A GEOPHYSICAL AND GEOLOGICAL INTERPRETATION OF THE WALLAROO - MOONTA PROVINCE IN SOUTH AUSTRALIA

By

Robin Alan Gerdes (B.Sc. General (Hons.), London)

(Post-Graduate Diploma of Applied Geophysics, Leeds)

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Department of Economic Geology

University of Adelaide.

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FORM B

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SUMMARY

SUMMARY

The Wallaroo-Moonta Province in Yorke Peninsula, South Australia, covers an area of about 10 000 km^2, and extends beneath Spencers Gulf. It is within the Torrens Hinge Zone, and is west of the Melrose-Kapunda-Palmer Lineament, which defines the eastern edge of the Gawler Craton. This Province contains two major concealed ore bodies, the Wallaroo and Moonta Mines, which from 1860 to 1923, produced 11.5 m tonnes of copper ore, with minor gold and silver. Some subeconomic deposits have been found since the mines' closure. The main lodes are relatively small exploration targets, as they are narrow, have short strike lengths, are limited by depth extent and by the distribution of fracture corridors, and are concealed by highly saline conductive Cainozoic sediments.

Despite the 80 years of geological exploration, 52 and 34 discontinuous years of geophysical and geochemical exploration, no comprehensive interpretation had previously been attempted. This thesis is intended to overcome this deficiency, and is concerned with the geophysical interpretation controlled by geological data, for a systematic and documented study of known concealed mineral deposits, as a key to the discovery of new polymetallic blind ore bodies in the Province.

This research contains a review of the pre-1970 unstandardised geological data, a geophysical case history, and a petrophysical and petrological study of the magnetic anomalies and units. A magneto-stratigraphic succession, combined with the detailed studies of specific geological problems and areas, at 1:100 000 scale, provides the structural framework and proposed stratigraphy of this Province. The regional study at 1:100 000 and 1:250 000 scales, defines the Province, and shows the association of the megastructures to mineralisation and adjacent Provinces, and their similarity to the Broken Hill Subdomain. Base metal and uranium mineralisations are compared with some major Australian and world deposits.

Geological concepts evolved during this research have been influenced by this study. These concepts are that the Province is a volcanogenic-metasedimentary evaporitic environment, with a close association with exhalative excentres (volcanic centres) and plutonic activity. The rocks of Late Early-Middle Proterozoic age have suffered at least 3 fold deformations, metamorphic and retrogressive events. Two possible major unconformities are present between the Devon Group and both the East Kadina and Willamulka metasediments.

The geophysical case history is limited at present by the lack of experiments with recent techniques, especially transient, electrical and electromagnetic methods.

The petrophysical and petrological data show the major magnetic units occur within pre-Adelaidean basement rocks, and that detrital magnetite occurs with minor pyrite and pyrrhotite. Some secondary magnetite is in recrystallised zones and in veins. The petrophysical data which was correlated with rock types, shows good agreement with interpreted magnetic susceptibility contrasts, and verifies the absence of a strong remanent component.

The interpretations of the reconnaissance aeromagnetic, Bouguer gravity and ERTS photolineament data show the Province is at the intersection of numerous orthogonal sets of fracture corridors. One set is the continuation of the Darling Lineament, another the continuation of the Elliston-Polda fracture system. These are overprinted by a major N-S fracture set, associated with the Roopena Fault. Numerous deep-seated fractures are present. The NW trending Dublin Lineament and associated fracture controls the Wallaroo-type mineralisation, and the E-W lineaments, (retrograde zones) the U-Cu-Mo mineralisation. This Province is separated from the surrounding Provinces by major lineaments to the north and west, and east by numerous hinge lines and the Orontes Structures. The extremities of the Province, although linear in form, are irregular, reflecting major disconformities, which may either relate to fracture zones, a metamorphic grade boundary, or, major angular unconformity, suggestive of the Devon-Hutchinson Group unconformity. The other concept is to consider the Province as a meso-structural knot, between two stable blocks, 'graben like', associated with volcanic and plutonic activity.

The detailed interpretations used ground vertical magnetic, I.P. (Induced Polarisation - Frequency Domain) and resistivity vertical electrical soundings data, controlled by geological and geochemical information, to resolve specific geological problems and mineralised areas. Analyses of five detailed aeromagnetic surveys and comparisons of INPUT-EM data with P.F.E. anomalies show that the INPUT anomalies combined with the magnetic data, resolved most exploration targets found in the previous 20 years, using blanket I.P., ground magnetic traverses and geochemical methods.

Detailed evaluations are integrated into a structural compilation, and the relationships of the mineralisation to structures within the Province are studied. The stratigraphic sequence, based on the magnetic data combined with other geophysical and geochemical data, is correlated with the Broken Hill

Mine Sequence. The Province's magnetic and density fabrics are similar to the Olary Subdomain. Four fold styles are resolved and correlated with the Kimba(k) and Willyama(w) Domains. The dominant fold style has steeply north dipping E-W axial planes within the Devon Group, and may correlate with either Archaean or D_4^k folds in the Gawler Domain. If the latter is assumed, then the N-S fold style in the Broughton and Curramulka Subprovinces is possibly controlled by deformations D_2^k and D_3^k. Deformation D_2^k/D_2^w is the major high grade metamorphic event.

Likewise, the Doora Schists within the Kadina Fold Belt have been folded by D_{1-2}^w or D_2^k/D_3^k in the Broken Hill Subdomain or Gawler Domain to produce the deep keeled synforms, which were refolded by D_4^k. Type 3 interference patterns were produced by superimposed D_2^k and D_4^k folds.

Fold style Fc, may be equivalent to $D_3^{k/w}$, a retrograde event in the Broken Hill Subdomain, observed in the Devon Group, and in the East Kadina and Willamulka metasediments. There is no geophysical evidence for D_2 within the East Kadina and Willamulka sequences. Deformation D_1^d (Delamerian) is locally present, associated with the marginal hinge zones and the Pine Thrust.

The distribution of fractures and their relationships to the NE-SW basic dyke swarms and to the fold systems is outlined. Most granite intrusions occur within E-W granitic gneiss antiforms, and the other higher level granites are cupolas, associated with the Tickera and Tiparra Batholiths. The volcanic centres coincide with the West Weetulta Complex, Moonta Caldera, Lucky Acres Gravity Low and Thrington Ring Structure. These fault-controlled ring structures are at the intersection of major NE-SW and NS corridors.

An intrusion hypothesis of the sequence of igneous events associated with the mineralisation is grouped into five phases:

1. Early volcanic and sedimentary phase: eruption of acid - basic volcanics from possible vents.
2. Caldera phase: eruption of rhyodacite, pyroclastic and some basic sills, with the development of ring structures and possible rhyolitic lava domes.
3. Granite intrusion phase: diapiric developments, ring dyke intrusions and batholithic development at depth.
4. Sedimentary phase: development of a thick sedimentary pile, associated with some volcanic (rhyodacite-dacite-andesite) flows and/or sills, basic (amphibolite) intrusions and dykes.
5. Batholithic front advance at depth phase: increased heat flow, accompanied by dyke intrusions, recrystallisation and metamorphic events, followed by retrogressive events, associated with the development of alteration zones.

This model is for an andesite-dacite-rhyolite volcano (stratovolcano) differentiated from a hornblende-monzonite suite with the development of cauldron subsidences, ring structures and rhyolite lava-domes, produced by rising plutons at depth.

The mineral potential and an hypothesis for conceptual exploration models for this Province are outlined. The copper potential alone is generally subeconomic near surface, and any mineralisation fitting the Butte, Kuroko and Aitik models is likely to be deep. The polymetallogenic Pb-Zn-Cu deposits warrant further investigation and geophysics, using the Broken Hill, Lady Loretta, H.Y.C. and Tynagh models. The Mo potential associated with the Tickera Granite Complex warrants evaluation using the molybdenum porphyry model, and the uranium potential requires further evaluation within the Wallaroo-Alford Alteration Zone and associated North Kadina Belt.

Exploration concepts for the search for blind ore bodies are given in an Appendix.

It is recommended that the reader consult Chapter 17 first, before referring to the more detailed information in other chapters, as Chapter 17 fully summarises most concepts developed during this research, thereby placing each chapter in perspective. It is impractical to place this concluding chapter elsewhere in the text.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, this thesis contains no material previously published or written by another person, except when due reference is made in the text.

Robin A. Gerdes

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During the research work, the Bureau of Mineral Resources, Canberra, provided the original aeromagnetic flight charts of BURRA and conducted an additional aeromagnetic survey over Spencers Gulf which provided regional continuity between the two peninsulas. The author thanks the Director for providing the data.

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While the research project was essentially geophysical, it was necessary to define and investigate the petrophysical and petrological properties of various core samples. The author gratefully acknowledges the help given by the staff of the Geological Survey's Geophysics Workshop especially B. Brice and A. Appleton for undertaking many petrophysical measurements of drill core samples, and the petrological work by Dr. P. Moeskops and Sylvia Whitehead of AMDEL under the Director-General of Mines and Energy's authority.

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PUBLICATIONS IN THESIS AREA

ABSTRACTS OF INTERNAL UNPUBLISHED REPORTS WRITTEN BY THE AUTHOR FOR THE SOUTH AUSTRALIAN GEOLOGICAL SURVEY, DEPARTMENT OF MINES AND ENERGY, COVERING TOPICS WITHIN THE M.Sc. THESIS AREA.

GERDES, R.A., 1970. The Bute Aeromagnetic Anomaly. S. Aust. Dept. Mines report 70/185 (unpublished).

ABSTRACT

Detailed total magnetic intensity traverses and a gravity traverse were recorded over the Bute Aeromagnetic Anomaly. The source of this anomaly was interpreted to be at 365 m below ground level. The susceptibility contrast of 2.4×10^{-3} c.g.s. units was attributed to a basic rock containing a small quantity of disseminated magnetite. Bute stratigraphic drill hole No. 2 intersected an amphibolite at 123 m below ground level. The estimated depth of 365 m placed the source of the anomaly beneath the amphibolite. The model assumed the magnetite was confined to a tabular body. However, this model is not really satisfactory for the case of the magnetite being disseminated throughout a large mass. The depth estimate appears to be an overestimate, which could be explained by either a thick section of weathered amphibolite, i.e. unmagnetic, with fresher material below 213 m, or, another intrusion below the amphibolite.

GERDES, R.A., 1972. Ground total magnetic intensity reconnaissance traverses in the east Bute area. Blyth 1:63 360 sheet area. S. Aust. Dept. Mines report 72/59 (unpublished).

ABSTRACT

Total magnetic intensity traverses over a low amplitude aeromagnetic anomaly east of Bute have been made with a vehicle mounted magnetometer.

The ground magnetic expression is approximately ten miles in length and of low amplitude. Either a thick tabular body dipping at 40 degrees east, or a fault downthrowing to the west is suggested as the probable source of the anomaly. Depth of burial in either case is of the order of 560 metres. Other near surface magnetic sources were also detected.

GERDES, R.A. and WIGHTMAN, W.E., 1973. Bute region resistivity of the proposed Bute diamond drill hole sites 1, 6 and 7 in Blyth and Wallaroo 1:63 360 sheet areas. S. Aust. Dept. Mines report 73/221 (unpublished).

ABSTRACT

Schlumberger Vertical Electrical Soundings (V.E.S.) undertaken at the proposed Bute diamond drill hole sites 1, 6 and 7 indicate that the thickness of the unconsolidated sediments were thin at site 6, being 3 metres, and deep at site 7, being 60 metres. The latter drill hole will require casing.

An attempt was made to correlate basement and shelf Proterozoic horizons with the resistivity layers near the probe site just west of Bute DDH1, and the proposed sites Bute DDH6 and 7. At the proposed site Bute DDH6, some resistivity boundaries were detected as possibly correlating

with the contact between the Pandurra Formation and metasediments (plus Amphibolite). No such resolution was possible for Bute sites DDH1 and DDH7.

GERDES, R.A., 1974. Tickera region geophysical investigation of the Tickera-Alford-Port Broughton area in Wallaroo and Broughton 1:63 360 sheet areas. S. Aust. Dept. Mines report 74/163 (unpublished).

ABSTRACT

The Tickera-Alford-Port Broughton area located in Broughton and Wallaroo is an area of relatively shallow metamorphic rocks, covered by a thin veneer of Quaternary and Tertiary sediments, which contain clays and highly saline layers. A systematic quantitative interpretation of Schlumberger Vertical Electrical Soundings was undertaken to delineate areas of high electrical transmissivity and the depth to the resistive basement as a feasibility study for future Electromagnetic and Induced Polarization surveys. A number of areas for future geophysical surveys have been outlined. Incorporated in the report is an appraisal of previous geophysical data, namely Induced Polarization and Vertical Magnetic Intensity, performed by Western Mining Corporation Ltd. in a relinquished portion of Special Mining Lease No. 87.

GERDES, R.A., 1978. A geophysical study of the Broughton area in Wallaroo and Blyth 1:100 000 sheet areas. S. Aust. Dept. Mines and Energy report 78/109 (unpublished) for Exploration Licence No. 207.

ABSTRACT

An interpretation of regional aeromagnetic and gravity data in the area near Port Broughton, supplemented by detailed gravity traverses and stratigrpahic information from recent drilling, Tickera DDH's 1 and 2, and Wokurna DDH's 1 to 3 inclusive, indicates that the metamorphic basement is shallow west of the Broughton Hinge Line, and unconformably overlain by an Adelaidean sedimentary sequence.

A gravity model along the east-west Tickera traverse across the basement-cover contact shows that the Broughton Hinge Line forms part of the eastern tectonic boundary of the Gawler Block, and is probably underlain at depth by a belt of granulite or amphibolite.

TERMINOLOGY AND GEOPHYSICAL UNITS USED IN TEXT

TERMINOLOGY AND GEOPHYSICAL UNITS

GENERAL ABREVIATIONS

ADEL. UNIV.	-	Adelaide University, Adelaide, South Australia.
A.N.U.	-	Australian National University, Canberra, A.C.T.
B.M.R.	-	Bureau of Mineral Resources (Geology and Geophysics) Canberra, A.C.T.
N.B.H.	-	North Broken Hill Pty Ltd.
E.L.	-	Exploration Licence in South Australia.
S.M.L.	-	Special Mining Lease in South Australia.
I.G.E.S.	-	International Geophysical Experimental Survey, 1930.
M.I.T.	-	Massachusetts Institute of Technology.
S.A.D.M.	-	South Australian Department of Mines, pre 1977.
S.A.D.M.E	-	South Australian Department of Mines and Energy post 1977.
W.M.C.	-	Western Mining Corporation.
D.D.H.	-	Diamond drill hole.
P847/72	-	Petrological sample No. 847 in 1972.

GEOPHYSICAL ABREVIATIONS

I.G.R.F.	-	International Geophysical Regional Field
a.g.l.	-	above ground level (aircraft ground clearance).
b.g.l.	-	below ground level.
a.s.l.	-	above sea level.
N.R.M.	-	Natural Remanent Magnetisation.
C.R.M.	-	Chemical Remanent Magnetisation.
T.R.M.	-	Thermal Remanent Magnetisation.
I.P.	-	Induced Polarization (Frequency Domain).
P.F.E.	-	Percentage Frequency Effect. (Frequency Domain).
V.E.S.	-	Vertical Electrical Sounding.
INPUT	-	Induced Pulse Transient Electromagnetic method. (Barringer Research Corporation, Canada).

