			33, 109, 464
Shock History			40, 296

NARETHA

L chondrite

Find

FIND	The data listed here has all been published under the name Kingoonya as it was thought this was a separate find but it has been shown to be a portion of Naretha. It was once thought that it might be related to Lake Labyrinth but this is impossible.	35, 131, 383, 488, 573, 586, 703

DISTRIBUTION	87+g	S.A.M.	143, 336
	12g	A.M.	35, 267, 268, 269, 483
	2.4g	U.S.N.M.	294, 384
SILICATES			
Olivine	X.R.D.	: Fa_{24}	374
	Probe	: $Fa_{23.8}$	383
Pyroxene	Probe	: $Fs_{20.2}$	383
CHEM. GROUP	L4		6, 35, 143, 144, 267, 268, 269, 284, 383, 384, 421, 586, 649

NILPENA

Chondrite

Find

FIND	11:00am on Wednesday June 4, 1975 by Donald Hugh McColl	*
LOCATION	In a sand blown depression in an interdune corridor between NW-SE trending sand dunes in the north western corner of the Hundred of Nilpena, County Taunton, north of the Parachilna-Motpena Station road and 3.7km from the site of the Motpena find. 31° 57'S 138° 18'E	*
IDENTIFIED	When found	*
DISTRIBUTION Main mass	B.M.R.	*
CHEM. GROUP	Chondrite	*

NINE MILE

L chondrite

Find

FIND	Between 1969 and 1975 by Werner Hollmayer	*
LOCATION	In the Popio Lakes area about 135km south of Broken Hill	*

IDENTIFIED	April 1975 by D.H. McColl and M.J. Fitzgerald	*
MASS	172.0g	*
DESCRIPTION	Recrystallization has effectively obliterated the texture of this chondritic meteorite and only rare chondrules can be seen.	*
DISTRIBUTION		
Main mass	107.0g Finder	*
Others	5.2g U.A.	*
ELEMENTAL COMPOSITION	Na *, Mg *, Al *, Si *, P *, S *, K *, Ca *, Ti *, Cr *, Mn *, Fe *, Ni *	
SILICATES		
Olivine	X.R.D. : $Fa_{23.5}$	*
	Probe : $Fa_{26.9}$	*
Pyroxene	Probe : $Fs_{23.4}$ $Wo_{1.4}$	*
CHEM. GROUP	L6	*

NORA CREINA

L chondrite

Find

FIND	In 1962 by Bertha Grace McDonald	*, 123, 140, 142, 143, 294, 318, 378
LOCATION	Nora Creina Bay, 19.5km SSE of Robe 37° 19'S 139° 51'E	123, 140, 142, 143, 294, 318, 378, 383
IDENTIFIED	When found	*
MASS	283.5g	123, 140, 142, 143, 294, 318, 378

DESCRIPTION	Chondrules and other inclusions can be seen on a cut surface. Veins are common and the degree of weathering suggests an old fall. A fairly well developed chondritic structure can be seen in thin section with most of the silicates being stained with limonite. Olivine grains in porphyritic inclusions are commonly euhedral and the matrix has usually been devitrified. Some of the larger olivine grains exhibit an undulatory extinction with occasional ones tending to a mosaic texture. Limonitic staining is present on the fracture planes of some olivine grains. Some chondrule boundaries, most of which are fairly obvious, are rimmed with opaque minerals. Glassy chondrules have been devitrified. Abundant polysynthetically twinned clinopyroxene is present. The matrix consists of small olivine and pyroxene grains.		*, 140, 142, 143, 294
DISTRIBUTION			
Main mass		S.A.M.	143, 294
Others	9.9g	N.Y.	294
	8.5g	U.S.N.M.	294, 384
ELEMENTAL COMPOSITION	Na *	Ca *	
	Mg *	Ti *	
	Al *	Cr *	
	Si *	Mn *	
	P *	Fe *	
	S *	Ni *	
	K *		
SILICATES			
Olivine	X.R.D. : $Fa_{25.6}$		*, 140, 378, 649
	Probe : $Fa_{25.1}$		294, 383
Pyroxene	Probe : $Fs_{19.4}$		383
CHEM. GROUP	L4		123, 140, 142, 143, 224, 294, 318, 378, 383, 384, 421, 649

NUTWOOD DOWNS

Medium octahedrite

Find

FIND	Prior to 1971, and possibly in 1970	85, 383, 694
LOCATION	Supposedly on Nutwood Downs Station, near Daly Waters in the Northern Territory, but the manager denies this.	383
DESCRIPTION	Has been shown to be part of Henbury	83, 85, 294, 551, 553, 649

DISTRIBUTION	78g	A.S.U.		694
	39g	U.C.		553, 652
ELEMENTAL COMPOSITION	Ni 83, 553, 649		Ge 83, 553, 649	
	Ga 83, 553, 649		Ir 83, 553, 649	
CHEM. GROUP	IIIA			383, 551, 553, 649, 652, 694

PINNAROO

Mesosiderite

Find

FIND	In May 1927 by Stanley Hamilton	7, 35, 141, 143, 268, 269, 376
LOCATION	In the SW corner of Section 6 of the Hundred of Pinnaroo in County Chandos. About 14.5km SSE of Pinnaroo. 35° 23'S 140° 56'E	*, 7, 35, 141, 143, 268, 269, 294, 336
IDENTIFIED	By Sir Douglas Mawson in 1939-1940	7
MASS	39.4kg	7, 141, 143, 268, 269, 315
DESCRIPTION	The meteorite was approximately ellipsoidal in shape with dimensions of 37, 29 and 17cm. It has been heavily weathered and outer layers break away readily. Nodules of troilite and metal are present with many of the latter showing a Widmanstatten pattern. The ratio of metal and troilite to silicate is about 1:1.1 by volume. Oldhamite and lawrencite have apparently assisted weathering and abundant limonite is present. Much of the silicate material exhibits a subophitic texture. Set in this material are rimmed megacrysts of olivine and clasts of fine material exhibiting varying degrees of devitrification. Some of the clasts have been completely recrystallized producing granular aggregates frequently having opaque grains at the triple point junctions. Strain is revealed by undulatory extinction and shock bands in the olivine megacrysts.	*, 7, 83, 108, 145, 187, 344, 356, 385, 487, 488, 716, 717

DISTRIBUTION			
Main mass	20.87kg	U.A.	*, 143, 294
Others	4.273kg	U.A.	*
	1.132kg	U.S.N.M.	384
	598g	S.A.M.	*, 143
	413g	B.M.	294
	183g	N.Y.	294, 376
	170g	A.M.	35
DENSITY	5.05		7

ELEMENTAL COMPOSITION	H 7	Mn *, 717	
	Na *, 7, 717	Fe *, 7, 145, 187, 717	
	Mg *, 7, 145, 717	Co 187, 269, 348, 717	
	Al *, 7, 717	Ni *, 7, 145, 187, 294, 351, 355, 383, 385, 649, 653, 717	
	Si *, 7, 717		
	P *		
	S *, 7, 717	Cu 269, 348	
	K *, 7, 717	Ga 269, 294, 348, 649, 653	
	Ca *, 7, 717	Ge 269, 294, 348, 383, 649, 653	
	Ti *, 7, 717		
	Cr *, 236, 269, 348, 717	Ir 294, 649, 653	

Ni-Fe ALLOYS		
Kamacite		717
Taenite		717
SILICATES		
Olivine	X.R.D. : $Fa_{10.8}$	*
	Probe : $Fa_{18.2}$	*, 717
Pyroxene	Probe : $Fs_{31.2}$ $Wo_{4.5}$	*, 385, 717
Feldspar	Optical : An_{90} Ab_{10}	7
	Probe : $An_{90.7}$ $Ab_{8.7}$	*, 717
Chromite		713, 717
CHEM. GROUP	Mesosiderite	7, 35, 83, 108, 145, 224, 268, 269, 344, 376, 380, 383, 384, 385, 477, 665
OTHER STUDIES		
Shock History		108

POONARUNNA

H chondrite

Find

FIND Mid 1970 by James Dunn *

LOCATION At the base of the eastern side of a sand dune in a series of N-S trending sand dunes on Kalamurina Station, about 2km north of the Warburton River and 15km from the Poonaruuna oil well. *

27° 46'S 137° 51'E

IDENTIFIED Subsequently by A.F. Williams *

MASS Unknown *

DESCRIPTION The meteorite was too big to be moved by the finder. Subsequent searches have failed to rediscover it. Occasional grains of metal and sulfide can be seen on the cut surface of the small piece examined. Many isolated grains of olivine and pyroxene the former generally being anhedral to subhedral, can be seen in thin section. Abundant limonitic staining is present along fracture planes in the olivine grains. Chondrules are not abundant but there are numerous porphyritic inclusions present, the matrices of this material are generally partly devitrified. *

DISTRIBUTION

Main mass	Unknown	In situ	*
Others	44.4g	U.A.	*

ELEMENTAL COMPOSITION

Na	*	Ca	*
Mg	*	Ti	*
Al	*	Cr	*
Si	*	Mn	*
P	*	Fe	*
S	*	Ni	*
K	*		

SILICATES

Olivine	X.R.D.	: $Fa_{18.1}$	*
	Probe	: $Fa_{19.9}$	*
Pyroxene	Probe	: $Fs_{17.8}$ $Wo_{1.5}$	*

CHEM. GROUP H5 *

POPILTA

L chondrite

Find

FIND Between 1969 and 1975 by Werner Hollmayer *

LOCATION In the Popio Lakes area about 135km south of Broken Hill *

IDENTIFIED April 1975 by D.H. McColl and M.J. Fitzgerald *

MASS 158.5g *

DESCRIPTION Isolated grains of olivine are present in this recrystallized chondrite from which most traces of a chondritic texture have been removed. *

DISTRIBUTION

4.5g U.A. *

ELEMENTAL COMPOSITION

Na	*	Ca	*
Mg	*	Ti	*
Al	*	Cr	*
Si	*	Mn	*
P	*	Fe	*
S	*	Ni	*
K	*		

SILICATES

Olivine X.R.D. : $Fa_{25.0}$ *

Probe : $Fa_{25.6}$ *

Pyroxene Probe : $Fs_{22.8}$ $Wo_{1.3}$ *

CHEM. GROUP L6 *

POPIO

L chondrite

Find

FIND Between 1969 and 1975 by Werner Hollmayer *

LOCATION Near Popio Lakes about 135km south of Broken Hill *

IDENTIFIED April 1975 by D.H. McColl and M.J. Fitzgerald *

MASS 747.3g *

DESCRIPTION The meteorite has been extensively recrystallized leaving little trace of a chondritic texture. *

DISTRIBUTION *

Main mass	545.7g	Finder	*
Others	109.7g	B.M.R.	*
	21.7g	U.A.	*

ELEMENTAL COMPOSITION

Na	*	Ca	*
Mg	*	Ti	*
Al	*	Cr	*
Si	*	Mn	*
P	*	Fe	*
S	*	Ni	*
K	*		

SILICATES *

Olivine	X.R.D.	: $Fa_{23.9}$	*
	Probe	: $Fa_{26.2}$	*
Pyroxene	Probe	: $Fs_{22.4}$ $Wo_{1.5}$	*

CHEM. GROUP L6 *

RABBIT FLAT

H chondrite

Find

FIND By a road gang in 1974 703

LOCATION On the road between The Granites and Rabbit Flat, Northern Territory 703

20° 22'S 130° 07'E (approximately)

MASS 295g 703

CHEM. GROUP H 703

RHINE VILLA

Coarse octahedrite

Find

FIND	Prior to November 1900 by Allen George Payne	*, 21, 83, 85, 141, 143, 144, 194, 240, 241, 267, 268, 269, 284, 394, 438, 481, 573, 586
LOCATION	Lying on the ground, partly covered with soil, in the vicinity of the town of Rhine Villa. This town, which is now known as Cambrai, is located in the Hundred of Angus, County Sturt and is about 80km NE of Adelaide. #34° 39'S 139° 17'E	*, 11, 83, 143, 241, 267, 268, 269, 284, 294, 336, 586
IDENTIFIED	When brought to the S.A. Museum in November 1900 by Howard William Payne, the finder's brother	*
MASS	3.325kg	6, 83, 85, 141, 143, 208, 241, 267, 268, 269, 291, 438, 514
DESCRIPTION	The original mass was somewhat tabular in shape with dimensions of 12, 10 and 5cm. The dark outer surface was coated with oxides. A coarse Widmanstatten pattern can be seen on an etched surface. Troilite and schreibersite are present, as is the carbide, haxonite, which is common in the plessite fields. Neumann bands are also common.	*, 83, 241, 291

DISTRIBUTION

Main mass	218g	Bonn	11, 13, 83, 143, 206, 284
Others	185g	B.M.	83, 206, 267, 268, 269, 284, 482
	183g	Vienna	83
	175g	Paris	83
	155g	F.M.C.	83, 269
	131g	Prague	83, 269
	123g	Berlin U.	83, 267, 268, 269, 284
	120g	Copenhagen U.	83, 85, 269
	118g	U.S.N.M.	83, 267, 268, 269, 284, 384, 394
	85g	S.A.M.	83, 143
	67g	Vatican	83
	c30g	U.A.	*
	28g	Strasbourg	83

DENSITY	7.693	241, 284, 514

ELEMENTAL COMPOSITION	P	83, 85, 193, 240, 241, 284, 514	
	S	193, 240, 241, 284, 514	
	Cr	83, 559, 560	
	Mn	263	
	Fe	193, 240, 241, 284, 514	
	Co	83, 193, 240, 241, 284, 514	
	Ni	83, 85, 87, 193, 240, 241, 284, 294, 514, 553, 649	
	Cu	83, 559, 560	
	Zn	83, 559, 560	
	Ga	83, 85, 294, 553, 559, 560, 649	
	Ge	83, 85, 289, 294, 383, 553, 559, 560, 649	
	As	559, 560	
	Mo	559, 560	
	Pd	146, 559, 560	
	Ag	100, 559, 560, 633	
	In	559, 560	
	Sb	559, 560	
	Re	208, 411, 559, 560	
	Ir	83, 85, 294, 553, 649	
	Au	208, 559, 560	
Ni-Fe ALLOYS			
Bandwidth	1.33mm		*, 83, 85, 553
Cooling Rate			*, 83
Hardness			83, 85
CHEM. GROUP	IIIE		83, 85, 87, 143, 193, 194, 240, 241, 267, 268, 269, 284, 383, 481, 514, 549, 551, 553, 564, 573, 633, 649
OTHER STUDIES			
Shock History			297

ROPER RIVER

Medium Octahedrite

Find

FIND	In 1921 by an aboriginal	83, 284, 573
LOCATION	On the Roper River 80km from Urapanga in the Northern Territory ?14° 45'S 134°E	267, 268, 269, 284, 330, 573
MASS	6.257kg	83, 267, 268, 269
DESCRIPTION	Numerous Brezina lamellae of schreibersite interfere with the appearance of the Widmanstatten structure. Troilite nodules are not visible. It is quite different from the other Northern Territory irons.	83
DISTRIBUTION		
Main mass	5.7kg N.M.V.	83, 267, 268, 269, 427
Others	133.7g A.N.U.	38, 83

ELEMENTAL COMPOSITION	P 83		Ge 83, 294, 348, 383, 553, 650	
	Cr 83, 348		Ir 83, 294, 553, 650	
	Co 83, 348			
	Ni 83, 294, 348, 383, 389, 553, 557, 650			
	Cu 83, 348			
	Ga 83, 294, 348, 553, 649			
Ni-Fe ALLOYS				
Bandwidth				83
CHEM. GROUP	IIIB			83, 141, 224, 267, 268, 269, 304, 383, 551, 649

SILVERTON

L chondrite

Find

FIND	During the 1880's by an unknown person. Rediscovered in the Port Adelaide Museum by Robert Bedford in June or July 1933		*, 35, 144, 267, 268, 269, 284, 581, 687
LOCATION	Actual finding site is unknown - it was described as having come from Silverton which is in County Yancowinna in New South Wales. #31° 53'S 141° 12'E		6, 35, 267, 268, 269, 284, 581
MASS	350.7g		6, 267, 268, 269, 284, 435, 687
DESCRIPTION	A complete stone showing some evidence of weathering. Most of the silicates are grey and unweathered but a weathered zone is present immediately below the fusion crust. Troilite and nickel-iron are present and they are generally surrounded by a limonitic staining. Chondrules are not abundant.		*, 581
DISTRIBUTION			
Main mass	107g	A.M.	35, 284
Others	69g	U.S.N.M.	294, 384
	32g	B.M.	267, 268, 269, 581
	24g	A.N.U.	38
	4.1g	U.A.	*
DENSITY	3.31		581

ELEMENTAL COMPOSITION	F 246, 311	Fe 246	
	P 246	Co 246, 269	
	Cl 246, 269	Ni 246	
	Sc 246, 269	Cu 246, 269	
	Ti 246, 269	Zn 246, 269, 655	
	V 325	Ge 246, 269, 289	
	Cr 246, 269	Sr 246, 269	
	Mn 246, 269	Ba 246, 269, 484	
SILICATES			
Olivine	X.R.D. : Fa_{25}		374
	Probe : $Fa_{25.8}$		*, 383, 649
Pyroxene	Probe : $Fs_{21.5}$ $Wo_{1.6}$		*, 383
CHEM. GROUP	L6		6, 35, 224, 267, 268, 269, 284, 383, 384, 421, 581, 628, 649, 687

"S.A. BETA"

Medium octahedrite

Find

FIND Possibly about 1963 by Arthur Shepherd *

LOCATION Possibly near Gawler north of Adelaide *

MASS 3.174kg *

DESCRIPTION An approximately rectangular mass measuring 15x11x3cm. The surface is quite irregular being covered with large regmaglypts. A polished specimen was examined by V.F. Buchwald who reported that it is a IIIA iron. He further stated that schreibersite occured only as rare small blebs while Neumann bands are prominent as are oriented match-like inclusions of carlsbergite. Likewise, fissures following cubic cleavage planes in the kamacite are common. He concluded that it is a transported Henbury mass. *

DISTRIBUTION

Main mass	1.490kg		*
Others	459g	A.M.	*, 35
	363g		*
	258g	B.M.R.	*
	257g		*
	204g	U.A.	*
	92g	U.A.	*
	43g		*
	36g		*

The mass was cut and weighed by the author but the present location of some of the fragments is unknown. One of the larger ones may have been cut into four again.

ELEMENTAL COMPOSITION	Ni *	
Ni-Fe ALLOYS		
Bandwidth	0.94mm	*
CHEM. GROUP	IIIA	*, 35

TAWALLAH VALLEY

Nickel rich ataxite

Find

FIND	In 1937 by Mr. Condon	35, 83, 141, 143, 268, 269, 286, 304, 376, 694
LOCATION	In the Tawallah Valley, 77km NW of Borroloola in the Northern Territory 15° 42'S 135° 40'E	35, 83, 143, 268, 269, 286, 694
IDENTIFIED	Possibly in the Australian Museum in April 1939	
MASS	75.75kg	83, 141, 143, 258, 268, 269, 286, 694
DESCRIPTION	An essentially flat trapezhoidal mass 38cm wide with a longer dimension of 65cm and a thickness varying from 5 to 90mm. Shallow, inconspicuous regmaglypts are present in places, otherwise the surface is flat. Both the original crust (in parts) and the heat affected zone are preserved. The meteorite is apparently a "spallation product" from a cosmic collision. Etching reveals an ataxitic nature with an oriented sheen broken by a few troilite inclusions. Kamacite spindles, usually with taenite rims, are present in a plessitic matrix. Schreibersite is common.	83, 172, 258, 285, 286, 295

DISTRIBUTION

Main mass	34.77kg	B.M.R.	*, 83, 143, 268
Others	28.82kg	A.M.	35, 83, 268, 269, 286
	1.267kg	U.S.N.M.	83, 294, 384
	552g	S.A.M.	143
	453g	U.M.	83, 286
	292g	A.N.U.	38
	256g	N.M.V.	427
	233g	U.A.	*
	217g	N.Y.	83, 294, 376
	158g	Moscow	83
	12g	A.S.U.	83, 694

DENSITY	8.02	258, 286

ELEMENTAL COMPOSITION	C 52, 286	Cu 83, 269, 348
	P 83	Ga 83, 269, 294, 348, 529, 645, 649
	Cr 83, 269, 348	Ge 83, 269, 289, 294, 348, 383, 529, 645, 649
	Fe 52, 258, 286	Ir 83, 294, 529, 649
	Co 52, 83, 258, 269, 286, 348	Pt 286
	Ni 52, 83, 235, 258, 269, 285, 286, 294, 295, 346, 348, 383, 389, 529, 645, 649	
Ni-Fe ALLOYS		
Bandwidth		235
Cooling Rate		235, 295
Hardness		83, 286
CHEM. GROUP	IVB	35, 52, 143, 172, 224, 235, 258, 268, 269, 286, 295, 347, 372, 376, 383, 384, 551, 645, 649, 694
OTHER STUDIES		
Ablation Losses		9, 83, 347
Age		637
Inert Gases		637
Thermo-magnetic Studies		83, 346

THACKARINGA No.1

H chondrite

Find

FIND	About 2:00pm on Sunday March 24, 1974, by Donald Hugh McColl	*
LOCATION	On Thackaringa Station, SE of Cockburn. About a kilometre north of the Ophara Hut ruins in County Yancowinna, New South Wales. About 8km east of the State border. 32° 07'S 141° 05'E	*
IDENTIFIED	When found	*
MASS	432.2g	360

DESCRIPTION A chondritic texture is visible on a cut surface. Thin section examination reveals numerous well preserved circular chondrules of the barred and radiating type. Numerous subhedral to anhedral grains of olivine are dispersed throughout the section. There is a relatively high content of opaque minerals. *

DISTRIBUTION

Main mass	359.3g	B.M.R.	360
Others	ca30g	Finder	360
	23.5g	U.A.	*

ELEMENTAL COMPOSITION

Na	*	Ca	*
Mg	*	Ti	*
Al	*	Cr	*
Si	*	Mn	*
P	*	Fe	*
S	*	Ni	*
K	*		

SILICATES

Olivine X.R.D. : $Fa_{17.2}$ *

CHEM. GROUP H5 *

THACKARINGA No.2

H chondrite

Find

FIND About 10:45am on Sunday June 8, 1975 by Wayne Desmond Mussared *

LOCATION On Thackaringa Station, SE of Cockburn and about 0.5km NW of the Ophara Hut ruins in County Yancowinna, New South Wales. About 8km east of the State border. *

32° 07'S 141° 05'E

IDENTIFIED When found *

MASS 6.4g *

DESCRIPTION A small crusted individual with the shape of a triangular bipyramid of height 14mm. Metal and sulfide grains which are rare are set in a matrix of iron-stained silicates along with well defined chondrules. Minimal devitrification of glassy areas has occured. Numerous isolated olivine and pyroxene fragments are present in the matrix. *

DISTRIBUTION			
Main mass	3.4g	U.A.	*
Others	1.2g	U.A.	*
CHEM. GROUP	H5		*

TWIN WELLS

H chondrite

Find

FIND	Between 1969 and 1975 by Werner Hollmayer		*
LOCATION	In the Popio Lakes area about 135km south of Broken Hill		*
IDENTIFIED	April 1975 by D.H. McColl and M.J. Fitzgerald		*
MASS	269.3+g		*
DESCRIPTION	Some chondritic structure can be seen in this recrystallized material. Many of the chondrules are present as broken fragments.		*
DISTRIBUTION			
Main mass	198.3g	Finder	*
Others	7.4g	U.A.	*

ELEMENTAL COMPOSITION	Na *		Ca *	
	Mg *		Ti *	
	Al *		Cr *	
	Si *		Mn *	
	P *		Fe *	
	S *		Ni *	
	K *			

SILICATES					
Olivine	X.R.D.	:	$Fa_{18.9}$		*
	Probe	:	$Fa_{21.1}$		*
Pyroxene	Probe	:	$Fs_{17.4}$	$Wo_{1.0}$	*
CHEM. GROUP	H5				*

UN-NAMED STONY IRON

Unclassified

Find

LOCATION	Possibly near the Western Australia-South Australia State border	*
DESCRIPTION	Appears to be an iron with silicate inclusions but a larger piece may suggest a different classification. Binns (pers. comm.) states that it is not part of Mundrabilla but he could see a resemblance to Donnybrook	*
DISTRIBUTION		
	77.8g U.A.	*
CHEM. GROUP	Unclassified	*

VINCENT

L chondrite

Find

FIND	In 1926 by Edmund Arthur Paul Hoff	*, 141, 143, 269, 374, 376, 567
LOCATION	About 9.5km NNE of the town of Karoonda. In the NE corner of Section 34 of the Hundred of Vincent in County Buccleuch. 35° 01'S 139° 56'E	*, 143, 294, 374, 383
IDENTIFIED	Possibly in 1956 when presented to the S.A.M.	143
MASS	425.2g	141, 143, 294, 374
DESCRIPTION	Chondrule boundaries are generally quite clear in this meteorite and the chondrules, in general, are less iron-stained than the surrounding matrix. The matrices of porphyritic inclusions have been devitrified. Chondrule types include barred and radiating ones. Olivine is generally present as anhedral grains and in some instances the fracture planes are stained with limonite. Many isolated olivine grains exhibit undulatory extinction.	*
DISTRIBUTION		
Main mass	318g S.A.M.	143, 294
Others	1.5g N.Y.	294, 376
	0.8g U.A.	*
	Slide U.S.N.M.	384

ELEMENTAL COMPOSITION	F	246, 269	
	Na	*	
	Mg	*	
	Al	*	
	Si	*	
	P	*, 246	
	S	*	
	Cl	246, 269	
	K	*	
	Ca	*	
	Sc	246	
	Ti	*, 246, 269	
	V	246, 269, 325	
	Cr	*, 246, 269	
	Mn	*, 246, 269	
	Fe	*, 246	
	Co	246, 269	
	Ni	*, 246	
	Cu	246, 269	
	Zn	246, 269, 655	
	Ge	246, 269, 289	
	Sr	246, 269	
	Ba	246, 269, 484	
SILICATES			
Olivine	X.R.D. :	$Fa_{23.9}$	*, 374
	Probe :	$Fa_{24.2}$	294, 383, 649
Pyroxene	Probe :	$Fs_{21.0}$	383
CHEM. GROUP	L5		141, 224, 376, 383, 384, 649

WEEKEROO STATION

Coarse octahedrite with silicate inclusions

Find

FIND	In 1924 by James Lane	21, 35, 83, 141, 143, 144, 267, 268, 269, 283, 284, 376, 438, 509, 573, 586, 694
LOCATION	On a quartz ridge on a hill on Weekeroo Station in County Lytton, about 30km NW of Mannahill. 32° 16'S 139° 52'E	6, 35, 83, 267, 268, 269, 283, 284, 330, 336, 586, 694
IDENTIFIED	Possibly by the Australian Museum in 1927	36
MASS	94.1kg	6, 36, 83, 141, 192, 267, 268, 269, 283, 284, 694
DESCRIPTION	An oval shaped mass with dimensions of 50, 27 and 19cm. Numerous 2-3cm deep regmaglypts are present on part of the surface. Numerous nodules of silicate minerals, about 4% by volume, are set in the nickel-iron which shows a coarse octahedrite pattern. Olivine is absent and much of the pyroxene shows a radiating structure. Two generations of Neumann bands can be seen in the metal. Schreibersite is common and troilite is present in very limited quantities. Other minerals include feldspar, tridymite, rutile, ilmenite, chromite, chloapatite and whitlockite.	*, 9, 42, 62, 83, 91, 94, 96, 214, 283, 284, 315, 379, 380, 441, 444, 451, 488, 586, 643, 646, 648

DISTRIBUTION

Main mass	47.06kg	A.M.	*, 35, 83, 267, 268, 269
Others	11.8 kg	U.S.N.M.	83, 268, 269, 283, 384
	5.076kg	A.S.U.	83, 268, 269, 283, 294, 436, 439, 444, 694
	3.35 kg	Harvard	83, 283, 647
	3.188kg	N.Y.	83, 268, 269, 283, 376, 509
	0.836kg	U.A.	*

ELEMENTAL COMPOSITION

H	449	Cu	83, 269, 348, 559
C	83, 283, 284, 449	Zn	83, 84, 94, 559
O	129, 552, 653, 691	Ga	83, 269, 294, 348, 552, 553, 559, 647, 649, 650, 653, 655
Na	83, 94, 449	Ge	83, 269, 289, 294, 348, 383, 552, 553, 559, 647, 650, 653
Mg	83, 94, 449	As	559
Al	83, 94, 186, 449	Rb	643
Si	83, 94, 449, 714	Sr	96, 239, 643
P	83, 94, 283, 449	Mo	559
S	83, 84, 94, 283, 284, 449	Pd	146, 559, 721
K	83, 94, 98, 449	Ag	100, 559, 633
Ca	83, 94, 269, 449	In	559, 653
Ti	83, 94, 449	Sb	559
V	84, 94	Ba	191, 484, 543
Cr	83, 84, 94, 269, 348, 449	Gd	192, 342
Mn	83, 84, 94, 449, 559	W	688
Fe	83, 84, 94, 283, 284, 449	Re	208, 411
Co	83, 94, 269, 283, 284, 348	Ir	83, 294, 552, 553, 647, 649, 650
Ni	83, 269, 283, 284, 294, 348, 380, 383, 389, 449, 552, 553, 647, 649, 650, 653, 688	Au	208
		U	204

SILICATES

Olivine	Absent	84, 94, 380
Pyroxene	Probe : $Fs_{22.2}$ $Wo_{2.8}$ (opx)	66, 84, 94, 380, 449, 450, 647
	Probe : $Fs_{17.6}$ $Wo_{36.3}$ (cpx)	66, 84, 94, 380, 449, 450, 647
Feldspar	Probe : An_{15}	61, 83, 84, 91, 92, 94, 294, 380, 444, 449, 450, 548, 644

Ni-Fe ALLOYS

Bandwidth	2.29mm	*, 83, 552, 553
Composition		380
Cooling Rate		*, 552
Hardness		83