International Metric Grid System adopted by the Department of National Mapping subdivides Australia into 1:250 000 sheet areas, defined as 1^0 of latitude by 1.5^0 of longitude. These areas are given the official names, and denoted by capital letters, e.g. MAITLAND, whereas the one mile sheet areas at the scale of 1:63 360 are denoted by lower case letters and underlined eg. Maitland. This terminology has been adopted by the B.M.R. and S.A.D.M.E. For 1:100 000 scale maps as no standard is specified, italics have been used for the map name, eg. Maitland.

GEOPHYSICAL UNITS

GRAVITY UNITS

The standard subdivision of the acceleration due to gravity, the milligal (mgal) is used. Thus 1 gal = 10^3 milligal = 1 cm/sec^2. and 1 milligal = 10μGalileo.

Specific Gravity is dimensionless.

Density is quoted in gm/cm^3.

MAGNETIC UNITS

The unrationalised c.g.s. system of units are used with the usual subdivision of the intensity of the magnetic field, (Oersteds) into gammas.

Thus 1 Oersted = 10^5 gammas

and 1 gamma = 1 nano-Tesla = 1nT, in the SI System.

Intensity of magnetisation is referred to in c.g.s. units.

Volume magnetic susceptibility is quoted in c.g.s. units. To convert to S.I. units multiply by 4π .

The standard formula for the effective magnetic susceptibility contrasts determined from bodies of various dimensions, e.g. Gay, (1963) are in c.g.s. units, as the dimensions of depth and width of the bodies cancel out. In the text the word effective is omitted. This is the true susceptibility contrast if the rock is homogeneous, isotropic and uniformly polarised in the earth's magnetic field, and if any remanent magnetisation present is codirectional with the normal field. These assumptions are an oversimplication of a complex situation when considering banded and folded metamorphic basement rocks, (further details given in Appendix I).

CHAPTER 1

SCOPE OF THESIS AND FRAMEWORK OF THE PROBLEMS

1.1 INTRODUCTION

A major challenge to base metal exploration today is the discovery of concealed or blind ore bodies (massive sulphide deposits), in all types of geological environments. The use of a geological model, incorporating both geophysics and geochemistry, and comprehensive joint disciplinary case history studies of large economic deposits, provides the scientific framework, for the discovery of concealed massive deposits of the future. In other words, systematic studies and documentation of known mineral deposits provides the keys to the future discovery of blind ore bodies.

This thesis is concerned with one such case history: the Wallaroo-Moonta Mines, situated in the Gawler Craton in northern Yorke Peninsula, South Australia, where the ore bodies and country rocks are almost entirely obscured by up to 200 m. of Quaternary and Tertiary cover. This is a geophysical appraisal, which relies strongly on both airborne and ground geophysical exploration methods.

In future exploration, both geophysics and geochemistry will increasingly rely on the petrophysical and chemical properties (statistical background chemical data of particular lithological units) of rocks and ore bodies, as most sulphide ore bodies will be either deep seated (concealed bodies) under areas of deep overburden, or concealed in basement outcrop areas.

It is the role of geophysics to help to resolve this problem of blind ore bodies and delineate targets for deep drilling programmes, before geochemistry can play a major role in the exploration. Roxby Downs (Olympic Dam), a copper-uranium-minor gold deposit, discovered by Western Mining

Corporation on the Stuart Shelf (Gawler Platform) in South Australia, is a successful example of the type of deep concealed sulphide deposit to be found. The W.M.C. exploration experience from 1961 to the present in Wallaroo-Moonta, and their study of the Mt. Gunson area, played an important part in this discovery, even though no combined case histories were available.

Haynes (1979) outlined the conceptual model and exploration parameters which led to the Olympic Dam discovery. The concentual model was that the source of copper for sedimentary copper deposits was derived from the alteration of continental-type basaltic volcanic rocks. The Stuart Shelf was selected for evaluation, based on:

(i) copper source rocks, altered basalts present at the surface and possibly concealed;

(ii) favourable host environment for sedimentary copper deposits;

(iii) several broad structural and lithological similarities with the Zambian Copper Belt;

(iv) consideration of the Bouguer gravity highs as potential favourable loci for sedimentary copper accumulations, interpreted as concealed piles of altered basalts;

(v) comparison of the gravity highs with the Mt. Gunson deposits;

(vi) lineament analysis and linear discontinuities based on geophysical data, (O'Driscoll, 1981), in addition to favourable targets with coincident gravity and magnetic anomalies at the intersections of major lineaments. These geophysical anomalies were the prime exploration targets.

Although the results showed the conceptual model was incorrect, this discovery showed the success of university research, team work and an integrated exploration philosophy. Haynes, did not mention the numerous concepts and ideas given by geoscientists from the South Australian Geological Survey in the initial and exploratory stages of this discovery, as the W.M.C. model was applied to the Late Proterozoic rocks only.

Most case history studies are geological, geochemical with a minor amount of geophysical information. In Australia, the few geophysical case histories relating to iron and copper deposits, e.g. the Savage River Iron Ore Deposit in Tasmania, (Eadie, 1970) and the Nangaroo Copper-Zinc Deposit in Western Australia, (Cowan et al., 1975) are related to one geophysical method, namely magnetic and electrical studies respectively. The omission of reporting on geophysical techniques which were tried and failed in exploration (Edge and Laby, 1931) can result in wasted time, duplicated effort and unnecessary expenditure. Therefore, case histories should contain the results and reasons for failure of a particular geophysical technique, so that the results can be re-assessed with new interpretation methods and advances in instrumentation. The recent Elura study in Cobar, New South Wales, (Emerson, 1980) and the Woodlawn case history, (Whiteley, 1981) are both very fully covered, as the original geophysical surveys were supplemented by numerous experimental surveys using the most recent advancements in geophysical techniques.

In Canada and the U.S.A. geophysical case histories summarise geophysical exploration, e.g. the Copper Mountain and Ingebella Deposits in British Columbia, (Dolan et al., 1975); the porphyry copper deposits in Arizona, (Lacy & Morrison, 1966, and Brant, 1966), but not with the same detailed coverage and integrated approach, as given by Malmqvist and Parasnis (1972) for the long exploration period of the Aitik copper deposits in northern Sweden, and as Buchans, Newfoundland (Moss and Perkins, 1981). Although Wallaroo-Moonta Province has been explored geophysically over the past 52 years, in similar detail to the Aitik deposit, no geophysical case history has been published.

1.2 WORLD COMPARISONS WITH THE WALLAROO-MOONTA MINES

The Moonta Lodes were first interpreted as copper-bearing schorlaceous pegmatite vein types, by Jack (1917), who compared it to the Khan Mine in South West Africa (Wagner, 1916), based on the latter mine being a copper pegmatite in a gneiss, having a similar mineral assemblage, comparable copper grades, and lode dimensions as the Moonta Lodes. This comparison led Jack to believe that the Wallaroo and Moonta Lodes, although having different mineral assemblages, were derived from the same source "the Arthurton Granite', the difference reflecting local variations of the original magma source and introduced into different country rocks.

Pellisonnier and Michel, (1972) in a summary of former metallogenic classifications, showed that

(i) Beyschlag, Krusch and Vogt (1909) had classified Moonta with Butte Mine, Montana, U.S.A. as quartz-cupriferous lodes, accompanied by tourmaline, in close proximity to acid to intermediate eruptive rocks, within groups of cupriferous lodes within the broad subdivision 'Filons, remplissages de vides et gites metasomatiques'. A subsection within this classification, contained lodes 'in schists, accompanied by similar eruptive rocks', which compares with the Wallaroo occurrence.

(ii) Routhier (1963) placed Butte (Montana) and Chuquicamata (Chile) a very massive deposit, with a chalcocite-covellite cementation in 'Type pertaining to veins, with copper arsenic, Zn, Pb (mesothermal); frequently in a dense and complex system of veins, within intraplutonic bodies associated with granite plutons frequently monzonites'.

Pellisonnier and Michel (1972), in their classification of the Copper deposits of the World, used their dimensions, total tonnage and percentage of ore producted as a major factor, and did not consider mines with production figures less than 1 million tonnes of Cu. The only Australian examples were Captains Flat, N.S.W., Mt. Isa, Queensland, and Rosebery-Hercules and Mt. Lyell in Tasmania. They classified, Chuquicamata in Type No. 6 porphyry deposits, and Butte, Montana in Type No. 7 deposits of enargite (copper, sulphur, arsenic). This agrees with Routhier (1963) except that Routhier had another group for porphyry copper, (Type 6) which included Globe, Miami (Arizona); Ely, (Nevada); Bingham (Utah) and Kounrad (U.S.S.R.) all having a chalcopyrite-bornite-chalcocite-pyrite assemblage. This mineral assemblage was reported in Moonta.

The Chatyrhul quartz-sulphide vein deposits in the U.S.S.R. were compared by Samonov and Pozharisky (1977) with the Butte deposit in Montana and the Chuquicamata deposit in Chile. The former was compared by Beyschlag et al, (1909) with the Moonta deposit. The geological map of the Chatyrhul deposit shows the ore zones in biotite and biotite-hornblende granites, and syenite-diorites. The distribution, dimensions and structural configuration of the Chatyrhul lodes and the cross-section of the quartz-magnetite-chalcopyrite ores, surrounded by hydrothermally altered rocks are comparable with the Moonta Lodes.

A comparative geological model for the Moonta Lodes and Moonta 'Porphyry' is the Butte Mine, in the Boulder Batholith, a comprehensive account of which was given by Meyer et al., (1968) and the aeromagnetic data was shown by Gay (1971). A comparison is made with this deposit in Chapter 16.

1.2.1 THE WALLAROO-MOONTA MINES COMPARED WITH OTHER MINES IN AUSTRALIA AND SOUTH AUSTRALIA

The Wallaroo-Moonta Mines, which were in operation for 63 years, were the largest and most productive copper mines in South Australia. A comparison of principal copper mines and their production figures in South Australia is shown in Table 1.1. Minor gold and silver were also extracted, and two mines east of the major mines produced minor lead and silver.

The Wallaroo-Moonta Mines have comparable production figures with present operating mines in Australia, e.g. Mt. Morgan in Queensland, Mt. Lyell in Tasmania and the Cobar Mines in New South Wales, (Table 1.2). Except for Cobar Mines, where the origin is debatable, all these mines are associated with volcanic material. Wallaroo-Moonta region may also be a volcanogenic mineral province.

TABLE 1.1

PRINCIPAL BASE METAL MINES IN SOUTH AUSTRALIA

Name of Mine	Period of Production	Tectonic Province	Stratigraphic Age of Host Rocks	Tonnages million tonnes ore (million tonnes copper)	Primary Percentage Grade of Ore	Minor Economic Elements Extracted
WALLAROO AND MOONTA	1860-1918	GAWLER BLOCK	LATE EARLY-MIDDLE PROTEROZOIC	6.5 to 11.5* (0.3336)	Primary 30% Cu Average 2-3% Cu	Minor Au, Ag.
		(ORIGINAL GRADE 30%Cu, with 5.33% Cu and 0.32 g/t Au. (4 g/t Au and 5 g/t Ag) in supergene zone and in 1908 and 1918 the average grade was reduced to 3.9% and 2.8% Cu respectively)				
	1923-1945	-	-	0.055327 (0.002947)	5.33% Cu	(slimes and tailings)
	1967-1972	(R.M.C. Minerals)		1 (0.00016)	20 to 25% Cu	(processing dumps)
OLYMPIC DAM (ROXBY DOWNS)	Not in production	GAWLER PLATFORM (IN STUART SHELF)	MIDDLE PROTEROZOIC	Assessment Jan 1979 750	1.5% Cu and 0.7 kg/tonne U_3O_8 Minor Au, Ag	
Pernatty Lagoon	1875-1937 & 1941-1943	Stuart Shelf	Adelaidean	0.032 (0.00435)	0.3 to 6.7% Cu	Minor Mg
Mt. Gunson	1920-1960	Stuart Shelf	Adelaidean	0.032 (0.001)	2.3% Cu	Minor Pb, Zn & Ag
	1970-1971	-	-	RESERVES 3.2 Removed 0.1626 (0.00186 concentrate)	1.03% Cu	Minor Ag (0.35 g/t)
Cattle Grid	1973-June 1980	Stuart Shelf	Adelaidean	RESERVES 4 2.796 (0.136 concentrate)	1.9% Cu at 1% cut off. 1.89 to 2.19 % Cu	Minor Co, Pb & Zn
Burra	1844-1913	Adelaide Fold Belt	Adelaidean	0.70 (0.0716)	7.55% Cu	(oxidized zone)
		RESERVE ESTIMATES IN 1970 AND 1973 WERE 4×10^6T AT +1% Cu cut off and 3×10^6T AT 1.5% Cu cut off respectively				
	1970-1979			1.148 (0.0162)	1.26 to 1.88% Cu	Copper only
OR	1970-1981	"	"	(offical figure) 2.122+	1.77% Cu	Oxide
		+ figure includes reprocessed copper scrap				
Blinman	1861-1918	Adelaide Fold Belt	Adelaidean	0.2 (0.0097)	4.7% Cu	-
Kapunda	1842-1878	Adelaide Fold Belt	Adelaidean	0.070 (0.013)	20.45% Cu	(supergene zone)
		RESERVES (NORTHLAND, 1975) 3×10^6T at 0.94% Cu and 5.5×10^6T between 0.5 to 0.9% Cu LATER ESTIMATES FOR TWO ORE BODIES, SUPERGENE RESERVES 9 to 17 x 10^6T to 60 m. Between 0.7 to 0.9% Cu AND SULPHIDES (lower ore body) few 10 x 10^6 T RESERVES less than 1% Cu. Figures for 1979.				
BELTANA (Puttapa)	1973-1975	Adelaide Fold Belt	Adelaidean	RESERVES 1 (0.11 of Zinc Ore) (0.01 of Pb ore)	37% Zn 40% Zn	Willemite Minor Pb.
		(under care and maintenance since 1976)				
Ediacara	1888-1913	Stuart Shelf	Cambrian	- (0.024) Reserves 30×10^6 tonnes @ 0.9% Pb (Nixon, 1961)	31% Pb	Minor Ag.
Callington-Kanmantoo	1846-1875	Kanmantoo Trough	Cambrian	0.060 (0.024)	8.5% Cu	
	1970-1976			RESERVES 5.2 (Extracted 3.5)	1% Cu	Minor S, Au, Ag.
		RESERVES JULY 1976. Open cut. 1.6 at 1% Cu cut off underground operation 7.3 at 1% Cu cut off and deeper operation 2nd body 1.0 at 1% Cu cut off (under care and maintenance since 1976)				

* Estimated due to filling of stopes

TABLE I.2

COMPARISON OF PRINCIPAL COPPER-LEAD-ZINC MINES IN AUSTRALIA

NAME OF MINE	PERIOD OF OPERATIONS	STRATIGRAPHIC AGE	TOTAL TONNAGE OF ORE (million tonnes)	AVERAGE ASSAY OF ORE					TOTAL COPPER PRODUCTION (million tonnes)	GOLD (kilogram)	SILVER (Kilogram)	LEAD (million	ZINC tonnes)	COMMENTS
				%Cu	%Pb	%Zn	Au (gm/ tonne)	Ag (gm/tonne)						
WALLAROO MOONTA (SOUTH AUSTRALIA	1860-1928	Lower Proterozoic	6.5-11.5* *estimated due to filling of slopes.	2-3 (some 3.85%)	-	-	0.31+	0.91+	0.3336	minor	minor	minor	minor	+based yearly production figures.
MT.MORGAN (QUEENSLAND)	1882-P.D.	Middle Devonian (Capelta Creek Beds)	79.890 (Reserves in 1973 ($5x10^6$ tonnes)	0.75	-	-	3.80	?	0.5964	5670	Greater than 5981	-	-	Associated with Volcanics and Porphyry Copper.
MT. LYELL (TASMAINIA)	1883-P.D.	Cambrian (Mt. Read Volcanic Group)	12.4698 (Reserves in 1974 $40.5x10^6$ tonnes at 1.45%Cu)	1.15	-	-	0.40	8.10	0.14338	4068	72685	-	-	Associated with Volcanics.
COBAR MINES (N.S.W.)	Disc. 1869 Mine Operations (1871-P.D.)	Silurian (Cobar Group)	13.946	1.66	?	?	1.93	14.15	0.239641	38103 (to May 1973)	117699 (to May 1973)	0.031 (for period	0.00873 1972-1976)	Stratiform Deposit(?) Volcanics(?)
MOUNT ISA (QUEENS - LAND)	1928 to P.D.	Lower Proterozoic (Mt. Isa Group)	102.223 (Reserves for 1976 $229.4x10^6$ tonnes Both Mt. Isa and Hilton Mines)	3	6.9	6.4	-	162	1.82939	-	6939104	2.913	2.7219	Black Shale Environment.
BROKEN HILL (N.S.W.)	1883 to P.D.	Lower Proterozoic (Mine Sequence)	120.0 Reserves $60x10^6$ tonnes	Assecory	13.2	9.1	-	210	0·000101 (101 tonnes) Umberumberka East Copper Mine.	-				Minor Copper

The Wallaroo and Moonta Mines produced 3.5 and 2.75 million tonnes of ore respectively, a combined total of 6.25 million tonnes of ore. However, a better total estimate is 11.5 million tonnes of ore processed; since a large quantity of low grade ore was separated from the higher grade material and used to infill the stopes. This reported tonnage of copper at current prices (i.e. $A1120 per tonne) would be $377 million, equivalent to 8.83 years production from Mt. Isa. Renewed prospecting from 1930-31 revealed small ore shoots in the southern extension of Taylor's Lode, carrying 16,250 tonnes of 6% copper ore (Dickinson, 1953) or 74,766 tonnes of 3.75% ore (Ward, 1940). This ore was not extracted due to water in the Karkarilla Mine.