SULFIDES

Troilite		84, 94
Others		94

OTHERS	Tridymite, rutile, ilmenite, chromite, chlorapatite, whitlockite	84, 89, 90, 94
CHEM. GROUP	IIE	35, 42, 83, 84, 89, 94, 208, 224, 267, 268, 269, 283, 284, 304, 376, 380, 383, 384, 438, 490, 551, 552, 553, 573, 633, 642, 649, 688, 694
OTHER STUDIES		
Age		9, 42, 68, 95, 97, 98, 192, 205, 294, 490, 491, 552, 558, 642, 643
Inert Gases		67, 68, 69, 97, 98, 490, 491, 552

WILBIA

H chondrite

Find

FIND	In May 1965 by James Eric Johnson	124, 143, 294
LOCATION	On a sand dune at the eastern end of Wilbia Hill, 32km SSW of St. Morris in the Musgrave Ranges 26° 27'S 131° 00'E	124, 141, 143, 294, 383, 421
IDENTIFIED	When found	*
MASS	94g	124, 143, 294
DESCRIPTION	This meteorite has been strongly recrystallized and little evidence of chondrule boundaries can be seen. Many of the olivine grains are heavily fractured, frequently showing an undulatory extinction and some exhibit a mosaic texture. No recognisable chondrule remains are present. Material is present which might once have been porphyritic inclusions. Many of the silicates, especially the finer grained ones, are stained with limonite.	*

DISTRIBUTION			
Main mass		S.A.M.	143, 294
Others	8.5g	B.M.	294
	3.8g	U.S.N.M.	294, 384
	1.3g	U.A.	*

ELEMENTAL COMPOSITION	Na	*	Ca	*
	Mg	*	Ti	*
	Al	*	Cr	*
	Si	*	Mn	*
	P	*	Fe	*
	S	*	Ni	*
	K	*		

SILICATES			
Olivine	X.R.D.	: $Fa_{19.0}$	*
	Probe	: $Fa_{19.0}$	294, 383
Pyroxene	Probe	: $Fs_{17.7}$	383
CHEM. GROUP	H5		124, 224, 294, 383, 421

WINGELLINA

H chondrite

Find

FIND	In 1958 by James Eric Johnson	143, 357, 374
LOCATION	On stony ground about 1km north of the Wingellina mining camp and 6.5km SW of the intersection of the South Australian, Northern Territory and Western Australian State borders. 26° 03'S 128° 57'E	143, 269, 357, 374, 383
IDENTIFIED	When found	*
MASS	200g	143, 269, 357, 374

DISTRIBUTION			
Main mass	28.5g	S.A.M.	143, 294
Others	Slide	U.S.N.M.	294, 384

SILICATES			
Olivine	Probe	: $Fa_{18.2}$	294, 357, 374, 383, 649
Pyroxene	Probe	: $Fs_{16.6}$	383
CHEM. GROUP	H4		143, 224, 353, 383, 384, 421, 649

WITCHELINA

H chondrite

Find

FIND	In 1920 by Thomas Phillip Gourlay	124, 294, 530
LOCATION	The meteorite was found in sandhill country on Witchelina Station south of the homestead. The exact site of the find is unknown. The station is about 23km SNW of Farina. #30° 01'S 138° 03'E	*, 124, 294, 383, 530
IDENTIFIED	Possibly when presented to the University of Adelaide by the finder's grandson in 1967	
MASS	3.637kg	124, 294, 530
DESCRIPTION	This is a well oriented meteorite with regmaglypts on the rear surface and an anterior aerothermal ablation surface. The meteorite has been extensively weathered. Numerous barred, radiating and glassy chondrules are present, which, together with the presence of polysynthetically twinned clinopyroxene point to the low petrologic grade.	530

DISTRIBUTION

Main mass	1.502kg	U.A.	*
Others	368g	S.A.M.	*
	156g	U.S.N.M.	294, 384
	81g	B.M.	294
	71g	A.N.U.	38

DENSITY	3.27	530

ELEMENTAL COMPOSITION

Na	*, 530	Ca	*, 530
Mg	*, 530	Ti	*, 530
Al	*, 530	Cr	*, 530
Si	*, 530	Mn	*, 530
P	*, 530	Fe	*, 530
S	*, 530	Co	530
Cl	530	Ni	*, 530
K	*, 530	Cu	530
		Zn	530

SILICATES

Olivine	X.R.D.	: $Fa_{19.1}$	*, 530
	Probe	: $Fa_{19.1}$	294, 383
Pyroxene	Probe	: $Fs_{17.3}$	383

CHEM. GROUP	H4	124, 224, 294, 383, 384, 421

YANDAMA

L chondrite

Find

FIND	During the decade 1914-1924 by Thomas Flinders Gill	*, 6, 35, 143, 144, 267, 268, 269, 284, 329, 376, 694
LOCATION	On the "Big Plain", Yandama Station (now Lake Stewart Station), County Evelyn, New South Wales. 29° 21'S 141° 10'E	*, 35, 143, 267, 268, 269, 330, 336, 381, 383, 421, 483, 694
MASS	5.68+kg	6, 143, 267, 268, 269, 694
DESCRIPTION	The meteorite was a rounded, sub-angular mass with dimensions of 19, 14 and 13cm. It has been extensively recrystallized but chondrules can still be recognized. Glassy regions have been devitrified to granular aggregates and as a result large subhedral to anhedral grains of olivine and pyroxene set in granular ground masses are common. Sulfide and metal grains are commonly surrounded by limonitic alteration. It is possibly related to Cartoonkana.	*, 6, 383

DISTRIBUTION

Main mass	3.63kg	S.A.M.	143, 483
Others	379g	S.A.M.	143
	377g	U.S.N.M.	294, 384
	276g	B.M.	269
	184g	N.Y.	294, 376
	150g	U.A.	*
	46g	A.N.U.	38
	30g	A.M.	35
	18g	A.S.U.	694

DENSITY	3.40	6

ELEMENTAL COMPOSITION

H	6, 623	K	*, 6
Na	*, 6	Ca	*, 6
Mg	*, 6	Ti	*, 6
Al	*, 6, 623	Cr	*, 6
Si	*, 6	Mn	*
P	*, 6	Fe	*, 6
S	*, 6	Ni	*, 6

SILICATES

Olivine	X.R.D.	: $Fa_{25.0}$	*, 374, 376
	Probe	: $Fa_{25.0}$	294, 383, 649
Pyroxene	Probe	: $Fs_{20.9}$	383

CHEM. GROUP	L6	35, 143, 224, 267, 268, 269, 284, 294, 376, 383, 384, 421, 438, 649, 694

OTHER STUDIES

Ultra Violet Reflectance		526

YARDEA

Coarse octahedrite

Find

FIND	In November 1875 by James Martlew	11, 21, 76, 83, 132, 135, 138, 139, 141, 143, 144, 194, 267, 268, 269, 284, 438, 481, 573, 586, 668
LOCATION	In County Bosanquet some 6.5km south of Yardea Station, near the Gawler Ranges. The meteorite was about 40cm below ground level and was covered with soil. 32° 27'S 135° 32'E	*, 6, 11, 78, 83, 132, 133, 138, 139, 143, 267, 268, 269, 284, 481, 586, 668
MASS	3.29kg	6, 11, 13, 83, 132, 133, 138, 139, 141, 143, 267, 268, 269, 330, 336, 481, 563, 564, 668
DESCRIPTION	The surface which is marked with regmaglypts is covered with an oxide coating. The presence, in places, of some of the original heat affected zone indicates a loss in other parts, by terrestrial oxidation, of about 2mm. A coarse Widmanstatten structure is present. Troilite and schreibersite are common with the latter enclosing numerous graphite and silicate grains. Carlsbergite and cohenite are also present.	*, 83, 132, 133

DISTRIBUTION

Main mass	2.54kg	S.A.M.	*, 83, 143
Others	79g	S.A.M.	*
	73g	F.M.C.	83, 641
	37g	U.A.	*
	1g	Berlin	83
	Section	A.N.U.	38

ELEMENTAL COMPOSITION	P	83	Ga	83, 294, 506, 507, 649
	Fe	*	Ge	83, 294, 383, 506, 507, 649
	Ni	*, 83, 294, 383, 506, 507, 649		

Ni-Fe ALLOYS		
Bandwidth	2.08mm	*, 83
Cooling Rate		*
Hardness		83
CHEM. GROUP	IA	6, 11, 33, 83, 138, 139, 141, 143, 193, 194, 224, 238, 267, 268, 269, 284, 383, 438, 481, 506, 551, 573
OTHER STUDIES		
Age		33, 56
Inert Gases		33, 109, 464

YENBERRIE

Coarse octahedrite

Find

FIND	On Tuesday July 30, 1918 by John Hoare	35, 83, 267, 268, 269, 376, 402, 438, 481, 573
LOCATION	Embedded in sandy soil about 32km SSE of Yenberrie in the Northern Territory 14° 15'S 132° 01'E	35, 83, 284, 294, 330, 573
MASS	131.82kg	141, 267, 268, 269, 284, 402, 438, 481, 509
DESCRIPTION	When found the meteorite was in two pieces which fitted togethere to give an irregularly shaped body about 43cm long. The meteorite has a coarse Widmanstatten structure of straight, bulky kamacite lamellae. Sharp Neumann bands are present, as is schreibersite and cohenite, both the latter being brecciated. The meteorite is thus a typical inclusion-rich coarse octahedrite.	83, 284

DISTRIBUTION			
Main mass	42.29kg	A.M.	35, 267, 268, 269, 284
Others	29.33kg	B.M.R.	*
	4.50kg	F.M.C.	83, 269, 284, 402
	3.83kg	U.S.N.M.	83, 269, 284, 402
	3.76kg	N.Y.	83, 269, 284, 376, 402, 509
	599g	B.M.	229
	107g	G.S.N.S.W.	136
DENSITY	7.93		258, 402

ELEMENTAL COMPOSITION	C	83, 284, 402	Cu	83, 269, 284, 348, 402
	Si	284, 402	Ga	83, 269, 294, 348, 552, 649
	P	83, 284, 402	Ge	83, 269, 289, 294, 348, 383, 552, 649
	S	402	Ir	83, 294, 552, 649
	Cl	284, 402	Pt	83, 284, 402
	Cr	83, 269, 348		
	Fe	258, 284, 402		
	Co	83, 258, 269, 284, 348, 402		
	Ni	83, 235, 258, 267, 268, 269, 284, 294, 348, 376, 389, 402, 552, 649		

Ni-Fe ALLOYS	
Bandwidth	83, 235, 552
Cooling Rate	235
Hardness	83
CHEM. GROUP IA	35, 83, 224, 235, 267, 268, 269, 284, 304, 376, 384, 402, 509, 544, 551, 552, 649
OTHER STUDIES	
Shock History	297, 469

APPENDIX B: SOME OTHER METEORITES

The following three meteorites, which were recovered from well outside the study area are described briefly here. They will be discussed in full elsewhere (cf. APPENDIX V).

Millbillillie No.3

At about 1 pm on an October day in 1960, two station workers, Messrs. F. Quadrio and F. Vicenti, were opening a gate in the boundary fence between Millbillillie and Jundee Stations in the Wiluna district, central Western Australia, when they saw a fiery object, with sparks coming from it, fall on a spinifex covered area on the plain to the north. A search was not carried out then. Subsequently, Mr. D. Vicenti found a piece of meteorite on the plain in 1970. This mass weighed about 20kg and another of 600g was found the next year by Mr. M. Finch.

Further material has been recovered in the area by local aborigines. The third recorded recovery was purchased by the late Mr. Clem Latz thereby precluding its export. This 368g individual was completely covered with a fusion crust when purchased and most of it is now the property of the University. To date some 26kg of material have been recovered from the area with other specimens in private collections in Wiluna and also the Australian Museum. The designation No.3 has been appended to the specimen examined in this work to indicate it is the third documented specimen recovered from the area.

The meteorite is a eucrite and as shown in Chapter 8 belongs with the bulk of the other known eucrites.

Mossgiel

This meteorite was found in 1967 by Mr. H. Watkin in a wheat field on his property "Killara" in central New South Wales. It was found during harvesting, but it had not been noticed the previous year when the crop was sown. It is possible that it had been uncovered by wind erosion during this period, as its weathered condition suggests that it is not a recent fall.

A specimen of the meteorite was sent to Mr. (later Dr.) K.D. Collerson of the Geological Survey of New South Wales Geological and Mining Museum, who identified it as a meteorite. Collerson subsequently acquired the meteorite, at which stage it was in 23 pieces, and brought to Adelaide where he was studying at the time.

He named it Mossgiel as it had been found to the south east of the town of Mossgiel. Killara is 72km from Hillston on the Ivanhoe road. The meteorite was registered by Collerson in a letter to the International Commission on Wednesday December 10, 1969. The bulk of the meteorite was taken by him to Canada in 1972, a small sample only remaining in this Department.

Olivine compositions measured both in this work, ($Fa_{23.6}$), and by Mason (1974) along with compositional and textural considerations suggest that Mossgiel is an LL chondrite rather than an H one as originally recorded (Krinov 1970b).

Oberon Bay

This meteorite was found during the Christmas holiday period, probably of 1962-1963, but possibly either the previous or following year.

The finder, Dr. Victor Andrew Gostin, was walking through the sandhills near Oberon Bay on Wilson's Promontory on the south eastern coast of Victoria, when he came across a "sand blow" among the dunes. The floor was scattered with pieces of driftwood, rock fragment and general debris. The 180g meteorite was lying amongst this material. Dr. Gostin picked it up as it seemed unusual, and after sectioning it, suspected that it was a meteorite. He retained the specimen until the author commenced this work and donated it to the University in March 1972 when his tentative identification was confirmed.

The overall texture is fragmental. Some of the clasts, which are coarse grained have been recrystallized and now have a granoblastic texture characterized by numerous triple point junctions. Other porphyritic clasts show minimal evidence of recrystallization. Many of the clasts have sharp boundaries while others grade into the matrix which consists of very fine material set in an opaque base. Several of the clasts are texturally similar to the C2 meteorites Adelaide and Murray. Olivine compositions are unusual in that there appears to be two distinct groups of grains having compositions of $Fa_{18.1}$ and $Fa_{25.6}$. The more iron-rich olivines are well equilibrated as indicated by a C.V. of 0, while a C.V. of 6 for the more magnesian grains is indicative of a lack of equilibrium. Nickel-iron is generally far more abundant in the dark

matrix material whereas troilite is ubiquitous.

Oberon Bay is classified as an LL 6 chondrite.

The bulk compositions of these meteorites are as follows:-

	Millbillillie No.3	*Mossgiel*	*Oberon Bay*
Fe	*15.30*	*18.38*	*18.43*
Mn	*0.46*	*0.26*	*0.28*
Ti	*0.44*	*0.088*	*0.081*
Ca	*7.42*	*1.14*	*1.30*
K	*0.071*	*0.050*	*0.126*
P	*0.034*	*0.061*	*0.084*
Si	*23.89*	*18.83*	*19.23*
Al	*7.03*	*1.27*	*1.17*
Mg	*4.42*	*15.44*	*14.96*
Ni	*0.015*	*1.15*	*1.28*
S	*0.003*	*1.93*	*2.15*
Cr	*0.21*	*0.29*	*0.31*
Na	*0.33*	*0.55*	*0.71*

APPENDIX C: GLASS ANALYSES

Analyses of the glasses described in Section 11.3 are given below. They are grouped together under the appropriate meteorite name.