Comparative production figures of Wallaroo-Moonta and Mt. Isa Mines, are significant (Table 1.2), as Wallaroo-Moonta total production represents approximately 27.2% of Mt. Isa production, based on copper estimates to 1976. This percentage is 13% of the total production of Mt. Isa, to 1976 for the copper, silver, lead and zinc.

The special features of Wallaroo-Moonta are-

(i) The area has potential for future mineral discoveries.

(ii) The availability of data over two important orebodies can provide a reliable geophysical model for application to other areas.

(iii) A potential ore body, is in a favourable location for mining, shipping, and has established infrastructure and services.

(iv) This mineral province is close to a major structural weakness in the crust, the Torrens Hinge Zone.

(v) As the Wallaroo - Moonta Mines are concealed with a thick overburden and no outcropping basement, except along portions of the coastline, base metal exploration of the basement rocks is a major problem, and is totally dependent on geophysics, geochemistry and drilling. (This overburden problem also applies to the southern portions of the Gawler Craton and Stuart Shelf).

Lack of significant lead and zinc associated with the Wallaroo-Moonta lodes, raises the question whether more copper ore and a large lead-zinc lode exist in this area, or, whether Wallaroo-Moonta Mines are just small mines compared to Mt. Isa and Broken Hill. Exploration programmes of Western Mining Corporation, North Broken Hill Pty. Ltd. and Broken Hill South Pty. Ltd. over the past 22 years suggests that Wallaroo-Moonta is a promising prospect for a significant orebody, as yet undiscovered. Small sub-economic copper prospects have been delineated in the West Doora and Vulcan areas. Both these deposits are comparable in size and grade with Wallaroo Main Lode (J. Lynch, pers. comm.). A sub-economic lead-zinc horizon, Smithams Prospect has also been discovered.

1.3 THE REASON FOR THE CHOICE OF THE WALLAROO-MOONTA AREA

Firstly research started in the Stuart Shelf in the northern part of the Torrens Hinge Zone. It became apparent that the aeromagnetic contour pattern between parts of ANDAMOOKA and TORRENS were geophysically similar to the Wallaroo-Moonta area. In addition, the magnetic basement in the former area was relatively deep, between 380 to 760 m, below ground level beneath Shelf Adelaidean sediments. However, drill hole information was lacking at that time. In the Wallaroo-Moonta area, by comparison, extensive geophysical and geological control was available from both S.A.D.M.E. and company exploration. Therefore, a comprehensive geophysical interpretation of this area would be beneficial to the understanding of the basement structures in the Gawler Platform. The geological data could be used to control the geophysical interpretation in a relatively known area and then extrapolated into areas of concealment.

Secondly, the basement rocks in the Wallaroo-Moonta Province have been the site of 80 years of geological and 34 years of geophysical exploration, but this data has not been previously systematically appraised nor placed in its regional setting.

Thirdly, there is the possibility of secondary stratiform or stratabound base metal deposits located at unconformities or hiatuses within the Middle to Late Proterozoic and Cambrian sequences, and along the Cambrian-Tertiary unconformity.

1.4 THE AIMS OF THIS RESEARCH

The major aim of this interpretation is to provide the structural picture, geophysical model and a case history of the Wallaroo-Moonta Province, and its association with the Torrens Lineament (Torrens Hinge Zone, Figure 1.1). This interpretation is geophysical, controlled by correlations between the petrophysical properties of drill core with lithology, and the relationship between these interpreted results with geology, ore bodies and known structures.

More specifically the aims are:-

(i) To provide a geophysical structural interpretation of the Wallaroo-Moonta Province. The two major detailed studies associated with the ore lodes are: (a) the Wallaroo Mines, (Kadina Fold Belt), and (b) the Moonta Porphyry, and to see how these orebodies relate to detailed structures.

(ii) To place these detailed complexes into the regional structural context.

(iii) To provide and document the geophysical case history of the Moonta and Wallaroo orebodies and set out clearly (define) the geophysical problems in this area

(iv) To stimulate further exploration, research and experimental feasibility surveys of different geophysical techniques.

In addition to the above are:

(a) to provide contours of the magnetic basement depths over the area to indicate the possible thickness of overburden and the edge of the shallow magnetic basement, as future exploration will be practical only in those areas where the basement is shallow for economic considerations.

(b) to delineate major lineaments within the basement, and to outline their relationship to the granite intrusions and mineralisation.

1.5 GEOPHYSICAL DATA USED IN THESIS

1.5.1 AEROMAGNETIC DATA

The regional aeromagnetic data was flown in different periods with different survey specifications (Table 1.3, Figure 1.2). In 1975, the B.M.R. flew the Spencer Gulf, to help complete the aeromagnetic coverage of Australia. The details of these surveys and some interpretations are given in later chapters.

In the Wallaroo-Moonta area, some extensive detailed aeromagnetic and ground follow-up studies have been carried out. Very little has been published as portions are confidential due to the continued private interests in the area. Consequently, about 70% of the data used and interpreted in this research is confidential at the request of the current mineral lessee holders.

The detailed aeromagnetic data used in this research project (Figure 1.3) are firstly the North Broken Hill Pty. Ltd. aeromagnetic and INPUT-EM survey at East Kadina, and the Bute aeromagnetic survey (open file); secondly, the Australian Aquitaine aeromagnetic surveys of the Price and Central Maitland (Curramulka) areas (open file) and the Jododex (Broughton-Tickera survey) used to interpret part of the regional setting of the basement structures.

1.5.2 DETAILED GROUND GEOPHYSICAL SURVEYS

The first major detailed ground vertical variometer surveys (Figure 4.1) were conducted for Zinc Corporation by Oscar Weiss over the Kadina area in 1948 and is still of considerable value. The second major group of survey data is the W.M.C. regional reconnaissance vertical variometer surveys, conducted after 1960 over the Wallaroo-Moonta Province. Some detailed magnetic data over local prospects was undertaken by W.M.C. and N.B.H.

Regional reconnaissance and detailed electrical surveys (Figure 4.2), were made using Induced Polarization, frequency domain, standard dipole-dipole array, and Schlumberger vertical electrical soundings. SADME surveys, carried out by the author, consist of magnetic surveys in the Bute and East

Bute areas; vertical electrical soundings in the Tickera area; and gravity traverses in the Broughton area. All other available gravity data has been compiled for detailed appraisal, (Chapter 16).

1.6 TREND OF RESEARCH

1. A regional interpretation of the aeromagnetic data was first compiled at the scale of $1:10^6$ based on a study of six 1:250 000 map areas, which includes the Torrens Hinge Zone. Relevant highlights are included.
2. A petrophysical study was undertaken on drill core which have intersected Cambrian and Proterozoic rocks within the Adelaidean Geosyncline, Stuart Shelf and Gawler Block, to obtain the expected magnetic and gravity responses of particular stratigraphic units.
3. The geophysical interpretation and available geological information was summarised at 1:100,000 for both Maitland and Wallaroo.
4. The following detailed studies were made of important areas where considerable geophysical data is available:

(a) The interpretation of the Kadina and East Kadina fold system associated with the Wallaroo Lodes.

(b) The interpretation of the Moonta Porphyry and its association with the Moonta Lodes.

(c) The structure and granitic areas in the Cape Elizabeth-Agery area, and the association with the New Moonta, Penang and Agery Mines.

(d) The interpretation of the Tiparra and Weetulta Complex areas.

(e) The interpretation of the Arthurton Granite.

(f) The interpretation of the North Kadina-Alford area.

5. As the study of these detailed areas, (a, b, and c,) revealed inconsistencies in the previously presented data, the Maitland and Wallaroo maps were revised.
6. The relationship of the mineralisation in the ore bodies to the geophysical responses and to the interpreted structure were studied.

7. The distribution of mines, with interpreted structures, was studied, based on the magnetics and the relationship of these two with the gravity results.

The interpretational techniques used are based on the author's experience whilst employed by B.M.R. and S.A.D.M.E. No new technique was devised, because a sufficient framework of interpretive techniques was already available.

1.7 THE APPENDICES

The appendices are a summary of the interpretation methods used in this study, and the proposed exploration programme for 'blind' sulphide ore deposits in this type of environment. A summary of lithological drill logs, petrophysical logs, petrological and geochemical data was compiled, but were too bulky to include and are being prepared as a S.A.D.M.E. report.

1.8 THE PROBLEM OF MAP SCALES

Many scales have been used in the past. The initial vertical variometer data of Zinc Corporation, of the Wallaroo-Kadina area was prepared as a series of 20 sheets at the scale of 1:2 400 and 1:600. The original contoured data was recontoured and compiled at the scale of 1:10 000.

The large scale reconnaissance ground variometer data of Gold Mines of Australia Ltd. and Western Mining Corporation Ltd., were prepared at 1:126 720. However, some local prospects were prepared and recontoured at 1:4 800 and 1:1 200. The data was compiled at 1:100 000 and 1:50 000. The changes from the Transverse Mercator projection of the Clarke 1858 spheroid of the Australian Map Grid in yards series, to the Universal Transverse Mercator Grid in metres, the Australian Map Grid (A.M.G.), adjusted to the Australian Geodetic Datum, (A.G.D.), provided a few location problems.

The scales used in this thesis are as follows:-

(i) Regional interpretation 1:1 000 000 and 1:250 000.

(ii) Detailed aeromagnetic interpretation 1:25 000. This may be reduced to 1:500 000 for plans within the text.

(iii) Detailed study of Wallaroo-Moonta at 1:100 000 and some detailed areas are presented at 1:50 000 or at a reduced scale for presentation.

For this thesis, maps have been simplified and generalised as much as possible without loss of important details and kept to a minimum practical size. In some cases, transparent overlays are used, with the same geographical projection as the base diagrams.

1.9 FRAMEWORK OF THE PROBLEMS IN GEOPHYSICAL CASE HISTORY STUDIES

Most of the existing economic base metal deposits in South Australia occur in exposed areas or regions having near surface outcrops. These deposits were found by a systematic search of old prospecting areas, based on early historical publications, especially the South Australian Record of Mines, (Brown, 1908); 'old' prospecting methods, such as ultraviolet light at night, geiger counters, and the use of correct field identification of economic minerals. Since 1960, deposits have been found in South Australia by the study of outcropping gossans and geochemical exploration, with geophysics playing a minor role in the location of the ore bodies. An important factor in past exploration, has been chance and good observations, e.g. the surface indications of copper observed from the greenish copper flame from a wood fire and from copper carbonates in wombat burrows led to the discovery of Wallaroo Mine.

Peters (1978), Kuzvart and Bohmer (1978), Bradshaw (1975), and Lovering and McCarthy (1978) have reviewed the principal geological and geochemical characteristics for case history studies of sulphide deposits, and provided the ideal parameters to locate deposits for a conceptual model with no reference to geophysics. In this thesis the geophysical characteristics of the orebody and its setting are included in this case history study and numerous geological conceptual models are discussed.

1.9.1 THE ROLE OF GEOPHYSICS IN BASE METAL EXPLORATION

In both the regional and detailed surveys, quantitative and qualitative interpretations of the geophysical data in shallow basement areas combined with geological control can help to define:

(i) the fold structures.

(ii) the distribution of fault and/or fracture systems, and possible unconformities.

(iii) the distribution of major lineaments and their relationship to the deposits.

(iv) the distribution of granite intrusions, the location and metamorphic aureoles and their relationship to mineralisation.

(v) the distribution of basic intrusions, dyke swarms, basic pipes and plugs and outline areas of complex ultrabasic structures.

The latter five concepts, together with the responses reported from local electrical traverse data over the mineralised zone, provide the basic geophysical characteristics required for the case history and the conceptual geophysical model applicable to the Wallaroo-Moonta Province.

These parameters and model may be used in the selection of relatively unknown target areas where geological data may be sparse. This geophysical role is important when working or extrapolating from the known into new or concealed areas. For example methods developed and tested in the detailed aeromagnetic surveys of the Kalgoorlie (Golden Mile) area by the B.M.R. (Dockery and Shelley, 1966) provided the basic interpretation procedures used by Young and Tipper (1966) for the regional reconnaissance of the Yilgarn Block. These procedures were used to define major fold structures, delineate greenstone belts within granite terrains, and identify possible ultrabasic target areas for nickel exploration.

The basic concept is the comparison of geophysical similarities based on experience, knowledge and numerous geophysical parameters between an area of known geology with an unmapped or concealed area having similar geology and structural history. The principal geophysical data required are, regional and detailed aeromagnetic, airborne radiometric, INPUT - electromagnetic, gravity and electrical survey data.

1.9.2 GENERAL GEOPHYSICAL EXPLORATION PROBLEMS OF BASEMENT AREAS

1.9.2.1. Regional Geophysical Data

Regional surveys, both aeromagnetic, aeroradiometric and gravity data cover most 1:250 000 sheet areas of Australia. The primary purpose was for the study and delineation of sedimentary basins prospective for oil, and the location of iron ore and uranium deposits based on high amplitude magnetic and radiometric anomalies. To this end, this data has been very useful. No detailed systematic interpretations have been published on basement areas, except for the preliminary reconnaissance interpretations by the B.M.R.

These reconnaissance aeromagnetic surveys have been flown with varying survey specifications such as altitude, ground speed, sampling intervals, sensitivity of the instruments and flight line spacing. Most of these surveys were flown with a flight line spacing of 1.6 km and at an elevation of 150 m above ground level. This is usually satisfactory for regional geological studies, but is not good for mineral exploration as the spacing must be less than the greatest dimension of the target. Agocs (1955) showed that for spacing of 1.6 km, the probability of detecting a rich magnetite ore body of 20.4 million tonnes with a depth: width: length ratio of 1:0.27:4.8 was 0.35. For weakly ferromagnetic minerals, e.g. pyrrhotite, associated and probably disseminated with other sulphides, then the probability of discovery for a body with the same dimension is much less. In the case of the Wallaroo and Moonta Lodes, assuming a strike length of 1 km, then the probability of finding these lodes, is 0.20 for a flight line spacing of 1.6 km, and 0.4 for a spacing of 0.8 km. This probability is further reduced by interfering anomalies from the neighbouring highly magnetic rocks near the Wallaroo Lode.