	Barratta		Carraweena									
	B1	B2	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Composition												
SiO_2	60.72	45.40	60.48	58.88	56.89	34.29	33.94	55.50	60.79	40.64	52.63	47.18
Al_2O_3	7.66	3.46	8.42	3.78	1.60	13.95	9.46	24.42	10.61	7.21	19.43	17.70
FeO	4.35	17.70	8.70	10.08	15.09	18.69	24.87	4.60	4.71	20.78	8.37	12.08
MnO	0.16	0.32	0.41	0.68	0.88	0.41	0.54			0.31		
MgO	11.49	30.17	17.07	22.61	21.80	31.55	30.56	5.16	8.10	28.10	10.23	15.43
CaO	12.06	1.95	1.34	1.33	2.32	0.28	0.22	0.18	11.39	0.13	0.17	0.24
Na_2O	2.61	0.99	2.78	1.63	0.76	0.66		7.83	3.07	2.30	7.98	6.30
K_2O	0.35		0.49	0.07	0.08	0.16	0.10	0.91	0.37	0.24	0.20	0.44
TiO_2	0.20		0.09	0.15			0.19	0.91	0.26	0.28	0.85	0.44
Partial Norm												
Q	8.8		6.6	4.5	3.7				10.5			
C			0.9			12.2	9.0	10.2		2.9	5.8	6.4
F	32.3	13.4	33.1	17.0	7.6	3.0	1.1	72.5	42.2	13.7	57.1	39.5
Di	41.3	3.8		3.1	8.8				34.2			
Hy	16.9	21.5	59.1	74.4	79.4			2.4	11.9			
Ol		61.4				82.2	89.1	12.6		78.6	28.6	43.5
Ne											6.8	9.5

	Carraweena											
	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
Composition												
SiO_2	52.11	48.72	53.88	54.09	41.15	39.82	55.19	56.03	35.14	60.79	53.72	54.09
Al_2O_3	25.80	24.09	26.40	25.39	10.25	4.31	23.68	24.31	20.42	17.71	5.16	3.31
FeO	6.73	11.60	4.92	5.13	14.99	20.55	3.77	2.79	18.84	4.45	9.07	8.71
MnO					0.25	0.40			0.32	0.22	0.33	0.27
MgO	3.72	5.00	4.70	4.22	23.90	31.95	2.96	2.50	22.38	4.47	24.60	26.82
CaO	0.32	0.50	0.44	0.38	4.96		0.43	0.15	0.31	4.97	5.04	4.78
Na_2O	9.22	8.09	7.62	8.71	3.22	2.14	12.45	12.75	1.92	6.54	0.36	0.24
K_2O	0.66	0.78	1.18	0.76	0.60	0.09	0.47	0.41	0.35	0.31		
TiO_2	1.16	1.09	1.14	1.17	0.18	0.12	0.84	0.79	0.20	0.27	0.68	0.49
Partial Norm												
Q										2.1		
C	9.3	9.0	11.8	9.6		0.7	1.9	2.6	16.3			
F	61.9	52.5	70.3	68.9	11.8	6.6	59.2	61.4	14.1	75.2	15.5	10.0
Di					10.4					5.4	10.0	12.5
Hy										16.6	71.0	72.1
Ol	14.6	23.8	13.7	13.2	59.5	85.3	9.4	7.3	66.0		1.2	3.2
Ne	11.7	12.5	1.8	6.1	14.8		27.7	26.9				
Lc					2.7							

	Carraweena											
	C23	C24	C25	C26	C27	C28	C29	C30	C31	C32	C33	C34
Composition												
SiO_2	51.92	54.98	60.54	58.95	56.83	56.65	62.78	63.28	54.98	63.46	61.76	66.01
Al_2O_3	9.77	2.98	13.35	1.93	1.96	5.16	20.79	13.13	2.98	7.25	5.93	9.08
FeO	8.97	14.60	4.99	8.84	12.32	9.02	1.50	3.16	14.60	4.41	6.53	3.83
MnO		0.35		0.46	0.46	0.59		0.15	0.35	0.25	0.25	0.26
MgO	21.07	23.95	4.94	25.38	24.78	24.32	1.90	6.02	23.95	8.34	16.79	7.95
CaO	6.48	1.47	3.73	2.69	2.04	2.02	3.99	6.45	1.47	10.73	4.61	6.94
Na_2O	0.47	0.89	6.88	0.71	0.85	1.46	7.71	6.69	0.89	4.25	2.80	4.80
K_2O			0.26	0.23	0.26	0.23	0.97	0.63		0.28	0.27	0.11
TiO_2	0.56		0.28				0.36	0.50		0.25	0.17	0.24
Partial Norm												
Q			3.2	5.2	0.9		2.0	2.8		10.2	8.3	14.5
F	28.5	11.7	64.5	8.8	9.5	20.6	90.2	64.3	11.7	37.4	28.1	44.2
Di	6.1	2.6	11.2	9.5	7.5	2.6	0.4	22.5	2.6	42.8	16.0	25.3
Hy	59.7	82.7	15.5	75.8	81.6	74.7	6.7	9.5	82.7	8.3	46.3	14.8
Ol	3.9	2.3				1.7						

	Carraweena			H0 06					Moorabie			
	C35	C36	C37	H1	H2	H3	H4	H5	M1	M2	M3	M4
Composition												
SiO_2	53.01	66.06	66.00	56.83	57.39	63.27	55.96	60.37	52.70	55.50	68.84	55.74
Al_2O_3	1.04	18.23	9.63	6.54	9.49	16.69	3.45	8.29	0.38	1.00	18.15	18.93
FeO	10.29	1.19	7.03	2.94	2.64	1.29	4.63	2.43	13.29	11.96	1.73	1.53
MnO	0.51	0.14	0.29				0.22		0.48	0.54		
MgO	21.31	2.15	11.21	12.01	0.28	3.08	16.38	9.79	27.83	25.81	2.87	4.91
CaO	11.30	1.88		17.45	15.56	6.00	16.75	12.44	3.68	3.95	0.97	11.26
Na_2O	0.57	9.40	4.38	2.94	4.66	7.69	1.40	3.97	0.24	0.33	5.39	5.62
K_2O		0.69	0.58	0.36	0.38	0.91	0.19	1.79			1.58	0.36
TiO_2	0.17	0.10	0.23	0.28	0.18	0.12		0.28	0.10		0.47	0.75
Partial Norm												
Q		1.3	15.6			0.1	0.1	1.2		0.1	24.0	
C			1.8								5.8	
F	5.1	89.1	40.5	30.3	35.6	78.8	15.5	43.3	2.0	4.0	59.8	68.1
Di	44.8	3.1		65.7	58.2	17.0	64.0	48.8	14.7	14.7		24.1
Hy	40.0	6.2	41.0			3.7	19.3	5.3	67.7	80.2	9.6	
Ol	8.1			2.7	0.1				14.2			1.8
Ne				0.2	5.4							3.8

	Moorabie								Oberon Bay			Poonaruuna
	M5	M6	M7	M8	M9	M10	M11	M12	O1	O2	O3	P1
Composition												
SiO_2	61.64	54.81	35.43	68.93	64.63	67.97	57.41	56.73	55.90	45.80	46.41	53.03
Al_2O_3	21.06	20.35	17.78	11.20	8.55	10.14	0.90	24.01	5.21	2.30	2.62	2.13
FeO	1.75	2.13	10.21	2.77	4.13	3.89	12.96	2.91	15.77	17.40	16.75	7.31
MnO			0.24	0.15	0.15	0.16	0.89	0.12	0.29	0.37	0.42	
MgO	2.20	5.34	34.48	5.64	9.05	5.68	24.26	5.36	17.19	29.86	29.06	15.58
CaO	2.39	9.84	0.70	3.98	8.36	5.30	2.32	1.45	2.09	2.25	2.29	20.61
Na_2O	6.41	5.40	0.57	6.14	3.24	5.46	0.76	6.87	1.14	0.31	0.27	0.94
K_2O	2.05	0.40	0.11	0.70	1.06	0.52		1.17	1.15	0.73	0.78	
TiO_2	1.11	0.83		0.28	0.31	0.42		0.87			0.13	0.33
Partial Norm												
Q	7.5			15.4	14.7	16.7	3.4		2.5			
C	4.0		15.5					8.8				
F	78.2	74.3	9.0	57.0	39.3	50.9	4.6	72.2	22.2	9.7	10.5	8.9
Di		14.8		15.1	28.7	20.0	9.3		3.8	6.8	6.2	80.7
Hy	6.9		0.5	11.7	16.2	11.3	81.4	15.1	70.1	27.4	32.4	
Ol		6.3	74.7					1.8		55.1	49.3	9.4
Ne		2.1										0.3