The general use of these reconnaissance aeromagnetic and gravity surveys is for regional mapping, showing the bulk magnetite and density distribution of suprabasement and intrabasement sources. Over basement areas, the magnetic data will outline the broader structures, but will not resolve units consisting of a number of magnetic units or complex fold systems. Two other problems generally overlooked, and which apply to the Wallaroo-Moonta Province are: positioning errors, which arise when the flight lines are plotted on uncontrolled mosaics or old and inaccurate topographic maps, and, the false trends which can arise in the contour data presentation, as most contours are produced by contouring amplitudes only.

Detailed aeromagnetic surveys flown at lower altitudes with closer flight line spacings are generally satisfactory, provided that the orientation, flight line-tie line system are oriented at right angles to the overall fabric of the basement rocks. This is difficult as metamorphic terrains generally have suffered numerous fold deformations which tend to give rise to structures in several directions. To overcome this problem, the best and most economic detailed surveys should have a flight line-tie line spacing ratio of 4:1 or 5:1.

Most detailed surveys undertaken by companies, are, for economic reasons, irregular-shaped, have variable survey specifications, cover relatively small areas, ie, a part or the whole of an exploration licence area, and until recently are not tied to the I.G.R.F. values. This produces a problem when combining surveys.

1.9.2.2 Ground Geophysical Data

In many areas, ground geophysical exploration is piece-meal in its development as in Wallaroo-Moonta, and consists of a few semi-randomly oriented traverses and/or grids over prospects. This produces inconsistencies, duplication and computational problems, when an attempt is made to construct and interpret the overall picture.

The lack of quality control on geophysical data is another significant problem when combining and compiling similar types of data. The Wallaroo-Moonta ground data is in this category.

1.10 PETROPHYSICAL PROPERTIES OF ROCKS

The interpretation of Archaean and Proterozoic rocks in Australia, and especially in South Australia is made difficult because of the lack of systematic petrophysical studies of these basement rocks. In geophysical exploration, the main petrophysical properties required for the potential field data are density, magnetic susceptibility and remanent magnetization. Similar information is required on electrical and elastic rock properties. A portion of this research project was devoted to the determination of the rock properties for potential field data, based mainly on drill core from Early Proterozoic to Cambrian rocks.

A literature search was made to evaluate remanent magnetization. When this research started, no petrophysical data was available in the Wallaroo-Moonta area, except for paleomagnetic data reported on basic dykes of Eyre and Yorke Peninsulas, (Giddings and Embleton, 1974). Previous, paleomagnetic studies were undertaken on the Middleback Iron Deposits, (Mumme, 1963; Gunn, 1967; and Chamalaun and Porath, 1968) and a preliminary study of the Gawler Range Volcanics (Chamalaun and Dempsey, 1978). The Adelaidean sediments of the Geosyncline were studied by Briden (1967) and Tucker (1972).

This information is required to define, which lithologies and/or stratigraphic units may produce a magnetic and/or gravity response, depending on the physical parameters, for the detailed analysis and comparisons with interpreted susceptibility or density contrasts, for the evaluation and correlation with the rock types encountered in drill holes and for the interpretation of cross sections.

CHAPTER 2

SUMMARY, GEOLOGY AND HISTORY OF PREVIOUS INVESTIGATIONS

Yorke Peninsula is a horst of Tertiary age, bounded by faults trending at 020°. It includes the Wallaroo-Moonta Province, where Proterozoic metamorphic and igneous rocks are almost totally concealed by Adelaidean, Cambrian and Cainozoic sediments. The basement stratigraphy in the Wallaroo-Moonta area is relatively unknown and a possible guide is outlined in Chapters 16 and 17. All available geological data is summarised in this chapter and is fundamental to the geophysical interpretation.

2.1 REGIONAL GEOLOGY OF THE WALLAROO-MOONTA PROVINCE

The Wallaroo-Moonta Province is near the boundary between the Gawler Block and the Adelaide Fold Belt. The number of tectonic terms used in the literature of South Australia has caused confusion. In this thesis, the *Gawler Block*, (Figures 1.1 and 2.1), is used for the outcrop areas of the Gawler Craton. The *Gawler Platform* defined by Thomson (1970), emphasises the age the basement was last folded (Kimban Orogeny), and consolidated, which occurred about 1450 ± 50 Ma, (Webb, 1978b). The *Gawler Craton* includes a large region of basement rocks, incorporating the Gawler and Denison Blocks, the Mt. Woods and the Wallabyng Inliers, and the Gawler Platform, (Thomson, pers. comm.).

The basement rocks of the Gawler Block have suffered two major orogenic events, separated by a major hiatus aged between 2 300 and 2 000 Ma (Figure 2.2), based on a study of granites in the Gawler Block, (Webb, 1978b). The regional stratigraphy of this block based on geological mapping by Daly (1981) in TARCOOLA, and Parker (1978) in WHYALLA, was compiled by Thomson, (1978) for the preliminary geological map of South Australia.

The earliest orogeny so far found is the Sleaford event of Archaean (?) - Early Proterozoic age, up to 2 300 Ma, represented on Eyre Peninsula by the Sleaford Complex (Tilley, 1921a) in LINCOLN, the Warramboo Complex in KIMBA (Thomson, pers. comm.), and the Mulgathing and Glenloth Complexes in TARCOOLA, (Daly et al., 1978). The rocks consist of foliated gneisses, granulites, metasediments including banded iron formations and mafic intrusions, which are all intruded by later granites, e.g. Kiana and Whidby Granites. The metasediments in LINCOLN are equivalent to the Flinders Series or Group of Tilley (1921b) and Johns (1961). These older basement areas are interpreted to occur as rafts, within the Middle Proterozoic sequence, which has been folded and metamorphosed by the Kimban Orogeny.

The second major orogenic event in the Wallaroo-Moonta Province, occurred between 1 800 and 1 550 Ma, followed by post-kinematic granite and volcanic events, (Figure 2.2).

The stratigraphy of Eyre Peninsula was resolved in a detailed structural study of the Cowell-Cleve area by Parker (1978). The main stratigraphic units are the Hutchison Group, (Tilley, 1920) which includes the Warrow Quartzite, Middleback Subgroup containing iron formations, amphibolite and amphibolitic schists derived from dolomites, marbles, metasiltstones, and the Cook Gap Schists. The term, 'Cleve Metamorphics' was formerly used to describe these metasedimentary rocks.

The Hutchison Group, is followed by the Lincoln Complex, which consists of a series of metasediments, granulite, augen and granite gneisses, and mafic intrusions. This sequence is equivalent to the Gneiss Complex of Tilley (1921b). Acid gneisses from the Corny Point-Berry Bay in *Deburg* and *Turton* in southwestern Yorke Peninsula, composed of potassium feldspar-quartz-plagioclase with variable amounts of biolite and hornblende have an Rb/Sr isochron age of 1808 ± 18 Ma, for an initial Sr^{87}/Sr^{86} ratio of 0.7043 ± 0.0013, (Steveson and Webb, 1977) which have been correlated with the Lincoln gneisses, (J. Parker, pers. comm). The basement rocks at Pt. Souttar in southwestern Yorke Peninsula are high grade hornblende - bearing acid metamorphic rocks, containing potassium feldspar-quartz-plagioclase-hornblende with minor biotite, sphene and opaques, of possible upper amphibolite facies grade derived from pre-existing intermediate acid igneous rocks, (Steveson, 1977b). The Rb/Sr isochron gave an age of 1671 ± 115 Ma for a low Sr^{87}/Sr^{86} initial ratio of 0.6999 ± 0.0129. This low ratio is interpreted to be produced by a loss of Rb or radiogenic Sr^{87} and gave a doubtful metamorphic age, (Webb, 1977). This data shows that Lincoln Complex equivalents are present in southern Yorke Peninsula. The Lincoln Complex was intruded by synorogenic granites, eg. Burkitt, Carpa, Middlecamp, Narridy Creek and Charleston Granites, which have isotopic ages between 1 700 and 1 520 Ma, (Webb, 1978b).

The period between 1 520 and 1 325 Ma has been defined by Thomson (1978) as the period of Transitional Tectonism, which incorporates the Basic, Lower and Upper Gawler Range Volcanics, Roopena Volcanics, Moonabie Formation, Corunna Conglomerate, Blue Range Beds, and the Tarcoola Beds. The granites of the Sir Joseph Banks Group (Spilsby Island Granite), the Hiltaba Granite, Cultana granophyre, the Moonta Porphyry, and the Arthurton and Tickera Granite Complexes have all been incorporated within this period, (Thomson, 1978).

The granites, Moonta Porphyry, and pegmatites in the Province have a radiometric age ranging between 1520 and 1400 Ma, with the initial crystallisation age of the porphyry being at least 1600 Ma, (Webb et al., in press), but the ages of the Doora Schists and the East Kadina metasediments are questionable, due to later metamorphic effects, feldspathisation, carbonatisation and retrogressive events, which have reset the initial Rb-Sr and K-Ar ratios, within the metasedimentary rocks. The K^{40}/Ar^{40} geochronological data on hornblende and biotite from the Doora Schists and related gneisses based on W.M.C. core samples gave ages between 1634 and 1441 Ma, with the major ranging between 1520 - 1420 Ma, similar to the K/Ar ages of the Moonta granite and pegmatites, (Webb et al., in press). Lower grade Willamulka metasediments and metavolcanics, (dacite and rhyodacite) have a comparable K/Ar age, between 1 230 and 1 350 Ma from hornblende in the Bute Amphibolite, (Webb, 1972). Thomson's hypothesis that these Willamulka metamorphics are equivalent to low grade metamorphics in the East Kadina area (East Kadina metasediments), require further studies.

The metamorphic basement of the Gawler Platform is unconformably overlain by Adelaidean and Cambrian platform sediments, which dip between 5° and 10°E on the Stuart and Spencers Shelves, towards the Adelaide Fold Belt. The folding on the platform is slight and increases eastwards. The region of tight folding accompanied by a N-S trending belt of fractures, and a rapid increase in sedimentary thickness adjoining the Stuart Shelf is called the *Torrens Hinge Zone* (Thomson, 1970) (Fig. 2.1). This zone was affected by the Delamerian Orogeny, (500 to 480 Ma, Thomson, 1980). East and southeast of the Wallaroo-Moonta Province, the coastal boundary of the Gawler Block is defined by a series of faults, across which there is a rapid thickening of Adelaidean sediments. The Adelaide Fold belt occupies a basin feature, in which the sedimentation, associated with rifting and minor volcanism, commenced between 1300 and 1400 Ma, (Thomson et al., 1976). Some faulting occurred intermittently during the deposition of the Adelaidean sediments, which were folded during the Cambro-Ordovician Delamerian Orogeny, (Thomson, 1970).

This orogeny in Yorke Peninsula, produced the high frequency folding and associated fracturing of both the Adelaidean and Cambrian sediments at the eastern edge of the Peninsula, which is controlled by fractures of this deformation, namely the Yarroo Fault and possible Pine Point Thrust, (Figure 3.1).

2.2 STRATIGRAPHY OF THE COVER ROCKS IN THE WALLAROO-MOONTA PROVINCE

The stratigraphy of the cover rocks was initially outlined by Jack (1917). Bacon (1948) briefly discussed these units, with an enlarged section on the Tertiary and Quaternary sediments based on the geochemistry of Sokoloff (1948). Chebotarev (1955) provided additional information on these two units. Crawford (1960 and 1965) outlined the Palaeozoic to Recent stratigraphy of Wallaroo and MAITLAND.

Investigations by the S.A.D.M. in *Wallaroo*, (E.L. 75 and 207) provided surface geological data, (McCallum, pers. comm.) and Adelaidean stratigraphy in the Bute area, (Thomson, 1978) and the Tickera-Broughton area, (Parker and

Thomson, 1977). WMC and NBH provided additional information on the Cambrian and Adelaidean distribution. Aquitaine Australia Minerals Pty. Ltd. in their search for Cambrian stratabound lead-zinc deposits in *Maitland* and *Stansbury*, (E.L. 314 and 315) provided detailed stratigraphic data.

Thomson (1978) for the compilation of the State geological map utilized all data on the cover rocks given above, and basement information provided by Wright and Lynch (1973). The resulting simplified geological map of Yorke Peninsula (Figure 2.3), with portions of the Cainozoic sediments removed, shows the basement cover relationships in the Wallaroo-Moonta Province.

ADELAIDEAN

The Adelaidean succession is mainly restricted to *Wallaroo* and *Blyth* and forms a continuous suboutcrop N-S strip from Port Broughton to Clinton.

The concealed Pandurra Formation intersected in Bute DDH1 (Figure 2.5) at a depth of 23 m and in Bute DDH6, is unconformably overlain by Sturtian tillite. The contact relationship between the Adelaidean and basement is unknown as this hole was terminated in the Pandurra Formation.

The Willouran Backy Point Formation was intersected in Wokurna W.R. 9, 10, and 11 on an E-W traverse, near Port Broughton, W.R. 15, and in Wokurna DDH 4, where this unit is 176 m thick and rests unconformably on basement metasiltstones. In N.B.H. E.L. 311, a thick sequence of 'Backy Point Formation', associated with Beda Volcanics overlies a thick evaporitic-marl sequence of the Callanna Group. A basal micaceous sandstone may be equivalent to the Pandurra Formation, (Lynch, 1978).

The Torrensian Aldgate Sandstone rests unconformably and laps onto the basement in the East Kadina and Bute areas. This unit was originally mapped as Shelf Proterozoic by Jack (1917) and Crawford (1960). The Sturt Tillite rests unconformably or disconformably on the lower Adelaidean units and was intersected in Bute DDH 1, 7 to 11 inclusive, in the Bute area, and in Workurna WR3, 13 and 17 and Wokurna DDH 2 and 4 in the Broughton area.

The Farina Subgroup containing the basal Woocalla Dolomite and Tapley Hill Formation transgresses, and is either unconformable or disconformable on the Sturt Tillite, and on basement amphibolite in Bute DDH3. These units are present in Bute DDH 2 and 7, and Wokurna DDH 2 and 5. The remaining Adelaidean units: Brighton Limestone, the Willochra Subgroup and the Wilpena Group rest conformably on the Tapley Hill Formation, have a N-S strike, (Figure 2.3), and are typical Adelaidean facies in the fold belt.

CAMBRIAN

The Cambrian sediments are widespread in southern and eastern Yorke Peninsula, and form a thick sequence in the Stansbury Basin. The basal Cambrian, Mt. Terrible Formation, intersected in Kulpara DDH 1 and 2, (Thomson, 1973a) and in Bute DDH 2, 3 and 5 (Parker and Thomson, 1977), is associated with weak sub-economic zones of base metals. The Transitional Beds consist of arkosic sediments, which are at least 56 m thick in Minlaton No. 1 in the Stansbury Basin, and are equivalent to the Mt. Terrible Formation. This unit which passes upward into the marine dolomitic Kulpara Limestone, intersected in Bute DDH 2, 3 and 5, is exposed in the Curramulka, Ardrossan and Winulta areas and forms embayments into the Wallaroo-Moonta Province. The embayments thicken eastwards and southwards away from the shallow basement areas.

Small areas of Cambrian limestones occur in Weetulta, Wallaroo, north of Kadina and around Bute. The first three basins of limestone occur in small depressions in the basement surface, and rest unconformably on the metamorphic basement. These areas contain the Parara and Kulpara Limestones, and the former contains a mineralised band of nodular limestone with sporadic pyrite, galena, and minor fluorite (Crawford, 1965). The Ramsay Limestone of early Middle Cambrian age, is generally restricted to the Stansbury Basin in southern Yorke Peninsula, but extends northwards into the Curramulka area. Elsewhere, it occurs locally as sedimentary breccias at Pine Point, and as a limestone conglomerate at Rocky Point, east of the Pine Point Thrust.

Elloy (1976) in a study of Cambrian limestones from Minlaton No. 1 and Wilkatana No. 1 in Stansbury and Pirie-Torrens Basins, found the Kulpara Limestone between 290 and 550 m contains a facies of abundant glauconite, phosphate and some sulphides, representing a deep water marine open environment. As the Kulpara Limestone occurs in the eastern part of the Wallaroo-Moonta Province, these glauconitic sediments may represent an important magnetic marker horizon, (see Chapter 15).

PERMIAN

Permian glacial sediments occur in the Stansbury Basin; in the Minlaton, Stansbury and Troubridge Shoal stratigraphic drill holes. These sediments crop out in isolated areas of the Wallaroo-Moonta Province, and have been found in numerous drill holes.

CAINOZOIC

The Quaternary sediments form a continuous unconformable blanket of variable thickness. Isolated areas of Tertiary sediments consist of limestones (Melton Limestone), sands, marls, clays, and some lignite. Two thin Tertiary greensand units occur in the Port Julia Greensand and within the Blanche Point Marls. They contain slightly magnetic glauconite, and depending on the percentage and thickness of these units, may produce low amplitude magnetic anomalies. Another magnetic source within these sediments are heavy mineral bands, containing magnetite and martite, which fortunately have a limited distribution. The Melton Limestone (Tertiary) increases in dip near the faults e.g. Tickera Fault (Lindsay, 1970).

2.3 THE HISTORY OF THE MINES AND EXPLORATION IN THE WALLAROO-MOONTA AREA

The only exposures of basement rocks are along the coast and a few outcrops inland. Almost all the information about the basement lithology has been obtained from mining operations, and from auger and diamond drilling.

Early drilling logs from 1906 to 1917 were reported by A.W. Matthews in Mining Reviews, in relation to the Bingo, Wandilta, Wallaroo Extended, Cornwall Copper, Poona, Yelta and Mattapara Mines, (Figure 2.4).

Comprehensive reports of the Yelta and Wandilta Mines, (Condor, 1912) and the Yelta and Paramatta Mines (Ward and Jack, 1912) provided data on the lithology, mineralogy of the lodes, sections of the underground workings and drillhole locations.

The most comprehensive study made by Jack (1917), whilst the mines were still in operation, was a major step forward in the understanding of this Province. Jack (1917) produced the first geological map of the Wallaroo-Moonta District and detailed maps of the main mineralised areas of Kadina and Moonta. He showed the basement rocks associated with the main mineralised areas, consist of metasediments, schists, gneisses, amphibolites, Moonta Porphyry, Tickera and Arthurton Granites. These maps were used by Crawford (1960 and 1965) for the mapping of <u>Wallaroo</u> and MAITLAND. Since 1923 when the mines closed, mapping and drilling has been done by S.A.D.M. and private companies. Jack's basement mapping was not revised until 1973, when N.B.H. compiled an interpretive pre-Tertiary geological map, (Wright and Lynch, 1973), (Figure 2.6).

At Wild Dog Mine, in the eastern part of the Yelta Lode system, Winton (1924) provided data on the drilling, mineralisation, ore produced and future developments. Further work was reported by Cornelius and Pearson (1939).

Pearson, from 1926 to 1936, reported on mine inspections for the reserves and treatment of the tailings, and the possibilities of re-opening some of the mines, eg. Wallaroo, Poona (Mattapara) and Yelta. Since then, some copper has been recovered from these tailing dumps.

Government assistance of \$(A)88,612 was paid to miners working uneconomically in the Wallaroo-Moonta district from 1931-1939. Cornelius (1939) conducted a feasibility study and appraisal of the Poona, Wild Dog, Moonta Extended, Moonta, Karkarilla Mines, and the Alice and Hall's Lodes, based on copper ore grades from 1.5% to 6%, estimated from drill hole data, and concluded that the better prospects were Wild Dog Mine, Moonta Extended and the deeper levels of Karkarilla Mine. Known tonnages were small. Most reserves would have been depleted within a few weeks, and would not have provided the minimum ore required to operate the treatment works.

Even for a nationalised mining operation, with the price of copper fixed at $(A)127.76 per ton by the Australian Government, and with the minimum number of miners, the additional expenditure required for dewatering the mines, and shaft and level maintenance before satisfactory mining operations could begin, made all operations uneconomic. A report by Ward (1940), based on 53 additional drill holes, showed no additional economic mineralisation.

The next major advance was by Dickinson (1942a), with his interpretation of the structural control of the major lodes, (see Section 3.2). The continuation of this concept to the Bingo Mine, (Dickinson, 1942b), showed from underground mapping, that this mineralisation was at the intersection of fracture systems, parallel to the principal Wallaroo and Wandilta Lodes. He provided new concepts and stimulus to future geological and geophysical investigations. Dickinson (1953) re-appraised the area, after the exploration programme of Zinc Corporation, given below.

Benedict et al., (1948) summarised surface diamond drilling. Benedict and Bacon (1948) summarised the geological data of shallow drill holes sited to evaluate some resistivity traverses, and to establish the northern boundary of the Moonta Porphyry in the Kadina Grid, by a series of deeper holes, spaced 150 m apart. Cornelius (1948) compiled a newspaper file covering mining activities from 1860-1877. The major geological reports were by Bacon (1948), a summary report of the history of the mining field (Benedict, 1948a) and an exploration summary, (Benedict, 1948b).

The major exploration contribution by Zinc Corporation, apart from later drilling, was the detailed geological compilations of the Kadina Grid, and the extensive use of geophysical and geochemical techniques in the area, (Chapter 4). An outline of the geochemical data of Sokoloff (1948), Hargraves (Appendix in Sokoloff, 1948) and Chebotarev (1955) is warranted, as geochemical anomalies associated with geophysical data have provided most targets for later diamond drill holes.

2.3.1 GEOCHEMICAL EXPLORATION

The first geochemical investigation in South Australia was by Sokoloff (1948). Chebotarev (1955) contributed the concept of auger sampling the basal clays of the overburden for copper, nickel and cobalt, as this horizon showed a considerable variation of these elements. By normalising the Cu and Ni assay values by the corresponding Co value, the supergene response for copper was greatly enhanced and showed a distinct increase with depth of the normalised nickel and copper values, with a maxima later defined as the geochemical basement surface. He also provided useful data on the possible metamorphic grade and rock forming minerals likely to be encountered in the area, based on vertical variations of the heavy minerals separated from silts and sands in the auger hole sections. This geochemical method was later used to define the geochemical basement, which is a zone of secondary enrichment and occurs near the top of the oxidised metamorphic basement. In places, the depth of oxidation or weathering of the basement is deep, and this study by Chebotarev saved considerable meterage of auger drilling.

Geochemical traverses over the principal lodes and geophysical targets were made by Gibson (1959). Two small geochemical anomalies were delineated east of Elder (Taylors) Lode. Auger geochemical programmes have been the major method of evaluating geophysical targets and have provided a high percentage of the basement rock chip data. The W.M.C. geochemical reconnaissance programme commenced in the Tiparra, Agery and Weetulta areas, with the auger samples being assayed for copper, lead and zinc, with some additional assays for silver, nickel, cobalt and molybdenum on selected samples, (Lynch, 1977a). The main anomalous values were copper, cobalt and nickel and minor isolated molybdenum associated with the West Weetulta Complex. McBriar, (1962) reported exceptionally high cobalt and nickel values associated with barite, sphalerite, and pyrite in Wallaroo and Moonta Lodes, with minor cobaltite in the Wallaroo sample. This suite of elements is the basis for both the W.M.C. and N.B.H's geochemical exploration programme. Further details are summarised by Mazzucchelli et al., 1980.

Soil geochemistry was attempted, but found unsatisfactory, (Sokoloff, 1948 and Gibson, 1959). N.B.H. retried soil sampling at depths of 1.2 m in the Tiparra-Weetulta areas over known mineralisation and found the lack of significant anomalies (Lynch, 1977a). They later conducted a feasibility study, which outlined the Schillings Prospect. The significance of the geochemical Pb, Zn, Cu anomalies and their source have not been evaluated.

2.4 ROCK TYPES OF THE WALLAROO - MOONTA PROVINCE

One of the major geological problems is the inconsistent terminology used for drill hole data, rock types, stratigraphic units, and petrological descriptions for the basement rocks by different authors.

The lithological relationships between drill holes are unknown, when the rocks in one hole cannot be correlated with another over distances using previous terminology, except those used to evaluate local mineralised prospects.

No attempt was made in this research to standardise drilling data by W.M.C. and N.B.H. However, some pre-1950 drill cores were relogged and submitted for petrological examination, to supplement petrophysical measurements. To help solve the structural and statigraphic problems, numerous core samples have been submitted, in collaboration with B. Thomson, for geochronological studies, and are reported by Thomson (1973a) and Webb, (1978b). Some of this data is incorporated in this chapter for clarity.

Basement rocks were studied by Jones (1940) and McBriar (1962). McBriar studied the primary copper mineralisation from museum collections. Callen (1966) studied the petrology of the metasediments, gneisses and granites from core in the Kadina area and Lemar (1975) studied the petrology of core from the Moonta Porphyry and some sediments.

The rock names used are based on Jack (1917), Jones (1940), Bacon (1948), McBriar (1962), Callen (1966), Wright and Lynch (1973), Lemar (1975), Lynch (1977a) and numerous petrological descriptions. This data is discussed in terms of the rock types present and the lithological or metamorphic group names used as field mappable units, by the exploration companies.

2.4.1 THE METASEDIMENTS

The metasediments in the Kadina area were reported by Jack (1917) to be schists, quartzite, slates, phyllites and calcareous dolomitic units. Ferruginous 'greywacke' and ferruginous 'chert' which grade into iron ore were reported in the Kadina area (Bacon, 1948). Whitten (1966b) proposed that sedimentary iron formations passed from schist to granite gneiss zones in the Balgowan, Weetulta and North Kadina areas. The magnetite-rich gneisses, in the North Kadina areas, showed minor chalcopyrite and pyrite within a fine grained foliated gneiss which contained variable potash feldspar and magnetite. The gneisses, which are siliceous and associated with amphibolite, pyroxene and epidote, were interpreted to represent shales, dolomitic siltstones and cherts (?) associated with iron formations, prior to metamorphism. Thomson (1973a) considered that the highly magnetic schists, (Doora Schists) and amphibolitic gneiss and carbonate rocks of the Wallaroo Mines, the Tiparra and Weetulta areas in the south, to be lower metamorphic grade variants of the North Kadina gneisses. Crawford (1965) considered the gneisses represented by feldspathic gneisses, feldspathic-biotite gneiss, hornblende gneiss and biotite-hornblende gneiss to be paragneisses.

Callen (1966) reported anthophyllite-cordierite gneiss from DDH27, (Figure 2.5). Cordierite was also found in a hornblende-rich (80%) rock in the same hole. Thomson (1973a) and Lynch (pers. comm.) considered that Jack's concept of a batholithic mass at depth may still be valid, and the granite gneiss transition may represent the initiation of anatexis or melting in place. Lynch considered the higher grade metasediments to represent rafts or roof pendants within a granite-gneiss terrain. The secondary magnetite, which shows local discordant development, within the metamorphic sedimentary units, can be explained on the anatexis model. Alkali and carbonate metasomatism, and chloritization has occurred on the regional scale, and appears to be present in the lode zones, (Thomson, 1973a). These events were considered to be an important process for the concentration of base metal sulphides and some metal oxides within some rock units.

2.4.1.1 Metasediments in the Kadina Area

In the Wallaroo Mine area, Jones (1940) showed the metasediments are mainly quartz-biotite schists, some of which contain amphibole and scapolite. Some calc-silicate rocks consist of scapolite, diopside, and others contain entirely hornblende. These metasediments were originally arkoses, slates and calcreous slates, associated with basic igneous rocks. A high percentage of feldspar is present, both microcline and plagioclase (oligoclase) with a relatively low percentage of quartz. He subdivided these metasediments into two groups:

(i) metamorphosed arkoses and slates

(ii) metamorphosed calcareous slates

McBriar (1962) studied similar rock types from the Wallaroo Mines, but did not investigate the slates, phyllites, or quartzites noted by Jack (1917). A combined summary of these metasediments is given as follows:

(i) METAMORPHOSED ARKOSES AND SLATES

Quartz-biotite schists, ranging from predominantly quartz-feldspar rocks with minor biotite, to quartz-biotite-feldspar schist, to biotite-rich rocks, were interpreted to range from argillaceous arkoses to slates containing quartz. Micaceous quartzite, consisting of quartz-feldspar-(oligoclase)-biotite ± chlorite rock, are the most common rocks in the mine dumps, and some show thin bands of biotite. The disseminated biotite shows alteration to chlorite, associated with some magnetite. Accessory minerals are pyrite, zircon, apatite and tourmaline.

Quartz-biotite schists have a higher percentage of biotite ± chlorite than the micaceous quartzite. The biotite occurs in bands within a quartz matrix. Fine grained plagioclase (albite) ± microcline is present and the accessories are apatite, tourmaline and zircon. McBriar (1962) classified these metasediments with the general composition of quartz-feldspar-biotite ± chlorite schists. Some of these rocks which Jones studied, contain minor amphibolite (actinolite) and scapolite, showing extensive alteration to sericite, and no chlorite. He considered these two minerals reflected a more calcareous composition in the original metasediment.

Biotite-rich rocks consist of biotite (± chlorite), with minor quartz and microcline, which contain some magnetite. Some chlorite aggregates may represent hornblende alteration products. The rocks generally show retrograde effects, (Jones, 1940). McBriar (1962) reported porphyroblastic schists, where the porphyroblasts are chlorite, tourmaline, actinolite or microcline. These schists are biotite-rich, with a felsic fraction representing 60% of the rock. This fraction contains 20% quartz, microcline and albite, with accessory apatite, sphene and schorlite (tourmaline).

(ii) METAMORPHOSED CALCAREOUS SLATES

These rocks are extensively represented by scapolite-biotite schist, which McBriar (1962) considered fell into two groups, one containing scapolite-biotite and the other scapolite-biotite-hornblende. In both rocks, the felsic and mafic minerals are present in equal amounts. The scapolite was considered to be mizzonite, (Jack, 1917), and dipyre, (Jones, 1940). Results of X-ray powder diffraction pattern analysis, (McBriar, 1962) show that the scapolite composition is 2/3 marialite and 1/3 meionite, i.e. the sodic variety, dipyre.

The scapolite-biotite schists, which contain predominantly biotite-quartz, some sericite, calcite, minor amphibole, and accessory sphene and apatite, were interpreted by Jones (1940) to represent metamorphosed impure limestones. The scapolite-hornblende-biotite schists show a marked linear schistosity. The scapolite being dipyre, which contains inclusions of quartz-biotite, hornblende and sphene, was interpreted to be metadiorite or calcareous slate. The scapolite-biotite ± amphibolite (actinolite) rocks, considered to be metamorphosed impure limestone, contain minor sphene and apatite, and show mineralised veins of chalcopyrite associated with microcline and quartz.