APPENDIX D: COMPUTER PROGRAMMES

This appendix contains the full listings of some of the programmes written by the author and used in this work.

```
      PROGRAM METEAN(INPUT,OUTPUT,TAPE1,TAPE2=OUTPUT,TAPE10)
* METEAN -- A PROGRAMME FOR METEORITE ANALYSIS ADAPTED FROM SILIANV2 BY
* M J FITZGERALD DURING THE PERIOD NOVEMBER-FEBRUARY 1972/1973
C*****DIMENSION VARIABLES
      DIMENSION CE(12), CM(12,14), CMG(12), PN(14), AW(14), SUM(20),
     1DA(20), AZ(14)
      COMMON/ABC/NAL,MN(200)
      COMMON    BG(12), BMG(12), CMX(12), Z(14), ZG(200,14), ZGG(14),
     1          EG(14), EM(200,14), EN(14), AN(14), AP(200,14), SL(200),
     2          TO(200), WR(200,15), AR(200,15), FF(12), AA(200,13)
C*****MASS ABSORPTION COEFFICIENTS FOR THE FLUX
      DATA (CE(I),I=1,12)/
     11.046,1.045,.851,.865,.897,.896,1.014,1.056,1.050,1.038,.894,.853/
C*****DEVIATIONS OF COMPONENT OXIDE MASS ABSORPTION COEFFICIENTS FROM THE FLUX
      DATA (CM(I),I=1,168)/
     1-.027,-.044,.081,.090,.098,.108,.082,.112,.136,.337,.086,.069,
     2-.031,-.044,.077,.092,.086,.094,.086,.116,.126,.334,.074,.060,
     3.146,.146,.179,.065,.017,-.020,-.034,-.032,.010,.124,.000,.698,
     4.134,.135,.647,.110,.000,-.037,-.042,-.037,-.021,.100,-.024,.631,
     5.126,.130,.644,.723,.069,-.047,-.055,-.048,-.043,.105,-.037,.647,
     6-.060,-.063,.181,.182,.179,-.063,-.061,-.060,-.016,-.071,.169,.136
     7,-.065,-.063,.110,.128,.119,.127,-.061,-.088,-.070,-.082,.132,.102
     9,-.074,-.074,.078,.105,.101,.110,.122,-.072,-.078,-.089,.112,.084,
     A-.090,-.078,.069,.068,.080,.094,.093,.116,-.084,-.096,.087,.061,
     B-.070,-.047,.141,.146,.136,.158,.182,.192,.221,-.070,.155,.133,  -
     C.062,-.038,.164,.298,.164,-.053,-.058,-.059,-.074,-.064,-.054,.156
     D,.244,-.092,.033,.036,.028,.043,.050,.054,.073,.238,.041,.028,
     E-.110,-.100,.051,.051,.057,.046,.063,.058,.080,-.103,.062,.040,
     F-.163,-.163,-.132,-.124,-.139,-.139,-.158,-.164,-.163,-.162,-.139,
     G-.133/
C*****FACTORS TO CORRECT NOMINAL MAGNESIUM PERCENTAGE
      DATA (CMG(I),I=1,12)/.0008,.0020,.0100,.0100,.0045,.0000,.0000,
     1.0000,.0000,.0008,.0010,.0000/
C*****FACTORS TO CONVERT OXIDES TO THE ELEMENTS
      DATA (PN(I),I=1,14)/.69944,.77446,.59950,.71469,.83015,.43642,
     1.46747,.52923,.60317,.78584,.40051,.68425,.74185,.00000/
C*****ATOMIC WEIGHTS OF ELEMENTS
      DATA (AW(I),I=1,14)/ 55.487,54.938,47.900,40.080,39.098,30.974,
     128.086,26.982,24.305,58.710,32.060,51.996,22.990,15.999/
C*****LABEL CODES
      DATA END,ANEW,WCH/6HEND    ,6HNEW BG,6HW CHAN/
C*****READ FORMATS
    1 FORMAT (12F6.3)
    2 FORMAT (A6,A2,10F7.6,/8X,5F7.6)
C*****WRITE FORMATS
    3 FORMAT (1H1,50X*METEORITE ANALYSIS*10X,A9)
    4 FORMAT (1H-,12X*FE2O3*3X*MNO*5X*TIO2*4X*CAO*5X*K2O*5X*P2O5*4X
     1        *SIO2*3X*AL2O3*4X*MGO*5X*NIO*5X*SO3*5X*CR2O3*)
    5 FORMAT (1H *BACKGROUND *F5.3,11F8.3)
    6 FORMAT (1H-*SAMPLE  *A8,75X*WEIGHT*F7.3,3X*WEIGHT FRACTION NA2O*
     1        F9.3)
    7 FORMAT (1H-,11X*FE2O3*3X*MNO*5X*TIO2*4X*CAO*5X*K2O*5X*P2O5*4X
     1        *SIO2*4X*AL2O3*3X*MGO*5X*NIO*5X*SO3*5X*CR2O3*3X*NA2O*4X*O2*
     2        6X*LOSS*3X*TOTAL*)
    8 FORMAT (1HO*NOMINAL *13F8.3,8X,F8.3)
    9 FORMAT (1HO*MG CORR *12F8.3,3X,*NEW MGO NOM PERCENTAGE*F7.3)
   10 FORMAT (1HO*MATRIX 2 *12F8.4)
   11 FORMAT (1HO*OXIDE   *13F8.3,8X,2F8.3)
   12 FORMAT (1HO*ELEMENT *14F8.3,9X,*100.000*)
   13 FORMAT (1HO,12X,A8,13F8.3)
   14 FORMAT (1HO*ELT NVOL*10F8.3,8X,2F8.3,17X,*100.000*)
   15 FORMAT (1HO,*ATOM    *14F8.3,9X,*100.000*)
   16 FORMAT (1HO,*WEIGHT RATIOS      CA/AL*F9.4,*  CA/TI*F9.4,*  SI/MG*
     1        F9.4,*  MG/CR*F9.4,*  FE/NI*F9.4,*  FE/SI*F9.4,4X
     2        *MG/AL*F14.4/1X*SI/TI*F12.4,*  AL/TI*F9.4,*  FE/MG*F9.4,
     3        *  CA/NA*F9.4,*  SI/AL*F9.4,*  SI/CA*F9.4,*  MG/CA*F9.4,4X
     4        *CA/(NA+K)*F10.4)
   17 FORMAT (1H ,*ATOMIC RATIOS      CA/AL*F9.4,*  CA/TI*F9.4,*  SI/MG*
     1        F9.4,*  MG/CR*F9.4,*  FE/NI*F9.4,*  FE/SI*F9.4,4X
     2        *MG/AL*F14.4/1X*SI/TI*F12.4,*  AL/TI*F9.4,*  FE/MG*F9.4,
     3        *  CA/NA*F9.4,*  SI/AL*F9.4,*  SI/CA*F9.4,*  MG/CA*F9.4,4X
     4        *CA/(NA+K)*F10.4)
   18 FORMAT (1H-,57X,*OXIDE  <<PERCENTAGES>>*)
   19 FORMAT (1H-,4X*SAMPLE*5X*FE2O3*3X*MNO*5X*TIO2*4X*CAO*5X*K2O*5X
     1        *P2O5*4X*SIO2*4X*AL2O3*3X*MGO*5X*NIO*5X*SO3*5X*CR2O3*3X
     2        *NA2O*4X*LOSS*3X*TOTAL*)
```

```
      20 FORMAT (1HO,4X,A8,15F8.3)
      21 FORMAT (1H-,57X,*ELEMENTAL  PERCENTAGES*)
      22 FORMAT (1H-,58X,*ATOMIC   PERCENTAGES*)
      23 FORMAT (1H-,12X*SAMPLE*6X*FE    *3X*MN *5X*TI   *4X*CA *5X*K   *5X
     1        *P    *4X*SI   *4X*AL    *3X*MG *5X*NI *5X*S   *5X*CR    *3X
     2        *NA   *)
      24 FORMAT (1HO,12X,A8,13F8.3)
      25 FORMAT (1H-,60X*WEIGHT    RATIOS*)
      26 FORMAT (1H-,60X*ATOMIC    RATIOS*)
      27 FORMAT (1H-*SAMPLE*4X*AL/TI*3X*CA/AL*4X*CA/TI*3X*CA/NA*3X
     1        *CA/(NA+K)*1X*FE/MG*4X*FE/NI*2X*FE/SI*4X*SI/AL*4X*SI/CA*
     2        3X*SI/MG*4X*SI/TI*4X*MG/CA*4X*MG/CR*3X*MG/AL*)
      28 FORMAT (1HO,A8,2F8.4,F9.4,F8.4,3F9.4,F7.4,2F9.4,F8.4,3F9.4,F8.4)
      29 FORMAT (A8,14F6.3)
      30 FORMAT (1H-,38X*THE FOLLOWING RESULTS ARE BASED ON NOMINAL OXIDE *
     1        *PERCENTAGES*//39X*CALCULATED USING THE FLUORESCENCE FACTO*
     2        *RS AS LISTED BELOW*//////52X*OXIDE*20X*FLUOR FACTOR*////
     3        52X*FE2O3*22X,F8.4///52X*MNO*24X,F8.4///52X*TIO2*23X,F8.4//
     4        /52X*CAO*24X,F8.4///52X*K2O*24X,F8.4///52X*P2O5*23X,F8.4///
     5        52X*SIO2*23X,F8.4///52X*AL2O3*22X,F8.4///52X*MGO*24X,F8.4//
     6        /52X*NIO*24X,F6.4///52X*SO3*24X,F8.4///52X*CR2O3*22X,F8.4)
      31 FORMAT (A6,A2,9F8.4/A6,A2,5F8.4)
      32 FORMAT (1HO,*INPUT    *12F8.5,F8.3,8X,F8.3)
      33 FORMAT (8F10.4/4F10.4)
      34 FORMAT (1HO*AT ABUN *13F8.3)
      35 FORMAT (1H-,44X*ATOMIC ABUNDANCES RELATIVE TO 10E2 SILICON ATOMS*)
      36 FORMAT (1HO,12X,A8,13F8.3)
      37 FORMAT (A6,A2,9F8.4/8X,4F8.4)
C*****CALL DATE SUBROUTINE
      CALL DATE(TODAY)
C*****SET ANALYSIS COUNTER INITIALLY EQUAL TO ZERO
      II = 0
C*****READ AND WRITE FLUORESCENCE FACTORS
      READ (1,33) (FF(I),I=1,12)
      WRITE (2,3) TODAY
      WRITE (2,30) (FF(I),I=1,12)
C*****READ WEIGHT AND SODIUM OXIDE FRACTION OF SAMPLE
      READ (1,1) WT, SOF
C*****READ AND WRITE BACKGROUND CORRECTIONS
  100 READ (1,1) (BG(I),I=1,12)
      WRITE (2,3) TODAY
      WRITE (2,4)
      WRITE (2,5) (BG(I),I=1,12)
C*****SET RESULTS PER PAGE COUNTER INITIALLY EQUAL TO ZERO
      IPG=0
C*****INCREMENT ANALYSIS COUNTER
  101 II = II + 1
C*****READ DATA CARDS
      READ (1,2) SL(II), MN(II), (AZ(I),I=1,14), WL
C*****END OF DATA, NEW WEIGHT, OXIDE FRACTION OR BACKGROUND CARDS
      IF (SL(II).EQ.END)  GO TO 117
      IF (SL(II).EQ.WGH)  GO TO 102
      IF (SL(II).NE.ANEW) GO TO 103
C*****PROCEDURE FOR NEW BACKGROUNDS -- DECREASE ANALYSIS COUNTER AND RETURN
      II = II - 1
      GO TO 100
C*****PROCEDURE FOR NEW SODIUM OXIDE FRACTION
  102 II = II - 1
      READ (1,1) WT, SOF
      GO TO 101
C*****INCREMENT RESULTS PER PAGE COUNTER
  103 IPG=IPG+1
C*****MULTIPLY INPUT VALUES BY FLUORESCENCE FACTORS TO CALULATE NOM. PERCENTAGES
      DO 5000 I=1,12
 5000 Z(I) = AZ(I)*FF(I)
      Z(13) = AZ(13)
      Z(14) = AZ(14)
C*****CORRECT NOMINAL MAGNESIUM PERCENTAGE FOR PHOSPHORUS FLUORESCENCE
      PFCF = 0
      DO 104 I = 1,12
      BMG(I)=CMG(I)*Z(I)
  104 PFCF = PFCF + BMG(I)
      Z(9) = Z(9) - PFCF
C*****STORE ADJUSTED MAGNESIUM NOMINAL PERCENTAGE
      ZM = Z(9)
C*****CORRECT SODIUM PERCENTAGE FOR BUTTON COMPOSITION
      WX = 0.28/WT
      SCF = SOF*WX*100.00
      Z(13) = Z(13) + SCF
C*****CARRY OUT MATRIX CORRECTIONS
C*****INITIALLY SET CORRECTED PERCENTAGES EQUAL TO NOMINAL PERCENTAGES
      DO 105 I=1,12
  105 ZG(II,I) = Z(I)
      DO 106 I = 13,14
  106 ZG(II,I) = Z(I)/WX
C*****SET UP DOUBLE DO-LOOP
      DO 109 L = 1,2
C*****INITIALLY SET OVERALL MATRIX FACTOR EQUAL TO ZERO
      DO 108 I = 1,12
      CMX(I) = 0
```

```
C*****SUM PRODUCTS OF CORRECTED NOMINAL PERCENTAGES AND OXIDE MATRIX FACTORS
      DO 107 J = 1,14
  107 CMX(I) = CMX(I) + 0.01*ZG(II,J)*CM(I,J)
C*****ADD ON MIX (FLUX) MATRIX FACTOR AND THUS CALCULATE OVERALL MATRIX FACTOR
      CMX(I) = CE(I) + CMX(I)
C*****MULTIPLY NOMINAL OXIDE PERCENTAGE BY MATRIX FACTOR AND SUBTRACT BACKGROUND
  108 ZGG(I) = CMX(I)*Z(I) - BG(I)
C*****RETRIEVE CORRECTED OXIDE PERCENTAGE FROM TEMPORARY STORE
      DO 109 I = 1,12
  109 ZG(II,I) = ZGG(I)
C*****ADJUST OXIDE PERCENTAGES FOR SAMPLE WEIGHT
      WC = (100.0-WL)/100.0
      DO 110 I=1,12
  110 ZG(II,I) = ZG(II,I)*WX*WC
      DO 1110 I=13,14
 1110 ZG(II,I) = ZG(II,I)*WX
C*****ADJUST MAGNESIUM NOMINAL PERCENTAGE FOR PHOSPHORUS FLUORESCENCE CORRECTION
      Z(9) = Z(9) + PFCF
C*****CALCULATE TRUE SODIUM PERCENTAGE OF SAMPLE
      ZG(II,13) = ZG(II,13) - SCF
C*****ADJUST SODIUM NOMINAL PERCENTAGE FOR CORRECTION FACTOR
      Z(13) = Z(13) - SCF
C*****SET OXIDE AND ELEMENT TOTALS EQUAL TO ZERO
      TO(II) = 0
      TT = 0
      TS = 0
      TE = 0
C*****SUM CORRECTED OXIDE PERCENTAGES
      DO 111 I = 1,14
      TO(II) = TO(II) + ZG(II,I)
C*****CALCULATE EQUIVALENT ELEMENTAL PERCENTAGES
      EM(II,I) = PN(I)*ZG(II,I)
C*****SUM ELEMENTAL PERCENTAGES
  111 TT = TT + EM(II,I)
      TS = TT - EM(II,11)
C*****CALCULATE OXYGEN PERCENTAGE
      EM(II,14) = 100.0 - TT
C*****CALCULATE NON-VOLATILE ELEMENTAL PERCENTAGE TO ONE HUNDRED PERCENT
      DO 114 I=1,13
  114 EN(I) = (EM(II,I)*100.0)/TS
C*****CALCULATE NUMBER OF MOLES OF EACH ELEMENT PRESENT
      DO 1140 I=1,14
      AN(I) = EM(II,I)/AW(I)
C*****SUM NUMBER OF MOLES
 1140 TE = TE + AN(I)
C*****CALCULATE ATOM PERCENTAGE OF EACH ELEMENT PRESENT
      DO 115 I=1,14
  115 AP(II,I) = (AN(I)*100.00)/TE
C*****WRITE VALUES OF ATOMIC PERCENTAGES ON TAPE
      WRITE (10,29) SL(II), EM(II,1), (AP(II,I),I=1,13)
C*****CALCULATE WEIGHT RATIOS
      WR(II,2) = EM(II,4)/EM(II,8)
      WR(II,3) = EM(II,4)/EM(II,3)
      WR(II,1) = WR(II,3)/WR(II,2)
      WR(II,4) = EM(II,4)/EM(II,13)
      WR(II,5) = EM(II,4)/(EM(II,13)+EM(II,5))
      WR(II,6) = EM(II,1)/EM(II,9)
      WR(II,7) = EM(II,1)/EM(II,10)
      WR(II,8) = EM(II,1)/EM(II,7)
      WR(II,11)= EM(II,7)/EM(II,9)
      WR(II,13) = EM(II,9)/EM(II,4)
      WR(II,14) = EM(II,9)/EM(II,12)
      WR(II,10) = WR(II,11)*WR(II,13)
      WR(II,9) = WR(II,2)*WR(II,10)
      WR(II,12) = WR(II,10)*WR(II,3)
      WR(II,15) = WR(II,13)*WR(II,2)
C*****CALCULATE ATOMIC RATIOS
      AR(II,2) = AP(II,4)/AP(II,8)
      AR(II,3) = AP(II,4)/AP(II,3)
      AR(II,1) = AR(II,3)/AR(II,2)
      AR(II,4) = AP(II,4)/AP(II,13)
      AR(II,5) = AP(II,4)/(AP(II,13)+AP(II,5))
      AR(II,6) = AP(II,1)/AP(II,9)
      AR(II,7) = AP(II,1)/AP(II,10)
      AR(II,8) = AP(II,1)/AP(II,7)
      AR(II,11)= AP(II,7)/AP(II,9)
      AR(II,13) = AP(II,9)/AP(II,4)
      AR(II,14) = AP(II,9)/AP(II,12)
      AR(II,10) = AR(II,11)*AR(II,13)
      AR(II,9) = AR(II,2)*AR(II,10)
      AR(II,12) = AR(II,10)*AR(II,3)
      AR(II,15) = AR(II,13)*AR(II,2)
C*****CALCULATE RELATIVE ATOMIC ABUNDANCES
      DO 1150 I=1,13
 1150 AA(II,I) = AP(II,I)*100.0/AP(II,7)
C*****MOVE TO NEXT PAGE AND HEAD SAME
      IF (IPG.LT.3) GO TO 116
      WRITE (2,3) TODAY
C*****SET RESULTS PER PAGE COUNTER EQUAL TO ONE
      IPG = 1
```

```
C*****PRINT OUT RESULTS
  116 WRITE (2,6) SL(II), WT, SOF
      WRITE (2,7)
      WRITE (2,32) (AZ(I),I=1,14)
      WRITE (2,8)  (Z(I),I=1,14)
      WRITE (2,9)  (BMG(I),I=1,12), ZM
      WRITE (2,10) (CMX(I),I=1,12)
      WRITE (2,11) (ZG(II,I),I=1,14),TO(II)
      WRITE (2,12) (EM(II,I),I=1,14)
      WRITE (2,14) (EN(I),I=1,10),(EN(J),J=12,13)
      WRITE (2,15) (AP(II,I),I=1,14)
      WRITE (2,34) (AA(II,I),I=1,13)
      WRITE (2,16) WR(II,2),WR(II,3),WR(II,11),WR(II,14),WR(II,7),
     1             WR(II,8),WR(II,15),WR(II,12),WR(II,1),WR(II,6),
     2             WR(II,4),WR(II,9),WR(II,10),WR(II,13),WR(II,5)
      WRITE (2,17) AR(II,2),AR(II,3),AR(II,11),AR(II,14),AR(II,7),
     1             AR(II,8),AR(II,15),AR(II,12),AR(II,1),AR(II,6),
     2             AR(II,4),AR(II,9),AR(II,10),AR(II,13),AR(II,5)
C*****COMMENCE PROCESSING NEXT SET OF DATA
      GO TO 101
C*****PRINT TABULATED FORM OF CORRECTED OXIDE <<PERCENTAGES>>
  117 END FILE 10
      NAL = II
      II  = 1
      J = 0
      DO 1170 I=1,15
 1170 SUM(I) = 0.0
  118 WRITE (2,3)  TODAY
      WRITE (2,18)
      WRITE (2,19)
      N   = 1
  119 IF (II.EQ.NAL) GO TO 120
      IF (N.GT.27)   GO TO 118
      I =14
      CALL SUMS(ZG,II,I,J,SUM)
      SUM(15) = SUM(15) + TO(II)
      IF (MN(II).EQ.MN(II+1)) GO TO 1190
      I = 15
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,20) SL(II), (ZG(II,I),I=1,14), TO(II)
      N = N + 1
      WRITE (2,20) MN(II), (DA(I),I=1,15)
      GO TO 1191
 1190 WRITE (2,20) SL(II), (ZG(II,I),I=1,14), TO(II)
 1191 N   = N  + 1
      II  = II + 1
      GO TO 119
C*****PRINT TABULATED FORM OF ELEMENTAL PERCENTAGES
  120 II  = 1
      J = 0
      DO 1200 I=1,13