Scapolite-rich rocks have a diopside, hornblende and scapolite assemblage. The scapolite represents 60 to 70% of the composition. The main assemblages reported by Jones (1940) and McBriar (1962) are:

a). scapolite-diposide-actinolite rock with minor plagioclase and microcline.

b). scapolite-chlorite-amphibole-quartz ± chalcopyrite rock.

All these scapolite-rich rocks show varying degrees of alteration, and seem to be similar in mineral assemblage to the quartz-feldspar-biotite ± chlorite schists and the scapolite-biotite-hornblende schists, which contain a high percentage of scapolite, assumed to reflect an increase in the degree of scapolitisation.

Jones (1940) observed foliated rocks with alternating bands and gradational contacts between quartz-feldspar-biotite schists and scapolite-diopside rock. They were interpreted to be sedimentary in origin, and to represent possible high grade metamorphosed impure dolomitic limestone or calcareous slate.

Callen (1966) identified scapolite in W.M.C. DDH 16, 25, 36 and 37, in bands within biotite-quartz gneisses and in amphibolitic-plagioclase-biotite-quartz gneiss. In the gneiss, apatite but no opaques were present. These drill holes are on the flanks or in magnetic lows between the magnetic units of the Doora Schists. Callen considered these rocks were regionally metamorphosed calcareous sediments, alternating with shales and Mg-Fe-rich sediments, the latter being dolomite or tuffaceous material. The diopside-plagioclase-scapolite rock in DDH16, containing lesser amounts of microcline, quartz, opaques and sphene, was interpreted to have been originally a ferruginous dolomite. Callen proposed a carbonate sequence to the east of the main mines area i.e. a general easterly increase of the carbonate content, representing a facies change within the metasediments towards or in the East Kadina metasediments.

Also Callen observed in DDH36, scapolite replacing plagioclase in a tightly folded banded biotite gneiss, suggestive of carbonate metasomatism. No scapolitisation was observed in the nearby DDH35, although DDH39 contains similar rocks. In the East Kadina Area, Lynch (pers. comm.) showed that scapolite spotting was a secondary effect and that it had crystallised across the earlier rock fabric, in NBH DDH111, 3 km east of Kadina. This spotting increases with depth, and shows the progressive and gradual change of the metasediments to the scapolite- rich rock, where the scapolite has completely obliterated the original rock fabric.

Whitehead (1973a) described samples from this drill hole as scapolite-bearing hornfels derived from a layered sediment, probably composed of clay, quartz and an iron compound deposited with the sediments. Some of these rocks were later metasomatically altered and contain sulphides.

Scapolite-rich zones are present in the magnetite-bearing basic gneiss in Balgowan DDH 1 and 2, which is composed of plagioclase (oligoclase) - hornblende-magnetite ± biotite ± clinopyroxene ± scapolite, with minor apatite, allanite, pyrite and sphene. There are minor interlayered bands of biotite schist, and thin layers containing concentrations (up to 30%) of apatite with scapolite. Whitehead (1978b) considered at least two episodes of metamorphism or recrystallization had occurred, and probably much of the earlier scapolite was replaced by plagioclase, and some of the hornblende replaced by clinopyroxene. Some zones still contain scapolite, almost certainly of metamorphic origin as the remaining scapolite has a composition of about Me_{20-25}, (sodium end of the marialite-meionite series) which agrees with McBriar (1962). Whitehead considered that this composition for the scapolite is present in calcareous rocks of this metamorphic grade. This indicates that the scapolite was derived from sediments containing evaporite minerals particularly halite. Whitehead considered that evaporitic sediments derived from seawater in Archaean - Proterozoic times, could contain concentrations of iron probably deposited as siderite. As no true banded iron formations are present in any of the drill holes in the Wallaroo-Moonta Province, except for a possible one in DDH100 (Warburto Magnetic Belt), this model suggests a possible environment for most of the iron-rich horizons in the Wallaroo-Moonta area.

2.4.2 THE MOONTA PORPHYRY

The Moonta Porphyry is defined as the igneous body occurring in the Moonta Mines area only, (Figures 2.6 and 9.8) with an areal extent as outlined by Jack (1917). This is different from that outlined by Wright and Lynch (1973), and the difference is discussed later in the geophysical interpretation. The original description of the petrology of the Moonta Porphyry given by H.W. Fander (AMDEL), in 1917, is as follows:

> "Glomeroporphyritic crystals of orthoclase set in a fine-grained groundmass of sodic plagioclase, microcline, quartz and chlorite laths. The grain size of the groundmass lies between microgranodiorite and dacite and this rock can be called a porphyritic granodiorite or porphyritic dacite".

The Moonta Porphyry rock type also crops out to the east and northeast of Moonta, and east of Thrington (Jack, 1917). Other similar porphyritic material has been reported in the Kadina area. The actual contact zone between the Moonta Porphyry and country rocks is not visible. Jack's boundary was controlled by the distribution of scattered workings and float mapping. Later drilling located the boundary east of Yelta Mines.

McBriar (1962) studied some Moonta Porphyry specimens and distinguished two main rock types: felspar porphyry and felsite which were both subdivided into normal and schistose varieties. The schistosity was produced by the addition of 8 to 20% biotite, with some alteration to chlorite and martite in layers or bands. The other major differences are the amount of biotite +

chlorite ± martite ± hematite in the matrix, and some microcline. The felsite compares with the matrix of the normal porphyry, but has introduced potash feldspar and traces of sulphide. The schistose felsite consists of alternating layers of normal pink felsite with chlorite and a slight increase in grain size. McBriar also reported metasediments from museum specimens from this area, consisting of a poorly foliated quartz-biotite schist with alternating felsic and mafic layers, and a quartz-microcline-tourmaline-biotite-chlorite schist. Some of the coarse-grained portions of the latter schist contain hematite and sulphides.

2.4.2.1 Summary of Petrological Data on the Moonta Porphyry

The petrology of some core samples from DDH 50, 57, 58, 114 and 151 (Figures 2.5 and 7.1) to establish the origin of the Moonta Porphyry, (Lemar, 1975), is as follows:

The most abundant and widespread component of the porphyry is ash flow tuff, interpreted from the poor sorting and random arrangement of the euhedral and fragmentary phenocrysts, and the discontinuous elongate lenticles (eutaxitic texture) defined by chloritic aggregates. The phenocrysts represent 1.8 to 36% of the rock. Plagioclase phenocrysts are small and minor in quantity. The ground mass has equal amounts of orthoclase and quartz, with minor amounts of chlorite and biotite. The biotite shows retrograde metamorphism to chlorite from greenschist facies. Some rock fragments of rhyolite and rhyodacite composition are present.

Locally developed west of Bald Hill, in DDH 151, are albitised rhyolitic tuff breccias which show chloritized glass shards and quartz-filled vesicles, interpreted to have originated as pumice.

Air fall tuffs interbedded with biotite schists were identified east of the main porphyry mass. The former are banded, shown by distinct cycles of grading in the bedding, and are extremely fine grained, consisting of a well sorted aggregate of 98% (quartz and feldspar) with 2% opaque minerals (ilmenite and rutile). The latter are associated with chlorite and sericite. The rocks show chloritisation in both varieties.

The other igneous materials are non-porphyritic microgranites and granites, identified in DDH 50, 57 and 114. The microgranites are equigranular mosaics of microcline (45%) - plagioclase (30%) - quartz (25%) with chloritised biotite and hornblende. Feldspar phenocrysts are rare and show microclination and sericitization. All samples have a distinct metamorphic foliation, produced by alignment of biotite, chlorite and sericite. These rocks were considered to be a hypabyssal intrusion, (Lemar, 1975), and show no albitization. They probably represent the porphyry with a gneissic foliation observed by McBriar.

Granite, which intrudes the ash flow tuff and microgranite, shows a contact aureole of a metre. The granite contains 35% microcline, 30% plagioclase and 30% quartz with up to 2% of the rock being chlorite (alteration of biotite). Minor hornblende is represented by epidote and chlorite and the whole rock has been sericitized. The pegmatites may be associated with this granite.

Lynch (pers. comm.) considered the pyroclastics studied by Lemar (1975), to be a local development, limited in area, and not representative of the Moonta Porphyry.

To obtain systematic petrophysical data of this porphyry for geophysical modelling, Moonta DDH E1 and E3 were selected. Radke (1977) investigated the opaque and sulphide minerals, and studied whether any pyroclastics were distinguishable or not in core samples. Radke called all samples meta-dacite, representing acid to intermediate igneous rocks containing plagioclase phenocrysts, which suffered greenschist facies-grade metamorphism, deformation and potash metasomatism. This metamorphism produced a well developed lepidoblastic foliation, mainly defined by chlorite and/or biotite flakes and most may be schists. The matrix was completely recrystallised, thereby obliterating any primary textural features, which could be used to determine whether these rocks had a flow, pyroclastic or shallow intrusive origin. Magnetite crystals with martite veins were found in the disseminated form. One sample, with disseminated pyrite, chalcopyrite and pyrrhotite, surrounded by magnetite, shows a lack of remnant plagioclase phenocrysts, and a dominance of potash feldspar.

In summary, the Moonta Porphyry, a porphyritic rock or meta-dacite sequence, is part of an igneous complex, containing a felsite intrusion, microgranite and granites, and contains some limited pyroclastic material which was generally recrystallised and metasomatised. The meta-dacite sequence contains distinct foliated zones and some disseminated magnetite/martite with minor traces of sulphides. The mineralisation is related to a later phase associated with secondary magnetite and/or hematite.

Jack (1917) first observed the lithological similarity between the Moonta Porphyry and the Gawler Range Volcanics, and later geologists have assumed Jack's observations were correct. However, Parker (1979, 1980b), who on the basis of textures and lithological association, suggested that the Moonta Porphyry should be correlated with the Myola Volcanics in NE. Eyre Peninsula, (Webb, et al., in press). This correlation assumes that the Moonta Porphyry is the time equivalent to the volcanics within the Doora Schists. These volcanics are considered different by the author on geophysical grounds. Details are given in later chapters. No world comparisons were made with the Moonta Porphyry, but comparisons have been made with the mineralisation and possible alteration zones, for a possible porphyry copper model, which appears to be accepted with little systematic scientific evidence, except for Lemar (1975).

2.4.3 INTERMEDIATE TO BASIC ROCKS OF EXTRUSIVE ORIGIN IN THE KADINA AREA

In the Kadina area, porphyritic rocks in dumps and drill holes were called Moonta Porphyry (Jack, 1917; Benedict and Bacon, 1948) as they are lithologically simlar to the type locality.

Bacon (1948) and Benedict believed the quartz-biotite rocks, previously interpreted as sedimentary in origin,by Stillwell and Whittle in 1940, to be intermediate to basic flows and tuffs, which were interbedded and folded within the metasedimentary sequence. This concept was based on a detailed study of the lithological logs in the Devon and Kurilla areas, and from DDH 1N, 2N, 4N and 5N, north of the Wallaroo Main Lode. These rock types were not recognised in the other dumps, except at Doora Mine, where andesite was found. Benedict based his knowledge on the Berens River Mines, in Ontario, where this rock type has shown effusive structures and was accepted as flows.

McBriar (1962) and Jones (1940) considered the quartz-biotite rocks to be metasediments. Callen (1966) noted the relative gradational contacts between the porphyritic felsite and biotite schists in DDH 12, 3.2 km south east of Moonta, supporting Bacon and Benedict's hypothesis.

Petrological data by A.W.G. Whittle and Associates for NBH added evidence for volcanics and/or pyroclastics in the sequence by the presence of scapolitised - carbonatised tuffaceous metasediments in West Alford area (DDH 150), Thrington area, etc., in a lower grade metamorphic sequence. Whitehead (1978a) reported metadacites of volcanic or shallow intrusive origin in Devon DDH 1, and metamorphosed porphyry or metadacite in Devon DDH 2. The former metadacite shows high copper values, (Moeskops, 1978). The significance of pyroclastics within the metasedimentary sequence is discussed in the section on the Kadina Area.

Recent mapping, (Lemon, 1978; Parker, 1979) east of the Middleback Ranges revealed acid volcanics: the Myola Volcanics, interbedded within meta-arkoses above the Broadview Schist, which were equated with the Doora Schists, (Parker, 1979). The Myola Volcanics are geochemically rich in copper, (D. Price, pers. comm.).

2.4.4 GRANITES

There are two main types of granites in the area. Firstly, gneissic granites and/or foliated granites, e.g. Tickera Granite. Numerous foliated gneisses were also interpreted as paragneisses, (Crawford, 1965). The common rock types are feldspathic gneiss, feldspathic-biotite gneiss, hornblende gneiss, biotite-hornblende gneiss and albite gneiss.

Secondly, non-foliated granites vary from fine to coarse grained, and from granite to adamellite or granodiorite in composition. Some are porphyritic. These granites are not metamorphosed or strongly foliated, except for occasional zones of shearing or mylonitisation. The Arthurton, Moonta and Thrington Granites are of this type, and are discordant non-disruptive presumably intruded at depth with very little temperature differential. They may relate to a major batholithic body.

2.4.4.1 The Tickera Granite Complex

The Tickera Granite exposed in the shore section near Tickera is a coarsely crystalline, foliated gneissic granite, considered by Jack (1917) to differ from the Arthurton Granite in appearance, and to have suffered greater stress than the latter granite and the Moonta Porphyry. Petrological studies show the Tickera Granite to be a deformed microcline granite, with a mineral assemblage of microcline - quartz - plagioclase (oligoclase-andesine) with minor apatite and biotite, which has been altered to chlorite.

Jones (1940) studied the basement rocks for approximately 28 km along the coast between Wallaroo - Point Riley - Tickera, and defined the main rock types in the Tickera Granite Complex as follows:

At Point Riley, the gneissic granite, a quartz-oligoclase ± minor microcline ± muscovite granite, has a vertical foliation and is oriented at 260°. It is impregnated parallel to the schistosity by red aplite veins, and contains quartz-microcline-plagioclase (oligoclase) - biotite with a trace of muscovite and two pegmatite types: a coarser grained aplite variety and a quartz-microcline variety. Also, a white aplite, 70 m wide, parallel to the foliation, has sharp and irregular contacts with the gneissic granite and is cut by the pegmatite. This aplite is different from the red variety and contains 65% felspar (plagioclase (oligoclase) with some microcline), quartz, minor disseminated zircon and sphene, traces of biotite and muscovite, and some ilmenite (limonite). Its contact relationship with the red aplite is not defined.

South of Point Riley, the southern edge and/or boundary of this gneissic granite body is shown by a decrease in gneissic texture, an increase in inclusions of country rock, pegmatite veins, and microcline content of the gneiss and sedimentary inclusions, possibly introduced by the intrusion. The inclusions are as follows:

(i) a fine grained plagioclase (oligoclase) - magnetite (ilmenite) amphibolite with traces of apatite, and minor quartz enclosed within the hornblende crystals. This rock was interpreted as a metamorphosed microdiorite.

(ii) Biotite-sericite schist, consists of quartz-biotite-muscovite (sericite) - microcline and a trace of tourmaline.

The microcline is considered to be secondary. This schist is intersected by quartz-feldspar veins.

North of Point Riley towards Tickera for approximately 4.8 km, this red gneissic granite is relatively uniform, except for variations in the microcline-plagioclase ratio, which increase northwards in microcline. Near Tickera, the inclusions increase, dominated by rafts of country rocks, consisting of the following:

(i) fine grained amphibole schist (hornblende-plagioclase-epidote-biotite (chlorite) showing a gradual change to a biotite - plagioclase (oligoclase) schist with minor microcline, traces of apatite and iron oxides. Biotite which decreases in content towards the granite, may have developed from hornblende.

(ii) zones of feldspathised quartzite showing gradual contacts at the boundary with the gneissic granite.

Further north, the gneissic granite is uniform in texture and contains some pegmatite dykes. At Tickera, a porphyritic granodiorite or adamellite occurs, but its relationship with the Tickera Granite is not reported. The phenocrysts in this granodiorite are dominantly plagioclase (oligoclase-andesine) with a minor proportion of microcline. The matrix of this rock is quartz-plagioclase-biotite (chlorite) ± microcline and apatite, and is considered to have crystallised under stress. This porphyritic granodiorite is comparable with the medium grained adamellite in Tickera DDH2, except that the latter is not porphyritic. Both rocks have undergone tectonic stress.

Total rock Rb/Sr geochronological data of a pegmatite and two adamellite samples of the Tickera Granite Complex plot close to the Moonta Granite isochron of 1200 ± 27 Ma, and are considered to be not older than the granites at Moonta, (Webb, 1978).

2.4.4.2 The Arthurton Granite

This granite is semi-exposed, occurs over an area of 18.78 km^2, south-east of Arthurton, and is a fine to coarse grained quartz-muscovite-microcline granite with some tourmaline, considered by Jack (1917) to have produced an extensive metamorphic aureole penetrated by numerous granitic, pegmatitic and aplite veins. Jones (1940) showed two granitic rock types within this granite, a quartz-microcline (pink feldspar) granite, and a quartz-microcline-plagicolase ± biotite (chlorite) granite, containing both primary and secondary opaque iron oxides.

Rock types eastwards from Arthurton, towards the main granitic body, (Jones, op. cit.) consist of coarse pegmatites, foliated scapolite-microcline-hornblende diopside rock (metasediment) and granite, with aplitic veins restricted to the outer edge.

The Parara pegmatite (P222/61) consisting of microcline, albite, quartz, muscovite and tourmaline, which may be related to the Arthurton Granite, has an Rb/Sr age of 1510 Ma (Composton et al, 1966). Microgranite, granite and pegmatites north and east of Arthurton, using K/Ar analysis on muscovite and biotite, fell within the range 1520 to 1420 Ma. This is identical with the spread of the granites and gneisses in the southwest Spencer Gulf, (Webb, 1978b).

2.4.4.3 The West Weetulta Complex

The central core of the West Weetulta Complex is composed of granite, adamellite and granodiorite, associated with some dolerite (Wright and Lynch, 1973). The outer magnetite-rich rim was investigated by 8 drill holes, of which 7 are on the western side. This rim is composed of both metasedimentary and igneous material. Details are given in Chapter 14. Petrological data on 8 samples in DDH 92, 159 and 178 are reported by Whittle in Lynch (1977a).

The metasediments are all strongly feldspathised, sericitised and chloritised to varying degrees. The major magnetite-rich metasediments are microcline-orthoclase-sodic plagioclase rocks with subordinate quartz, biotite, magnetite and chlorite, (243.5 m in DDH92). The magnetite may have originated along the foliation planes of a felspathised schistose rock.

In DDH 178, at a depth of 74 m, a feldspathised magnetite-bearing metasediment, shows alternate lamellae of quartz, amphibole (chloritised), biotite, which is interlayered with equally fine grained feldspar, (orthoclase and minor plagioclase) containing some fine grained magnetite and chloritised biotite. Some amphiboles were porphyroblasts in the original rock. These rocks were interpreted as silicate B.I.F. facies or at least magnetite-bearing quartzite, which were subjected to selective feldspathisation (Whittle, op. cit.). Other sediments reported are feldspathised biotite-sericite schist, (at 120 m in DDH 159) and feldspathised biotite schist (at 174 m in DDH 178).

Igneous rocks reported in this area are "silicified-feldspathised-chloritised ?biotite microgranodiorite", (at 157 m in DDH 92); porphyritic pyritic microadamellite and pyritic quartz-feldspar porphyry (at 160 and 182 m in DDH 159) and slightly altered microtonalite (quartz-mica-diorite) at 198 m in DDH 178. The principal components are hornblende and sodic andesine with minor biotite and quartz. Sphene, apatite and magnetite were plentiful accessary minerals. Both plagioclase and orthoclase displayed incipient sericitisation and scapolitisation.

The West Weetulta Complex is a discordant granite mass interpreted from the geophysical data as either a dome and/or diatreme, or, an acid igneous ring complex. A sample of scapolite/aegirine float (280S, OONS) on the southern margin, was described (Whittle, 1973) as a possible metasomatised equivalent of an undersaturated nepheline/aegirine derivative, suggesting an undersaturated alkaline igneous rock and possible carbonatite.

2.4.5 INTERMEDIATE - BASIC ROCKS

No large plutonic masses of intermediate, basic or ultrabasic composition are known and smaller basic intrusives are rare. However, the known basic rocks can be grouped into amphibolite and basic sills and/or dykes. Three ages are possible the oldest being the amphibolites.

2.4.5.1 Amphibolites

In the Kadina area, numerous biotite-amphibole gneiss and amphibolites were recorded in WMC drill holes. Callen (1966) interpreted these to be meta-diorite and hornblende gabbro. McBriar (1962) reported metadolerite, consisting of hornblende-andesine - quartz (5%) - sphene, and other amphibolites have a hornblende-biotite (chloritised) - albite assemblage. She considered these basic rocks to have been regionally metamorphosed to almandine-amphibolite facies, and later suffered retrograde metamorphism (greenschist facies). Amphibolites at Tickera and Port Riley may be concordant narrow bodies possibly sills, and the few discordant bodies may be dykes.

2.4.5.2 Diorites

Jack reported some diorite float in the Kadina area. Bacon (1948) identified fine to coarse grained diorite, as an abundant rock in dumps at the eastern end of the Kadina Grid, at the western end of the Wallaroo Main Lode, on dumps of old costeans west of Kurilla Mine, and in workings southeast of

Duryea Mine. These diorites, one of which intrudes a ferruginous greywacke in the Wandilta Mine, were intruded by pegmatites.

2.4.5.3 Basic Dykes

Jack (1917) described three basic dykes in the Province:

(i) At the New Moonta Mine, a porphyritic foliated coarse grained hornblende-feldspar ± quartz rock with minor apatite and epidote, termed an amphibolite, was considered to be a gabbro.

(ii) a coarse grained hornblende-quartz-magnetite-plagioclase rock, affected by later silicification, is in the main shaft at Wallaroo Extended.

(iii) a medium grained altered hornblende-plagioclase ± epidote rock termed amphibolite, interpreted as a basic body, SE of Bingo Mine.

Crawford (1965) reported a dark green rock intruding the Cambrian limestones in the Wallaroo Harbour area, of Lower Palaeozoic age. These results suggest at least two ages for basic dykes in the area.

Giddings and Embleton (1974) constructed rose diagrams for the orientations of dykes cropping out in Port Victoria striking at 100° to 200° and Corny Point striking at 090^0 to 140^0, with a mean direction of 140°. The paleomagnetic inclination and declination data of these dykes are similar, but the pole positions and ages were unresolved.

2.5 METAMORPHISM

No systematic studies of the metamorphic grades and fabrics have been reported or compiled in the concealed Province. This section is a review of previous studies, which are mainly concerned with the two mining areas, and using the author's terminology. Recent petrological data has provided some additional information, but this is still limited, as it is dependent upon the drill hole distribution and the lack of outcrops.

In the Kadina Area, Jack (1917) considered the metasediments had suffered gneissification, with later feldspathisation and chloritisation, representing an extensive metamorphic aureole related to the Arthurton Granite.

Jones (1940) believed that the regional metamorphic grade reached was comparable with Barrow's biotite zone, as the quartz-biotite schists contained amphibole and scapolite, and the calcsilicate rocks contained scapolite, diopside and some hornblende. The chlorine was introduced during this metamorphic event to produce the scapolite. Later retrograde metamorphism converted the pyroxene to amphibole, and some biotite to chlorite. He considered the apatite, tourmaline and feldspar were introduced and associated with the mineralisation.

McBriar (1962) interpreted the fine grained quartz-feldspar-biotite ± chlorite schists to be derived from quartz-feldspathic sediments, initially regionally metamorphosed to upper green schist or lower amphibolite facies. The development of chlorite from biotite and possibly from staurolite or amphibolite was a later retrogressive metamorphic effect, reducing the metamorphic grade to green schist facies.

The scapolite-bearing schists and scapolite-rich rocks (derived from either impure limestones or basic rock), and the amphibolites reached almandine-amphibolite facies, (McBriar, 1962). They were later metasomatised by pegmatites or siliceous solutions, and/or suffered retrograde metamorphism.

Callen (1966) thought that the scapolite and diopside in WMC DDH 16 suggested pyroxene granulite facies, and the anthophyllite and cordierite in WMC DDH 27 suggested granulite facies. Chebotarev (1955) observed in the heavy mineral separation in various silts of aolean origin, other high grade metamorphic minerals. Their origin is unknown, but was assumed to reflect granulite facies.

Lynch (1977a) considered the schists, gneisses and quartzites in the Weetulta-Tiparra area are of moderate metamorphic grade, possibly almandine-amphibole facies; staurolite-almandine subfacies, which would explain the staurolite, and basically agrees with McBriar (1962). Their composition is variable, from chlorite schists and quartzites to feldspar-quartz-biotite-hornblende-chlorite mica schists and gneiss. Rocks of igneous origin were described by Whittle from DDH 102 and 166 as gneissic biotite microgranodiorites and silicified-feldspathised chloritised-biotite microgranodiorites.

There is some evidence for contact metamorphism, as actinolite-epidote hornfels facies occurs, particularly north of Pine Point and in numerous boreholes, DDH MG5 and H49, (Whitehead, 1978d) and DDH 111, 123, 127, (Whitehead, 1973a) in the Kadina, East Kadina Areas, and North Kadina DDH NK4 and 5. An increasing degree of scapolitisation or spotting with depth was observed in DDH 111, and similar variable degrees of feldspathisation are present in the Kadina area (Lynch, pers. comm.).

Lynch considered that the metamorphic grade increases westwards and southwards across the Kadina Area. The east-west metamorphic gradient is truncated in the west by a feature sub-parallel and coincident with the Warburto Belt of magnetic anomalies.

In the Moonta Area, Jack (1917) observed the fractured and elastic deformation of the phenocrysts, and the varying degrees of schistosity within the Moonta Porphyry.

The poor foliation of the schistosic rocks and simple porphyritic appearance of the Moonta Porphyry indicate low deforming pressures, (McBriar, 1962). The development of chlorite from biotite indicates a retrogressive metamorphic event to green schist facies, i.e. quartz-albite-muscovite-chlorite subfacies. McBriar considered the original grade may have been biotite grade or the slightly higher quartz-albite-epidote-almandine subfacies. The Moonta Porphyry also suffered sodic and potassic metasomatism, silica mobility, (McBriar, 1962) sericitization, chloritization and recrystallisation, (Thomson, 1973a).

The data implies that the Kadina Area reached a higher metamorphic grade than the Moonta Area, and petrological studies of the Devon DDH 1 and 2 (Whitehead, 1978a) suggest a possible two division metamorphic history for these metasediments. Whitehead (1978c; 1978d) in a petrological study of MG3A and 4, MG5 and H49), speculated that the quartz-microcline hornfels could be the metamorphosed equivalent of some sandstones from NBH DDH PP 10 in the Pirie Area. Some of these low grade metamorphic rocks in DDH MG3A and MG5 may be metamorphosed Willamulka metasediments.

2.6 RELATIONSHIPS BETWEEN ROCK TYPES

The interpretive pre-Tertiary geological map of the Wallaroo-Moonta Province (Figure 2.6), by Wright and Lynch (1973) is based on drilling of the W.M.C. reconnaissance magnetic data, and on some initial interpretations by the author. This compilation over-simplifies the subsurface basement geology, and should be considered as a first approximation towards solving the geological problems of the Province.

THE MAJOR METASEDIMENTARY UNITS

The metasedimentary rocks were divided into four major units, (Wright and Lynch, 1973). The field names used by the companies will be adopted to avoid confusion. These names are not valid under the stratigraphic code.

Major Unit I

The major magnetite-rich units represented by quartz-feldspar-biotite ± amphibole-chlorite-magnetite gneiss and schists of the Doora Schists are located in the Jericho, West Doora, Doora, and Vulcan areas and form the Kadina Fold Belt. Wright equated the Doora Schists with the magnetic rocks of the Warburto Magnetic Belt, which may be a different unit, as these rocks have a different feldspar composition, (Lynch, pers. comm.), and with the magnetite-rich units in the Weetulta, Tiparra and North Kadina areas.

Major Unit II

This unit is composed of metasediments and meta-volcanics present as remnants in granite intrusions. Some of these members within this unit are magnetic, and may be comparable with the Doora Schists.

Major Unit III

This unit is represented by relatively low grade metamorphic sediments, the *East Kadina metasediments* (Lynch, pers. comm.) consisting of fine grained tuffs, tuffaceous sediments, shale, siltstone and black shales.

Major Unit IV

This unit or group, which covers a large area of the Province, consists of schists, gneiss, quartzite and amphibole rocks, in a predominantly later acid igneous rock, in the Tickera - Alford, Cape Elizabeth and Balgowan areas. Lynch considers these rock types to be the oldest group of metasediments.

The age relationships between these units are unknown. Whitehead (1978a) suggests a tectonic break or unconformity may exist between the Doora Schists and East Kadina metasediments in Devon DDH 1 and 2.

The Willamulka metasediments and volcanics, in the Bute area, were tentatively considered by Thomson (1973a) to represent the period of Transitional Tectonism, and correlate with, or are equivalent to the very late Proterozoic, namely Roopena Volcanics, and/or Gawler Range Volcanic metasediment equivalents. This correlation is supported by the K/Ar age of between 1230 and 1350 Ma for the Bute Amphibolite, (Webb, 1972) and the Rb/Sr age for the Roopena Volcanics of 1345 Ma. (Compston et al, 1966), used to define early Willouran time. These dates suggest that the Willamulka metasediments and volcanics are pre-Willouran time.

The relationship between these Willamulka metasediments and the East Kadina metasediments is controversial. Lynch and Thomson, (pers. comm.) suggest that the Willamulka (Wandearah) metasediments and Willamulka Volcanics are the less metamorphosed equivalent of the East Kadina metasediments. Thomson, (1978) also suggests the East Kadina metasediments and Doora Schists may be equated with the Hutchison Group.

CHAPTER 3

STRUCTURE AND MINERALISATION IN THE WALLAROO - MOONTA PROVINCE

No detailed systematic structural analysis was previously made of this concealed Province because (i) Structural data is minor, available only from coastal sections with limited surface outcrops. (ii) Structural data from the main mineral fields were recorded before the concepts of detailed structural mapping had been developed. (iii) Subsequent drill holes contained mainly lithological data, with limited reference to fractures, brecciated zones, limited bedding, foliation and/or cleavage data.

This chapter summarises previous structural interpretations, which are mainly related to the concepts developed by Dickinson in 1942. The correlations with fold deformations in modern terms are based on the author's interpretations, outlined later in this thesis. The significance of the uranium mineralisation is discussed and its association with base metals. Comparisons are made with deposits of similar age in Australia and the World.

3.1. KNOWN STRUCTURES IN THE WALLAROO-MOONTA PROVINCE

A lineation based on the strike of the gneiss foliation, was interpreted from petrological data by Crawford (1965) as a bedding or foliation. It trends as follows: 45°in the Point Riley area; 175° on Wardang Island and at Point Victoria; 000°-010° east of Maitland; 145° near Point Souttar, and on the coast between Corny Point and Royston Head; and 080°-090° between Cape Spencer and Point Yorke.