 1200 SUM(I) = 0.0
  121 WRITE (2,3)  TODAY
      WRITE (2,21)
      WRITE (2,23)
      N   = 1
  122 IF (II.EQ.NAL) GO TO 123
      IF (N.GT.27)   GO TO 121
      I = 13
      CALL SUMS(EM,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 1220
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,24) SL(II), (EM(II,I),I=1,13)
      N = N + 1
      WRITE (2,24) MN(II), (DA(I),I=1,13)
      GO TO 1221
 1220 WRITE (2,24) SL(II), (EM(II,I),I=1,13)
 1221 N   = N  + 1
      II  = II + 1
      GO TO 122
C*****PRINT TABULATED FORM OF ATOMIC PERCENTAGES
  123 II  = 1
      J = 0
      DO 1230 I = 1,14
 1230 SUM(I) = 0.0
  124 WRITE (2,3)  TODAY
      WRITE (2,22)
      WRITE (2,23)
      N   = 1
  125 IF (II.EQ.NAL) GO TO 126
      IF (N.GT.27)   GO TO 124
      I = 14
      CALL SUMS(AP,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 1250
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,13) SL(II), (AP(II,I),I=1,13)
      WRITE (2,13) MN(II), (DA(I),I=1,13)
      N = N + 1
      GO TO 1251
 1250 WRITE (2,13) SL(II), (AP(II,I),I=1,13)
```

```
 1251 N    = N  + 1
      II   = II + 1
      GO TO 125
C*****PRINT TABULATED FORM OF WEIGHT RATIOS
  126 II   = 1
      J = 0
      DO 1260 I=1,15
 1260 SUM(I) = 0.0
  127 WRITE (2,3)  TODAY
      WRITE (2,25)
      WRITE (2,27)
      N    = 1
  128 IF (II.EQ.NAL) GO TO 129
      IF (N.GT.27)   GO TO 127
      I = 15
      CALL SUMS(WR,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 1280
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,28) SL(II), (WR(II,I),I=1,15)
      N = N + 1
      WRITE (2,28) MN(II), (DA(I),I=1,15)
      GO TO 1281
 1280 WRITE (2,28) SL(II), (WR(II,I),I=1,15)
 1281 N    = N  + 1
      II   = II + 1
      GO TO 128
C*****PRINT TABULATED FORM OF ATOMIC RATIOS
  129 II   = 1
      J = 0
      DO 1290 I=1,15
 1290 SUM(I) = 0.0
  130 WRITE (2,3)  TODAY
      WRITE (2,26)
      WRITE (2,27)
      N    = 1
  131 IF (II.EQ.NAL) GO TO 132
      IF (N.GT.27)   GO TO 130
      I = 15
      CALL SUMS(AR,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 1310
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,28) SL(II), (AR(II,I),I=1,15)
      N = N + 1
      WRITE (2,28) MN(II), (DA(I),I=1,15)
      GO TO 1311
 1310 WRITE (2,28) SL(II), (AR(II,I),I=1,15)
 1311 N = N + 1
      II   = II + 1
      GO TO 131
C*****PRINT TABULATED FORM OF RELATIVE ATOMIC ABUNDANCES
  132 II = 1
      J = 0
      DO 133 I=1,13
  133 SUM(I) = 0.0
  134 WRITE (2,3) TODAY
      WRITE (2,35)
      WRITE (2,23)
      N = 1
  135 IF (II.EQ.NAL) GO TO 138
      IF (N.GT.27) GO TO 134
      I = 13
      CALL SUMS(AA,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 136
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,36) SL(II), (AA(II,I),I=1,13)
      N = N + 1
      WRITE (2,36) MN(II), (DA(I),I=1,13)
      GO TO 137
  136 WRITE (2,36) SL(II), (AA(II,I),I=1,13)
  137 N = N + 1
      II = II + 1
      GO TO 135
  138 STOP
      END

      SUBROUTINE SUMS(DA,II,J,M,SUM)
      DIMENSION DA(200,20), SUM(20)
      M = M + 1
      DO 100 I=1,J
  100 SUM(I) = SUM(I) + DA(II,I)
      RETURN
      END

      SUBROUTINE AVRAGE(SUM,J,N,DA)
      DIMENSION DA(20), SUM(20)
      DO 100 I=1,J
      DA(I) = SUM(I)/N
  100 SUM(I) = 0.0
      N = 0
      RETURN
      END
```

```
      PROGRAM MINORM(INPUT,OUTPUT,TAPE2=OUTPUT,TAPE10)
      DIMENSION WM(20),CP(13),CM(20),AMW(20),PM(200,20),WP(200,10),
     1AP(200,10),SUM(20),DA(20),SL(200), MN(200)
      DIMENSION AR(200), AL(200)
C*****MOLECULAR WEIGHTS OF MINERALS
      DATA(AMW(I),I=1,20)/0.0,87.907,310.183,151.744,0.0,278.030,262.222
     1,278.208,223.835,0.0,116.163,100.388,131.930,0.0,100.388,131.930,
     20.0,203.776,140.692,60.084/
C*****READ FORMATS
    1 FORMAT (A6,A2,9F8.4/8X,5F8.4)
C*****WRITE FORMATS
    2 FORMAT (1H1,55X,*MINERAL ANALYSIS *,A9)
    3 FORMAT (1HO,*SAMPLE   NIF   TRO  WHT    ILM    FEL    ORT    ALB
     1  ANO   CRT   DIO    WOL    ENS    FSL    HYP    ENS   FSL   OLV
     2 FAY   FOR   QTZ*)
    4 FORMAT (1HO,A8,F5.2,F6.2,F5.2,5F7.2,2F6.2,5F7.2,5F6.2)
    5 FORMAT (1HO,29X,*SAMPLE    ORT    ALB    ANO    WOL    ENS    FSL
     1   ENS    FSL    FAY    FOR*)
    6 FORMAT (1HO,29X,A8,F6.2,9F7.2)
    7 FORMAT (1HO,59X*MOLAR  PERCENTAGES*)
    8 FORMAT (1HO,59X*WEIGHT PERCENTAGES*)
    9 FORMAT (6X,A2,/)
*******************************************************************************
C*****HEAD PAGE AND READ DATA
      DO 170 I=1,20
  170 SUM(I) = 0.0
      REWIND 10
      II = 1
  300 READ (10,9) MN(II)
      IF (EOF(10)) 302,301
  301 II = II + 1
      GO TO 300
  302 REWIND 10
      CALL DATE (TODAY)
      II = 1
      N = 1
      WRITE (2,2) TODAY
      WRITE (2,8)
      WRITE (2,3)
   10 READ (10,1) SL(II), MN(II), TI, (CP(I),I=1,13)
      IF (EOF(10)) 19,12
*******************************************************************************
C*****NICKEL IRON
   12 CP(1) = CP(1) + CP(2)
      CM(1) = CP(10)
C*****ASSIGN TO H- OR L- TYPE CHONDRITE ON BASIS OF TOTAL IRON CONTENT
      IF (TI.GT.23.0) GO TO 13
*******************************************************************************
C*****L CHONDRITES
      E = 7.2*CM(1)
      CP(1) = CP(1) - E
      WM(1) = 460.224*CM(1)
      GO TO 14
*******************************************************************************
C*****H CHONDRITES
   13 E = 11.4*CM(1)
      CP(1) = CP(1) - E
      WM(1) = 695.366*CM(1)
*******************************************************************************
C*****TROILITE
   14 CM(2) = CP(11)
      CP(1) = CP(1) - CM(2)
      F = CP(1)
C*****WHITLOCKITE
      CM(3) = CP(6)/2.0
      CP(4) = CP(4) - (3.0*CM(3))
C*****ILMENITE
      CM(4) = CP(3)
      CP(1) = CP(1) - CM(4)
C*****ORTHOCLASE
      CM(6) = CP(5)
      CP(7) = CP(7) - (3.0*CP(5))
      CP(8) = CP(8) - CP(5)
C*****ALBITE
      CM(7) = CP(13)
      CP(7) = CP(7) - (3.0*CP(13))
      CP(8) = CP(8) - CP(13)
C*****ANORTHITE
      CM(8) = 0.5*CP(8)
      CP(4) = CP(4) - (0.5*CP(8))
      CP(7) = CP(7) - CP(8)
C*****FELDSPAR
      CM(5) = CM(6) + CM(7) + CM(8)
C*****CHROMITE
      CM(9) = 0.5*CP(12)
      CP(1) = CP(1) - CM(9)
C*****WOLLASTONITE
      CM(11) = CP(4)
C*****DIOPSIDE
      CM(10) = 2.0*CM(11)
```

```
C*****CALCULATE REMAINING COMPONENTS AFTER FUTURE DIOPSIDE FORMATION
      FM = CP(1) + CP(9) - CM(11)
      S = CP(7) - (2.0*CM(11))
*****************************************************************************
C*****TEST TO SEE WHETHER QUARTZ IS GREATER THAN FERROMAGNESIAN SUM
      IF (S.GT.FM) GO TO 140
*****************************************************************************
C*****HYPERSTHENE AND OLIVINE FORMED
*****************************************************************************
C*****ASSIGN TO H- OR L- TYPE FERROMAGNESIAN MINERALS ON BASIS OF TOTAL IRON
      IF (TI.GT.23.0) GO TO 1400
C*****L CHONDRITES
      R = 1.178
      GO TO 1410
C*****H CHONDRITES
 1400 R = 1.117
*****************************************************************************
C*****FORM TOTAL AMOUNT OF EACH FERROMAGNESIAN MINERAL
C*****HYPERSTHENE
 1410 CM(14) = (2.0*S) - FM
C*****OLIVINE
      CM(17) = FM - S
C*****DISTRIBUTE THE IRON AMONGST THE FERROMAGNESIAN MINERALS
      RF = CP(1)/(CM(10) + CM(14) + (2.0*R*CM(17)))
C*****FORM THE IRON COMPONENT OF EACH OF THE FERROMAGNESIAN MINERALS
C*****FERROSILLITE IN DIOPSIDE
      CM(13) = RF*CM(11)
C*****FERROSILLITE IN HYPERSTHENE
      CM(16) = RF*CM(14)
C*****FAYALITE IN OLIVINE
      CM(18) = R*RF*CM(17)
C*****FORM THE MAGNESIUM COMPONENT OF EACH OF THE FERROMAGNESIAN MINERALS
      RM = 1.0 - RF
C*****ENSTATITE IN DIOPSIDE
      CM(12) = RM*CM(11)
C*****ENSTATITE IN HYPERSTHENE
      CM(15) = RM*CM(14)
C*****FORSTERITE IN OLIVINE
      ORM = 1.0 - R*RF
      CM(19) = ORM*CM(17)
C*****QUARTZ PERCENTAGE SET TO ZERO
      CM(20) = 0.0
      GO TO 141
*****************************************************************************
C*****HYPERSTHENE AND QUARTZ FORMED
C*****HYPERSTHENE
  140 CM(14) = FM
C*****CALCULATE THE PROPORTIONS OF IRON AND MAGNESIUM IN (IRON + MAGNESIUM)
      FR = CP(1)/(CP(1) + CP(9))
      GR = 1.0 - FR
C*****FORM THE IRON COMPONENT OF EACH OF THE FERROMAGNESIAN MINERALS
C*****FERROSILLITE IN DIOPSIDE
      CM(13) = FR*CM(11)
C*****FERROSILLITE IN HYPERSTHENE
      CM(16) = FR*CM(14)
C*****FORM THE MAGNESIUM COMPONENT OF EACH OF THE FERROMAGNESIAN MINERALS
C*****ENSTATITE IN DIOPSIDE
      CM(12) = GR*CM(11)
C*****ENSTATITE IN HYPERSTHENE
      CM(15) = GR*CM(14)
C*****OLIVINE PERCENTAGES SET TO ZERO
C*****OLIVINE
      CM(17) = 0.0
C*****FAYALITE
      CM(18) = 0.0
C*****FORSTERITE
      CM(19) = 0.0
C*****QUARTZ
      CM(20) = CP(7) - CM(14)
*****************************************************************************
C*****CALCULATE MOLAR PERCENTAGE COMPOSITION OF MAJOR MINERALS
C*****FELDSPAR PERCENTAGES
  141 FRM = 100.0/CM(5)
      AP(II,1) = CM(6)*FRM
      AP(II,2) = CM(7)*FRM
      AP(II,3) = CM(8)*FRM
C*****DIOPSIDE PERCENTAGES
      FAM = 100.0/CM(10)
      AP(II,4) = CM(11)*FAM
      AP(II,5)  = CM(12)*FAM
      AP(II,6)  = CM(13)*FAM
C*****HYPERSTHENE PERCENTAGES
      FCM = 100.0/CM(14)
      AP(II,7)  = CM(15)*FCM
      AP(II,8)  = CM(16)*FCM
C*****OLIVINE PERCENTAGES
      IF (CM(17).LT.0.1) CM(17) = 1.0
      FTM = 100.0/CM(17)
      AP(II,9) = CM(18)*FTM
      AP(II,10)= CM(19)*FTM
      IF (AP(II,9).LT.0.1) CM(17) = 0.0
```

```
C*****************************************************************************
C*****CALCULATE WEIGHT PERCENTAGE MINERAL COMPOSITION OF THE METEORITE
      DO 15 I =2,20
   15 WM(I) = CM(I)*AMW(I)
      TM = 0
      DO 16 I = 1,20
   16 TM = TM + WM(I)
      TMP = 100.0/TM
      DO 17 I = 1,20
   17 PM(II,I) = WM(I)*TMP
C*****************************************************************************
C*****CALCULATE WEIGHT PERCENTAGE COMPOSITION OF MAJOR MINERALS
C*****FELDSPAR PERCENTAGES
      WM(5) = WM(6) + WM(7) + WM(8)
      PM(II,5) = WM(5)*TMP
      FR = 100.0/WM(5)
      WP(II,1)= WM(6)*FR
      WP(II,2)= WM(7)*FR
      WP(II,3)= WM(8)*FR
C*****DIOPSIDE PERCENTAGES
      WM(10) = WM(11) + WM(12) + WM(13)
      PM(II,10) = WM(10)*TMP
      FA = 100.0/WM(10)
      WP(II,4)= WM(11)*FA
      WP(II,5) = WM(12)*FA
      WP(II,6) = WM(13)*FA
C*****HYPERSTHENE PERCENTAGES
      WM(14) = WM(15) + WM(16)
      PM(II,14) = WM(14)*TMP
      FC = 100.0/WM(14)
      WP(II,7) = WM(15)*FC
      WP(II,8) = WM(16)*FC
C*****OLIVINE PERCENTAGES
      WM(17) = WM(18) + WM(19)
      PM(II,17) = WM(17)*TMP
      IF (WM(17).LT.0.1) WM(17) = 1.0
      FT = 100.0/WM(17)
      WP(II,9)= WM(18)*FT
      WP(II,10)= WM(19)*FT
C*****************************************************************************
C*****MINERAL PERCENTAGES IN TABULATED FORM
      J = 0
      IF (N.LT.28) GO TO 18
      N = 0
      WRITE (2,2) TODAY
      WRITE (2,8)
      WRITE (2,3)
   18 I = 20
      CALL SUMS(PM,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 180
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,4) SL(II), (PM(II,I),I=1,20)
      N = N + 1
      WRITE (2,4) MN(II),  (DA(I),I=1,20)
      GO TO 181
  180 WRITE (2,4) SL(II), (PM(II,I),I=1,20)
  181 N = N + 1
      II = II + 1
      GO TO 10
C*****************************************************************************
C*****MOLAR PERCENTAGES OF MAJOR MINERALS IN TABULATED FORM
   19 NAL = II
      II = 1
      J = 0
      DO 190 I=1,10
  190 SUM(I) = 0.0
   20 WRITE (2,2) TODAY
      WRITE (2,7)
      WRITE (2,5)
      N = 1
   21 IF (II.EQ.NAL) GO TO 22
      IF (N.GT.27) GO TO 20
      I = 10
      CALL SUMS(AP,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 210
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,6) SL(II), (AP(II,I),I=1,10)
      N = N + 1
      WRITE (2,6) MN(II), (DA(I),I=1,10)
      GO TO 211
  210 WRITE (2,6) SL(II), (AP(II,I),I=1,10)
  211 N = N + 1
      II = II + 1
      GO TO 21
C*****************************************************************************
C*****WEIGHT PERCENTAGES OF MAJOR MINERALS IN TABULATED FORM
   22 II = 1
      J = 0
      DO 220 I=1,10
  220 SUM(I) = 0.0
```

```
   23 WRITE (2,2) TODAY
      WRITE (2,8)
      WRITE (2,5)
      N = 1
   24 IF (II.EQ.NAL) GO TO 25
      IF (N.GT.27) GO TO 23
      I = 10
      CALL SUMS(WP,II,I,J,SUM)
      IF (MN(II).EQ.MN(II+1)) GO TO 240
      CALL AVRAGE(SUM,I,J,DA)
      WRITE (2,6) SL(II), (WP(II,I),I=1,10)
      N = N + 1
      WRITE (2,6) MN(II), (DA(I),I=1,10)
      GO TO 241
  240 WRITE (2,6) SL(II), (WP(II,I),I=1,10)
  241 N = N + 1
      II = II + 1
      GO TO 24
   25 STOP
      END


      SUBROUTINE SUMS(D,II,J,M,SUM)
      DIMENSION D(200,20), SUM(20)
      M = M + 1
      DO 100 I=1,J
  100 SUM(I) = SUM(I) + D(II,I)
      RETURN
      END


      SUBROUTINE AVRAGE(SUM,J,N,DA)
      DIMENSION DA(20), SUM(20)
      DO 100 I=1,J
      DA(I) = SUM(I)/N
  100 SUM(I) = 0.0
      N = 0
      RETURN
      END
```

```
      OVERLAY(AURPAK,4,0)
      PROGRAM PRINCA
C*****PRINCA -- A PROGRAMME FOR PRINCIPAL COMPONENT ANALYSIS WRIITEN BY
C*****M.J. FITZGERALD IN JULY 1974.
      DIMENSION SN(200),E(16),LAB(16),SA(32),XA(200),YA(200),B(16,16),
     1X(200,16),Y(200,16),Z(200,16),C(136),R(136),IFORM(8),SUMV(16)
      COMMON/LABELS/IMESS(8),IL,IW,IC,IQ,IP,IS
    1 FORMAT (2A3,I2)
    2 FORMAT (16A5)
    3 FORMAT (1H1,63X*INPUT DATA*)
    4 FORMAT (1HO,*SAMPLE*1X,16(3X,A5))
    5 FORMAT (1HO,A8,16F8.3)
    6 FORMAT (1H1,60X*NORMALIZED  DATA*)
    7 FORMAT (1H1,59X*CORRELATION MATRIX*)
    8 FORMAT (1HO,A8,16F8.4)
    9 FORMAT (8A10)
   10 FORMAT (//////,1H ,62X*MEAN VALUES*)
   11 FORMAT (//////,1H ,58X*STANDARD DEVIATIONS*)
   12 FORMAT (1HO,8X,16F8.3)
   13 FORMAT (1H-,62X*EIGENVALUES*)
   14 FORMAT (1H-,61X*EIGENVECTORS*)
   15 FORMAT (1H1,57X*TRANSFORMED  VARIABLES*)
   16 FORMAT (1H1,4(/),54X*PRINCIPAL COMPONENT ANALYSIS*///64X,A9,5(/)
     1       ,28X,8A10,5(/),
     1        34X*NUMBER OF SAMPLES (M)*43X,I4,///34X*NUMBER OF ANALYTICA
     2*     *L POINTS (N)*33X,I4,///34X*LOGARITHMIC TRANSFORMATION OPTIO
     3*    *N*32X,A3,///34X*NORMALIZATION OPTION*45X,A3,///15X*THE TRANS
     4*     *FORMED VARIABLES WILL BE COMPUTED BY TAKING THE MATRIX PROD
     5*     *UCT OF EITHER THE RAW OR NORMALIZED DATA*//20X*(DEPENDING O
     6*     *N WHETHER NORMALIZATION HAS BEEN CHOSEN) AND THE EIGENVECT
     7*     *ORS (PRINCIPAL COMPONENTS)*)
   17 FORMAT (1H1,59X*COVARIANCE  MATRIX*)
   18 FORMAT (1HO,8X,16F8.4)
   19 FORMAT (1H-,41X*EIGENVALUES AS PERCENTAGES - ABSOLUTE AND *
     1      *CUMULATIVE*)
```

```
   20 FORMAT (5(/),1HO,58X,*PERCENTAGE  VARIANCE*)
   21 FORMAT (1H1,53X*SOLUTIONS OF COVARIANCE MATRIX*)
   22 FORMAT (1H1,57X*ACCURACY CHECK MATRIX*)
   23 FORMAT (1H1,56X*LOGARITHMS OF INPUT DATA*)
   24 FORMAT (1H1,////*TOO MANY SAMPLES TO PERFORM PRINCIPAL COMPONENT A
     1*     *NALYSIS*)
   25 FORMAT (1HO,54X,*EIGENVECTORS AS PERCENTAGES*)
   26 FORMAT (1HO,64X,*ABSOLUTE*)
   27 FORMAT (1HO,64X,*RELATIVE*)
   28 FORMAT (1HO,A8,16F8.3)
   29 FORMAT (1H1,60X,*DATA  STATISTICS*)
   30 FORMAT (6(/),1H ,56X,*COEFFICIENT OF VARIATION*)
   31 FORMAT (1H-,7X,16(3X,A5))
C*****READ VALUES OF ANALYTICAL PARAMETERS
   90 READ (1,1) LO, NO, N
      IF (EOF(1)) 108,91
C*****READ FORMAT OF INPUT DATA
   91 READ (1,9) IFORM
C*****READ INPUT DATA VALUES
      REWIND 10
      M = 1
   92 READ (10,IFORM) SN(M), (X(M,J),J=1,N)
      IF (EOF(10)) 94,93
   93 M = M + 1
      GO TO 92
   94 M = M - 1
      IF (M.GT.200) GO TO 1070
      P = M - 1
      SAM = SQRT(P)
      K = 1
      MAXN  = 16
      MAXM  = 200
      MAXMZ = 200
C*****READ NAMES OF ELEMENTS INVOLVED IN THE ANALYSIS
      READ (1,2) (LAB(I),I=1,N)
C*****CALL DATE SUBROUTINE
      CALL DATE(TODAY)
C*****WRITE VALUES OF ANALYTICAL PARAMETERS
      WRITE (2,16) TODAY,IMESS,M,N,LO,NO
      WRITE (8,9) IMESS
C*****WRITE INPUT DATA VALUES
      WRITE (2,3)
      WRITE (2,4) (LAB(I),I=1,N)
      LINE = 0
      DO 100 I = 1,M
      LINE = LINE + 1
      IF (LINE.LT.30) GO TO 100
      WRITE (2,3)
      WRITE (2,4) (LAB(J),J=1,N)
      LINE = 1
  100 WRITE (2,5) SN(I), (X(I,J),J=1,N)
C*****TAKE LOGS OF DATA IF REQUIRED AND WRITE OUT NEW VALUES
      IF (LO.NE.3HYES) GO TO 1001
      DO 1002 I = 1,M
      DO 1002 J = 1,N
 1002 X(I,J) = ALOG10(X(I,J))
      WRITE (2,23)
      WRITE (2,4) (LAB(J),J=1,N)
      LINE = 0
      DO 1003 I = 1,M
      LINE = LINE + 1
      IF (LINE.LT.30) GO TO 1003
      WRITE (2,23)
      WRITE (2,4) (LAB(J),J=1,N)
      LINE = 1
 1003 WRITE (2,8) SN(I), (X(I,J),J=1,N)
C*****STORE INPUT DATA FOR NON NORMALIZED CALCULATIONS
 1001 IF (NO.EQ.3HYES) GO TO 101
      DO 1000 I=1,M
      DO 1000 J=1,N
 1000 Y(I,J) = X(I,J)
C*****CALCULATE CORRELATION MATRIX
  101 CALL CMR(X,M,N,MAXM,K,SA,P,R)
C*****WRITE OUT MEAN VALUES OF ANALYTICAL DATA
      WRITE (2,29)
      WRITE (2,10)
      WRITE (2,31) (LAB(I),I=1,N)
      WRITE (2,12) (SA(I),I=1,N)
C*****WRITE STANDARD DEVIATIONS OF ANALYTICAL DATA
      WRITE (2,11)
      WRITE (2,31) (LAB(I),I=1,N)
      II = N + 1
      IJ = (2*N)
      WRITE (2,12) (SA(I),I=II,IJ)
C*****CALCULATE AND WRITE COEFICIENT OF VARIATION (%AGE STD DEV)
      DO 1004 I=1,N
      J = N + I
 1004 SA(I) = SA(J)*100.0/SA(I)
      WRITE (2,30)
      WRITE (2,31) (LAB(I),I=1,N)
      WRITE (2,12) (SA(I),I=1,N)
```

```
C*****WRITE NORMALIZED VALUES OF INPUT DATA
      IF (NO.NE.3HYES) GO TO 1034
      DO 1010 I=1,M
130   DO 1010 J=1,N
 1010 Y(I,J) = X(I,J)*SAM
      LINE = 0
      WRITE (2,6)
      WRITE (2,4) (LAB(I),I=1,N)
135   DO 103 I =1,M
      LINE = LINE + 1
      IF (LINE.LT.30) GO TO 103
      LINE = 1
      WRITE (2,6)
140   WRITE (2,4) (LAB(J),J=1,N)
  103 WRITE (2,5) SN(I), (Y(I,J),J=1,N)
C*****WRITE CORRELATION MATRIX
 1034 WRITE (2,7)
      CALL SMPRIN(R,LAB,N)
145 C*****COVARIANCES ARE CALCULATED FOR NON NORMALIZED DATA
      IF (NO.EQ.3HYES) GO TO 1035
C*****RELOCATE STANDARD DEVIATIONS
      DO 1031 I=1,N
      J = N + I
150  1031 SA(I) = SA(J)
C*****CALCULATE COVARIANCE MATRIX
      DO 1030 I=1,N
      DO 1030 J=1,N
      IF (J.LT.I) GO TO 1030
155   NN = I*((2*N)+1-I)/2 - N + J
      R(NN) = R(NN)*SA(I)*SA(J)
 1030 CONTINUE
C*****WRITE COVARIANCE MATRIX
 1035 WRITE (2,17)
160   CALL SMPRIN(R,LAB,N)
C*****CALCULATE AND WRITE PERCENTAGE VARIANCE
      SUMVAR = 0.0
      DO 1020 I=1,N
      J = I*((2*N)+1-I)/2 - N + I
165   SA(I) = R(J)
 1020 SUMVAR = SUMVAR + SA(I)
      DO 1021 I=1,N
 1021 SA(I) = SA(I)*100.0/SUMVAR
      WRITE (2,20)
170   WRITE (2,12) (SA(I),I=1,N)
C*****CALCULATE EIGENVALUES, EIGENVECTORS AND TRANSFORMED VARIABLES
 1037 CALL PCA(Y,M,N,MAXM,R,E,B,MAXN,Z,MAXMZ,C)
C*****CORRECT TRANSFORMED VARIABLES FOR EXTRA NORMALIZING FACTOR
      DO 1038 I=1,M
175   DO 1038 J=1,N
 1038 Z(I,J) = Z(I,J)/SAM
C*****WRITE EIGENVALUES
      WRITE (2,21)
 1039 WRITE (2,13)
180   WRITE (2,18) (E(I),I=1,N)
C*****CALCULATE EIGENVALUES AS PERCENTAGES
      SUME = 0.0
      DO 1032 I=1,N
 1032 SUME = SUME + E(I)
185 C*****WRITE EIGENVALUES AS PERCENTAGES
      DO 1033 I=1,N
 1033 SA(I) = (E(I)*100.0)/SUME
      SUMV(1) = SA(1)
      DO 4000 J=2,N
190   I = J - 1
 4000 SUMV(J) = SUMV(I) + SA(J)
      WRITE (2,19)
      WRITE (2,18) (SA(I),I=1,N)
      WRITE (2,18) (SUMV(I),I=1,N)
195 C*****WRITE EIGENVECTORS
      WRITE (2,14)
      DO 104 I = 1,N
  104 WRITE (2,8) LAB(I), (B(I,J),J=1,N)
C*****CALCULATE AND WRITE EIGENVECTORS AS PERCENTAGES
200   DO 1043 I=1,N
      DO 1043 J=1,N
 1043 B(I,J) = 100.0*B(I,J)*B(I,J)
      WRITE (2,21)
      WRITE (2,25)
205   WRITE (2,26)
      DO 1044 I=1,N
 1044 WRITE (2,28) LAB(I), (B(I,J),J=1,N)
      DO 1045 I=1,N
      DO 1045 J=1,N
210  1045 B(I,J) = B(I,J)*SA(J)/100.0
      WRITE (2,27)
      DO 1046 I=1,N
 1046 WRITE (2,28) LAB(I), (B(I,J),J=1,N)
C*****WRITE ACCURACY CHECK MATRIX
215   WRITE (2,22)
      IF (NO.EQ.3HYES) GO TO 112
      DO 110 I=1,N
```

```
      E(I) = 0.0
      DO 110 J=1,M
  110 E(I) = E(I) + Z(J,I)
      AM = M
      DO 111 I=1,N
      DO 111 J=1,N
      IF (J.LT.I) GO TO 111
      NN = (I*((2*N)+1-I)/2 - N + J)
      C(NN) = (C(NN) - (E(I)*E(J))/AM)/P
  111 CONTINUE
      GO TO 1121
  112 NN = (N*(N-1))/2 + N
      DO 1120 I=1,NN
 1120 C(I) = C(I)/P
 1121 CALL SMPRIN(C,LAB,N)
C*****WRITE VALUES OF TRANSFORMED VARIABLES
 1041 LINE = 0
      WRITE (2,15)
      DO 109 I=1,M
      LINE = LINE + 1
      IF (LINE.LT.30) GO TO 105
      LINE = 1
      WRITE (2,15)
  105 WRITE (2,5) SN(I), (Z(I,J),J=1,N)
  109 WRITE (8,1042) SN(I), (Z(I,J),J=1,3)
 1042 FORMAT (A8,3F8.4)
C*****PLOT VALUES OF TRANSFORMED VARIABLES
      DO 113 I=1,M
      XA(I) = Z(I,1)
  113 YA(I) = Z(I,2)
      CALL QIKPLT(XA,YA,-M,1,28H*FIRST TRANSFORMED VARIABLE*,29H*SECOND
     1TRANSFORMED VARIABLE*)
      DO 114 I=1,M
  114 YA(I) = Z(I,3)
      CALL QIKPLT(XA,YA,-M,1,28H*FIRST TRANSFORMED VARIABLE*,29H*THIRD
     1TRANSFORMED VARIABLE*)
      DO 115 I=1,M
  115 XA(I) = Z(I,2)
      CALL QIKPLT(XA,YA,-M,1,29H*SECOND TRANSFORMED VARIABLE*,28H*THIRD
     1TRANSFORMED VARIABLE*)
      GO TO 90
 1070 WRITE (2,24)
  108 CONTINUE
      END


      SUBROUTINE SMPRIN(R,LAB,N)
      DIMENSION R(136), A(16,16), LAB(16)
    1 FORMAT (1H-,7X,16(3X,A5))
    2 FORMAT (1HO,A8,16F8.4)
C*****REFLECT MATRIX IN LEADING DIAGONAL
      K = 0
      DO 100 I = 1,N
      DO 100 J = I,N
      K = K + 1
      A(I,J) = R(K)
  100 A(J,I) = A(I,J)
C*****HEAD MATRIX
      WRITE (2,1) (LAB(J),J=1,N)
C*****WRITE OUT MATRIX VALUES
      DO 101 I = 1,N
  101 WRITE (2,2) LAB(I), (A(I,J),J=1,I)
      RETURN
      END
```

```
      PROGRAM FIRST3(INPUT,OUTPUT,TAPE3,TAPE2=OUTPUT)
      DIMENSION IMESS(8),FV(100),SV(100),TV(100),SN(100)
C*****READ AND WRITE INPUT DATA
      READ (8,10) IMESS
   10 FORMAT (8A10)
      IF (EOF(8).EQ.1) GO TO 109
      WRITE (2,20) IMESS
   20 FORMAT (1H1,44X,*PROJECTION OF FIRST THREE TRANSFORMED VARIABLES*
     *///29X,8A10)
```

```
      I = 1
      WRITE (2,22)
   22 FORMAT (1HO,*VALUES OF INPUT DATA*//
     *1X,*SAMPLE*9X*NUMBER*7X*1ST*7X*2ND*7X*3RD*)
  100 READ (8,12) SN(I), FV(I), SV(I), TV(I)
   12 FORMAT (A8,3F8.5)
      IF (EOF(8).EQ.1) GO TO 101
      WRITE (2,23) SN(I), I, FV(I), SV(I), TV(I)
   23 FORMAT (1H ,A10,I9,3F11.5)
C*****CALCULATE MAXIMUM AND MINIMUM VALUES
      N = I
      I = I + 1
      GO TO 100
  101 FMIN = 10E10
      SMIN = 10E10
      TMIN = 10E10
      FMAX = -10E10
      SMAX = -10E10
      TMAX = -10E10
      DO 102 I=1,N
      IF (FV(I).LT.FMIN) FMIN=FV(I)
      IF (FV(I).GT.FMAX) FMAX=FV(I)
      IF (SV(I).LT.SMIN) SMIN=SV(I)
      IF (SV(I).GT.SMAX) SMAX=SV(I)
      IF (TV(I).LT.TMIN) TMIN=TV(I)
  102 IF (TV(I).GT.TMAX) TMAX=TV(I)
C*****WRITE OUT MAXIMUM AND MINIMUM VALUES
      WRITE (2,30)
   30 FORMAT (1HO,5X*MAXIMUM AND MINIMUM VALUES*)
      WRITE (2,31) FMIN,FMAX,SMIN,SMAX,TMIN,TMAX
   31 FORMAT (1H ,*1ST : *2F10.5/* 2ND : *2F10.5/* 3RD : *2F10.5)
      FRANGE = FMAX - FMIN
      SRANGE = SMAX - SMIN
      TRANGE = TMAX - TMIN
      CALL PAUPLOT(25HWHITE PAPER 0.3 BLACK PEN,25)
      CALL PLOT25
      CALL SYMBOL(1.0,7.5,1.0,11HBOX 115 PLS,90.0,11)
      CALL SYMBOL(5.0,1.0,0.3,IMESS,90.0,80)
C*****DRAW IN CONTAINING OUTLINE
      CALL PLOT(10.0,-1.5,-3)
      CALL PLOT(18.0,0.0,2)
      CALL PLOT(18.0,26.0,2)
      CALL PLOT(0.0,26.0,2)
      CALL PLOT(0.0,0.0,2)
      CALL PLOT(0.2,0.7,3)
      CALL PLOT(8.0,8.5,2)
      CALL PLOT(8.0,25.8,2)
      CALL PLOT(8.0,8.5,3)
      CALL PLOT(17.8,8.5,2)
      CALL PLOT(8.0,8.5,-3)
      CALL DASHLN(9.5,0.0,9.5,17.0)
      CALL DASHLN(9.5,17.0,0.0,17.0)
      CALL SYMBOL(-2.1,17.0,0.25,9H1ST P. C.,0.0,9)
      CALL DASHLN(0.0,17.0,-7.0,10.0)
      CALL DASHLN(-7.0,10.0,-7.0,-7.0)
      CALL SYMBOL(-7.5,-8.0,0.25,9H2ND P. C.,0.0,9)
      CALL DASHLN(-7.0,-7.0,2.5,-7.0)
      CALL DASHLN(2.5,-7.0,9.5,0.0)
      CALL SYMBOL(9.8,-2.1,0.25,9H3RD P. C.,90.0,9)
C*****CALCULATE AXIS INTERCEPTS
      FO = FMIN - 0.5*FRANGE/16.0
      FL = FMAX + 0.5*FRANGE/16.0
      SO = SMIN - (SQRT(2.0))*0.5*SRANGE/60.0
      SL = SMAX + (SQRT(2.0))*0.5*SRANGE/60.0
      TO = TMIN - 0.5*TRANGE/8.5
      TL = TMAX + 0.5*TRANGE/8.5
      WRITE (2,36) FO,FL,SO,SL,TO,TL
   36 FORMAT (1HO,*CO-ORDINATES OF AXIS POSITIONS*//
     *8X,*ORIGIN*3X*AXIS INTERCEPT*//* 1ST.  *F7.3,
     *F12.3/ * 2ND.  *F7.3,F12.3/* 3RD  *F7.3,F12.3)
C*****PLOT IN THE FIRST SEGMENT
      WRITE (2,32)
   32 FORMAT (1H1,*PLOT INFORMATION FOR 1ST AND 3RD PLANE*//
     ** SAMPLE     X AND Y IN CMS RELATIVE TO ORIGIN*)
      DO 130 I=1,N
      X = (TV(I)-TMIN)*8.5/TRANGE + 0.4
      Y = (FV(I)-FMIN)*16.0/FRANGE + 0.4
      WRITE (2,33) SN(I), I, X, Y
   33 FORMAT (1H ,A8,I3,2F9.3)
      CALL NUMBER(X,Y,0.2,I,0.0,2HI2)
  130 CONTINUE
C*****PLOT IN THE SECOND SEGMENT
      WRITE (2,34)
   34 FORMAT (1H1,*PLOT INFORMATION FOR 1ST AND 2ND PLANE*//
     ** SAMPLE     X AND Y IN CMS RELATIVE TO ORIGIN*)
      DO 131 I=1,N
      X = -((SV(I)-SMIN)*6.0/SRANGE) - 0.6
      Y = (FV(I)-FMIN)*16.0/FRANGE + X + 0.6
      WRITE (2,33) SN(I), I, X, Y
  131 CALL NUMBER(X,Y,0.2,I,0.0,2HI2)
```

```
C*****PLOT IN THIRD SEGMENT
      WRITE (2,99)
   99 FORMAT (1H1,*PLOT INFORMATION FOR 2ND AND 3RD PLANE*//
     ** SAMPLE     X AND Y IN CMS RELATIVE TO ORIGIN*)
      DO 132 I=1,N
      Y = -((SV(I)-SMIN)*6.0/SRANGE) - 0.6
      X = (TV(I)-TMIN)*8.5/TRANGE + Y + 0.4
      WRITE (2,33) SN(I), I, X, Y
  132 CALL NUMBER(X,Y,0.2,I,0.0,2HI2)
  109 STOP
      END
```

```
      SUBROUTINE DASHLN(XO,YO,X1,Y1)
      DI = 0.5
      DX = X1 - XO
      ADX = ABS(DX)
      DY = Y1 - YO
      ADY = ABS(DY)
      CALL PLOT(XO,YO,3)
      IF (ADX.LE.ADY) GO TO 520
      DLTX = 0.2
      DLTY = 0.2*ADY/ADX
      N = ADX*5.0
      GO TO 521
  520 DLTY = 0.2
      DLTX = 0.2*ADX/ADY
      N = ADY*5.0
  521 IF (DX.LT.0.0) DLTX=-DLTX
      IF (DY.LT.0.0) DLTY=-DLTY
      X = XO
      Y = YO
      DO 526 I=1,N
      X = X + DLTX
      Y = Y + DLTY
      IVAR = 2.5 - DI
      CALL PLOT(X,Y,IVAR)
  526 DI = -DI
      CALL PLOT(X1,Y1,2)
      RETURN
      END
```

APPENDIX E: NEWSPAPER ARTICLES

As part of a campaign to obtain further information, and possibly new specimens of South Australian meteorites, the following article was submitted to all of the South Australian country Newspapers in August 1972. The article was printed to a greater or lesser extent, under varying titles in thirteen of these papers as in the following list.

The results of the article were unfortunately dissappointing in terms of meteorite material. Specimens returned as possible meteorites included samples of ferruginous sandstone, flint, haematite and amphibolite. Some useful information, however, was gathered in the course of investigating these specimens.

Thursday August 24.
S.A. Scientists Seek Strange "Rocks". The Southern Argus 107, 5.

Saturday August 26.
Scientists Looking for Strange "Rocks" in S.A. The Border Watch 112, 4.

Wednesday August 30.
S. A. Scientists Seek Strange "Rocks". Yorke Peninsula Country Times 4, 9.

Thursday August 31.
Seeking Strange Rocks. The Naracoorte Herald 98, 5.
S.A. Scientists Seek Strange "Rocks". The Pennant 26, 3.
S.A. Scientists Seek Strange "Rocks". The South Eastern Times 10.

Wednesday September 6.
Scientists Seek Strange "Rocks" - Sequel to Kybunga Day-Light Meteor. The Northern Argus 102, 9.
South Australians Seek Strange "Rocks". The Producer 65, 8.
A Space "Dropout" in Your Backyard. The Whyalla News 33, 10.

Thursday September 7.
S.A. Scientists Seek Strange "Rocks" from Space. Port Lincoln Times 45, 26.
S.A. Scientists Seek Strange Rocks. South East Kingston Leader 11, 6.

Tuesday September 12.
S.A. Scientists Seek Strange Rocks. The Burra Record 94, 5.

Thursday October 5.
Don't Knock This Rock; Scientists Want It! Murray Valley Standard 37, Supplement, 8.

The following is the text of the original article.

S.A. Scientists Seek Strange "Rocks".

At 4:20pm on Sunday September 7, 1941, people in an area to the north of Adelaide, in the vicinity of the town of Kybunga, were aroused into a startled state of awareness. Some had seen a "fireball" descend from the sky, others had heard the reverberation of something hitting the ground, some both and one lady, who was feeding her fowls at the time, had even seen a cloud of dust rising into the air. Had World War II come even to this quiet little country town?

Further away in Adelaide the fireball had also been seen, while at Nairne, a young man preparing to photograph his parents who were standing in their garden, recorded the event on film.

As the dust settled and no more "bombs" fell, silence descended again on the countryside but this was not the last that was to be heard of the event. Scientists in Adelaide who were fairly certain of the extra-terrestrial nature of the body began the collation of facts, assisted by people on the spot such as the local school teacher, scoutmaster etc. Ultimately sufficient data was collected to predict the probable location of the body but by this stage war time petrol restrictions precluded any attempts to visit the area to carry out a systematic search.

Sporadic attempts at recovery over the years did little to produce results. The first break-through came in the autumn of 1963 when Mr. G.C. Wiech dug up a piece of strange looking rock while ploughing one of his paddocks. It was not until 1969 however, that this piece of material was brought to Adelaide and recognized as a meteorite. This recognition ended a 28 year period of wondering - the original suggestion as to the meteoritic origin of the 1941 disturbance was fairly well confirmed. In 1971 three more pieces of meteorite were discovered in the area, one which perfectly fitted onto the first piece and two other quite separate fragments. Thus to date a total of some 8kg (18lbs) of material have been recovered. All of them bear marks probably produced by previous ploughings and thus it was only through bad luck that they weren't recovered earlier.

Of the 40 known South Australian meteorites some 30 have been found by

observant farmers and allied workers who are so familiar with the rocks of their properties that they immediately notice anything which is different. This interest in the rocks of the countryside is reflected in numerous collections of rock material on farmhouse mantlepieces, office desks and back sheds. There is a more than even chance that there are several unknown meteorites so dispersed throughout the countryside.

At present there are several theories concerning the origin of meteorites but at the same time there is universal agreement that there is much to be learnt from the composition and structure of these heavenly bodies.

Meteorites can be grouped into three broad classes - stones, irons and stony irons.

Stones. These are usually grey to black in colour, the outside skin sometimes being shiny. They are fairly heavy and minute particles of metal can commonly be seen dispersed throughout the material.

Irons. These are brown to black in colour on the outer surface, are very heavy and internally resemble pieces of steel. The surface is usually pitted to a greater or lesser extent; the pits are often referred to as "thumbprints".

Stony Irons. These are intermediate in type between the first two; while externally they usually resemble the Stones their internal structure is a mixture of metal and stony material.

The actual circumstances of the finding of meteorites are many and varied. At one extreme, as it were, we have the Kappakoola meteorite which was picked up on Eyre Peninsula by Mr. F.W. Daniel to throw at a flock of parrots eating his crops, while on the other hand there is the Karoonda meteorite which was recovered by Professor Sir Kerr Grant on an expedition mounted from Adelaide for this purpose.

This meteorite was also observed in flight over Adelaide - the night sky was lit up at 10:53 on Tuesday the 25th. November 1930. So bright was this light that many thought that the meteorite had landed in the suburbs and the next morning's paper carried the suggestion that a search ought to be carried out on the Morphettville racecourse. The meteorite was recovered the following Tuesday morning at Karoonda about 80 miles to the east of Adelaide.

No matter what the circumstances most of the meteorites recovered have at first simply been recognized as being different from the usual rock material of the area. Do you have any unusual rocks in your possession or know of the whereabouts of any?

The Geology Department of the University of Adelaide is currently engaged in a programme of research on meteorites and accordingly would welcome any relevant information. Such information could be sent to:-

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University of Adelaide,
G.P.O. Box 498D,
ADELAIDE. S.A. 5001

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PROCEEDINGS

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M. J. FITZGERALD



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