Some drill holes show micro-and macro-structures. Although beyond the scope of this thesis, microstructures are discussed in association with petrophysical core data in the Kadina Grid Area, (Chapters 5 and 8).

The tectonic map of MAITLAND (Crawford, 1965) outlines the distribution of Tertiary faults, and the extrapolated position of the Pine Point Thrust, of post-Cambrian pre-Permian age (Figure 3.1). These fractures trend between

000° and 045°.

The interpreted pre-Tertiary geological map, (Figure 2.6) is controlled by the W.M.C. reconnaissance magnetic data. It shows the major folds have axial planes trending at 080° for the East Weetulta and Tiparra antiforms and from 060° to 080° in the East Kadina and Kadina areas.

The variable arcuate or sigmoidal anticlinorium interpreted by the author for the Warburto and North Kadina areas, has an axial plane trending from 020° to 060°. The central core of this anticlinorium consists of granitic material, surrounded by a belt of sigmoidal synforms, containing magnetite-rich metasediments of the Warburto and North Kadina sequences.

The intensity of folding progressively increases westwards from the Bute area, where the folds are open, becoming tighter in the East Kadina area, and then overturned and sheared out, until abruptly stopped or thrusted out against the Warburto Belt of magnetic metasediments, (Lynch pers. comm.). West of this discontinuity, which is poorly defined geophysically, is the Warburto Belt. The metasediments within the belt are folded into relatively long wavelength folds in an anticlinorium, and have a different fold axial direction to those in the Kadina Area. The fold style of the Warburto Belt is similar to the F_3 folds outlined by Parker (1978) and Glen et. al. (1977) in the Gawler Orogenic Domain.

3.2. STRUCTURAL FEATURES OF THE WALLAROO-MOONTA LODES

The structural patterns in the Moonta and Wallaroo-Kadina areas were analysed by Dickinson (1942a) in terms of the stress and strain ellipsoid concept. No recent concepts have since been applied. Dickinson stated:

"the Precambrian rocks were intersected by numerous faults and zones of fracturing. The known fissures were confined to zones or belts, and data was insufficient to determine the nature and displacement of their movements."

He classified these fractures according to their average strike direction, into the following three main types, a simple empirical concept for assumed closely related fissures: Type A fractures, oriented NE-SW, Type B fractures, oriented NW-SE and Type C fractures, oriented E-W.

Type A are the dominant lodes of the Moonta Mines, and are subparallel to the interpreted elongation of the Moonta Porphyry. These three fracture zones were known as the eastern, central and western belts of fracturing, (Jack, 1917). The major fissures in the Wallaroo - Kadina Mines area are Type C.

3.2.1. MOONTA MINES AREA

The principal lode shears (Type A) in the Moonta area were considered by Dickinson 'to be high angle thrusts, formed at the earliest stage in the structural development of the area.' They strike 020° to 030°, dip 40° to 65°NW, contain the largest ore bodies which were narrow, up to 12 m. wide, 610 m long and mined down dip to 695 m. Some movement occurred along these fissures, based on grooving and slickensiding which pitch at 80°, but no displacement was specified, as no marker horizons were present. The West Lode Shears, which strike at 045°, dip 60° SE and have low grade mineralisation, displace the Main Lodes (Type A). The wall rock alteration is more intense than along the Main Lode Shears. The angular divergence between the West Lode shears is approximately 15°. A strike fault, the Taylor's Fault, in the Elder Main Lode workings, is subparallel to Type A fractures and dips at 45°W.

Minor structural features, which nevertheless influenced the ore deposition and concentrations are Types B and C fractures. These generally dip at steep angles, and had variable movement in direction and magnitude. Dickinson, believed these "to be the initial tension joints which developed when the Moonta Porphyry was subjected to stress".

Type C fractures, the E-W near vertical transverse faults, are only known from Beddome's section of Hamley Mine. The fracture pattern for the Moonta Mines area, derived from Dickinson, who based it on Hogg's Mine, is shown in Figure 3.2a.

3.2.2. WALLAROO-KADINA MINES AREA

The Wallaroo fissures or Main Lode Shears are the Type C fractures and strike between 090° and 120°. In the upper levels of the Wallaroo, Devon and Kurilla Lodes, they dip 75°S and at depth, steepen to the vertical and finally dip 75^{o}N. Some lodes were 1525 m long and the depth of mining operations extended to 884 m in the Main Lode.

Type A shears were interpreted by Dickinson to be major zones which disturb and restrict the mineralisation in the Wallaroo Lodes. The two principal zones named by Dickinson the *Western Shear Zone* and the *Eastern Shear Zone*, strike between 030^{o} and 045^{o} and dip at 70^{o}W. They are composite, composed of faults, and were interpreted as thrusts where they intersect shears of different orientations. Dickinson recognised these shear zones by the disturbance and offsetting of the Wallaroo fissures, although the displacement produced an aspect of a drag fold rather than a fault.

Type B fissures were observed at the Wandilta, Cornwall and Doora Mines. Little data is available, except at Wandilta Mine, where three steep southwesterly dipping lodes, are associated with numerous flat dipping irregular lenticular mineralised fractures. These were considered by Dickinson as stress-relief features, and interpreted as tension joints of the ellipsoid for the fracture pattern at the Doora Mine, Wallaroo Area (Figure 3.2b). Type C shears are earlier as they were truncated and offset by the other two fissures.

Dickinson assumed that

'the same deforming stresses which produced the Moonta fracture pattern, caused a slightly different fracture pattern to develop at Wallaroo.' He assumed 'the oldest pattern occurs at Wallaroo, since firstly, the Wallaroo fracture shows a greater variation in strike and dip, and secondly shows numerous displacements produced by later fractures. Their folded and faulted character was attributed to continued stress.' He postulated 'a rotation of stresses, to explain the different preferred direction of the mineralised tension fractures.'

The continuity of the Eastern Shear Zone between Wallaroo and Doora Lodes is an assumption, as it is unknown between the two mines. Dickinson described 'the Shear Zone as the locus of smashed ground or fault zones, at the eastern ends of the mine workings in the Wallaroo area. The line of loci trends NE-SE.' Wegerle (1948) and Weiss (1948) interpreted a similar feature based on ground magnetic data, which corresponds to this Shear Zone. Dickinson considered that 'the major controlling structures for the mineralisation were the location of the shear intersections and folds.'

Dickinson (1942b) continued his structural concepts to the Bingo Lode, which trends 145° for 30 m and dips 70° to 80° SW, and stated 'the known ore shoot in the Bingo Mine occurs where a Type A shear or shear zone intersects, offsets and/or bends the lode with a dextral movement.' Here the lode is wider and has a high ore grade 8% Cu. This intersection was traced down dip for 80 m. The Bingo Lode belongs to either the Wallaroo Main Lode (Type C) or the Wandilta type, (Type B).

The lode dimensions indicate that the mineralisation was confined to a pipe-like body with an elliptical cross-section 2 to 3 m in diameter, and a strike length of 30 m. The mine to a depth extent of 30 m, contained 7 to 8% Cu primary ore, with a secondary enriched zone (gossan) of sulphide and oxidised minerals of 10 to 20% Cu. Production was 3050 tonnes to 1900. Later drilling showed the lode extended to a depth of 150 m, with a grade 7% Cu.

3.3. BASE METAL MINERALISATION IN THE WALLAROO-MOONTA PROVINCE

This section summarises available information compiled before this research was started. It includes some information provided by N.B.H.

3.3.1. MOONTA MINES

The ore bodies of the Moonta Mines are considered by Thomson (1965):

> "to consist of pegmatitic and quartzose lodes filling multiple fractures in, and replacing the brittle porphyry, or disseminated through, and replacing, schistose bands thought to have been formed by shearing of the porphyry along fault zones. All of the Moonta lodes lay within the boundaries of the irregular teardrop-shaped Moonta Porphyry".

The principal lodes are arranged along three main lines of weakness sub-parallel to the axial trend of the porphyry mass. Dickinson (1942 a) considered "the strike was arcuate in shape, concave toward the east, and assumed a more meridional trend going south". This group of lodes extends for 2816 m. The individual lodes which were traceable along strike from 305 to 915 m, were 3 to 7.6 m wide with a mean of 1 to 2 m, and occurred in a multiple lode zone 220 to 300 m wide containing numerous veins. The near surface or 'supergene' zone may be up to 730 m wide and extend to 290 m e.g.

Elders Main Lode confined at depth by the Taylors Fault. Dickinson classified these lodes based on their stoped dimensions and strike length, as tabular and pipe ore bodies. The actual dimensions used for his classification are difficult to establish in available information. The likely dimensions for the tabular and pipe bodies are variable and show a wide range.

	Width	Depth Extent	Strike length
Tabular	1-2 m	141 m	240
Pipe	164 m (stoped width)	440 m Hoggs	-
	0.15 m	36 m Dominicks and MacDonnell's	?

Hayes (1920) and Jack (1917) provided some Moonta mine cross sections indicating the area stoped. Dickinson probably used this data in this classification.

The mineralisation consists chiefly of bornite and hematite with minor chalcopyrite in a quartz-feldspar-biotite (pegmatitic) gangue. The main accessory minerals are tourmaline, molybdenite and fluorite. The bornite was important at first with an ore grade of 30% Cu, which reduced at depth to 4% Cu as chalcopyrite.

In the Moonta Lodes, McBriar (1962) states the mineralisation is a bornite-chalcopyrite-pyrite assemblage with minor magnetite, specularite, martite derived from magnetite, limonite and hematite. It is associated with pegmatitic minerals in lodes enclosed within schistose portions of the Moonta Porphyry (Callen, 1966). Johnson (1965) observed that the chalcopyrite tends to be associated with the quartzose portion of the lode and bornite with the more feldspathic portion.

The vertical distribution in the Moonta Lodes, observed from Taylors Lode (Moonta), shows the upper section is pegmatite (quartz-microcline-biotite facies) with a high percentage of hematite and minor martite. The lower facies are basically quartz veins with pyrite at a depth of 768 m. The host rock away from the mineralised zones is barren, except for some disseminated magnetite and minor pyrite.

Jack (1917) considered 'the mineralisation assemblage to be a schorlaceous pegmatite,' and that 'the economic minerals showed a possible zonation,' but this was based on limited data. The mineralogical zones which may occur within pegmatitic lodes in ascending order are: hematite - pyrite, pyrite - chalcopyrite - bornite, and chalcopyrite - bornite. Later workers have interpreted this distribution to fit a porphyry copper model.

Benedict (1948 b), from evidence of unsheared pegmatite cutting sheared porphyry in drill core, considered there was a time interval between intrusions of Moonta Porphyry and the pegmatite emplacement, which preceeded or accompanied the copper mineralisation, which was therefore not genetically related to the Moonta Porphyry. Lemar (1975) compared the Moonta mineralisation with copper deposits associated with porphyry copper and volcanogenic massive sulphide deposits, and found that the Moonta deposits did not fit either model. Lemar referred to no specific deposits in this comparison. Previously, the Moonta Mines had been compared with the Khan Mine, South West Africa, Jack (1917), and with the Butte Mine, Montana (Beyschlag, Krusch and Vogt, 1909). Details are given later in this chapter.

3.3.2. WALLAROO MINES

The host rocks and lodes of the Wallaroo-Kadina Mines which differ from those at Moonta, (Table 3.1), are metasediments and metavolcanics intruded by porphyry dykes and some possible porphyritic intrusions, previously correlated with the 'Moonta Porphyry'. This research shows that these porphyritic units, originally interpreted as 'Moonta Porphyry' are interbedded within the metasediments. Some porphyritic intrusions in this region are lithologically similar to the Moonta Porphyry, but are different geophysically. This problem is discussed in Chapters 7 to 9. The lodes at Kadina are interpreted to be replacement-type rather than the fracture fillings (Thomson, 1965). The principal sulphide ore is chalcopyrite, accompanied by pyrite and pyrrhotite. The gangue minerals are different from those in Moonta Lodes, (Table 3.1), and the accessory mineral suite is more varied.

McBriar (1962) showed the Wallaroo mineralisation is a pyrrhotite-chalcopyrite assemblage, associated with a siliceous gangue. The sphalerite ores with minor chalcopyrite and galena are associated with carbonates in adjacent lodes, which occur in regionally metamorphosed schistose and amphibolite rocks. McBriar proposed two periods of mineralisation for these two mineral assemblages at Wallaroo, based on formation temperatures of the two lode types, and also considered that the Wallaroo Lodes were emplaced before the Moonta Lodes, the reverse of that suggested by Jack (1917).

3.3.3. THE DIFFERENCES BETWEEN THE MOONTA AND WALLAROO-KADINA LODES

Apart from the dimensions, different strike directions and host rocks, the fundamental differences are two fold: The first is mineralogical, as shown by McBriar's research (Table 3.1), and the second is structural, based on Dickinson's concepts and this research.

This research indicates that the Moonta Mines are a mono-metallic deposit restricted to the Moonta Porphyry, and the Wallaroo-Kadina Mines are part of a possible larger poly-metallic deposit of copper, lead and zinc, comparable to the distribution of these elements in the Broken Hill Province. The Kadina main copper lodes relate to fractures, associated with stratabound copper in a particular sequence: Doora Schists, and may relate to a mineralogical zone of a richer lead-zinc deposit, not yet found, but highly prospective, based on geochemical and geophysical data. Other mineralogical differences are:

In the Moonta Lodes, the sulphur content of the source material is lower than in Wallaroo-Kadina, as the copper at Moonta formed a higher sulphide, bornite, chalcopyrite and minor pyrite, but with a high hematite content. At Wallaroo, pyrrhotite, pyrite and low grade chalcopyrite occurred in large quantities whilst hematite was absent. This increase in sulphur content at Wallaroo may be related to a different lithology of the host rock, such as a black shale environment. Jack (1917) advocated a pegmatitic origin and a common source for the vein filling, based on the same mineral assemblage but not on this sulphur difference.

The wall rock alteration is more extensive at Wallaroo than at Moonta,

TABLE 3.1.

GEOLOGICAL DIFFERENCES BETWEEN THE MOONTA AND WALLAROO-KADINA MINES.
(Based on Jack, 1917 and Johnson, 1965).

PARAMETER	MOONTA LODES	WALLAROO-KADINA LODES
ost rocks of lode	Restricted to the Moonta Porphyry	Metasediments(calc-silicates, mica schist and quartzite intruded by porphyry).
ode types	Pegmatites and quartz veins(located in multiple fractures and schistose bands within porphyry)	Replacements type deposits (fractures)
ineral suite of lodes McBriar, 1962)	Bornite-chalcopyrite-pyrite suite	Pyrrhotite-chalcopyrite-pyrite assemblage.
quivalent associations Johnson, 1965)	Bornite-hematite association.	pyrite-pyrrhotite association.
ODE MINERALS		
PRIMARY		
Major minerals	Bornite (associated with feldspathic portion of lode)	Chalcopyrite
Minor minerals	Chalcopyrite (associated with the quartz portion of lode).	Pyrite, pyrrhotite
Accessory minerals	Hematite, schorl, molybdenite, fluorite, zincblende, pyrite, chalcocite, tourmaline.	Galena, zincblende, ferberite, scheelite, molybdenite, smaltite, fluorite, rhodocrasite.
Extra trace elements present	Gold, silver and bismuth.	Gold, silver, bismuth, lead, zinc, tungste and traces of nickel and cobalt.
GANGUE MINERALS	Quartz, felspar(microcline), biotite.	Quartz, carbonates(calcite, dolomite) biotite, plagioclase.
Accessory gangue minerals	Apatite, titanite, pyroxene.	Pyroxene, apatite, amphibole, mizzonite, chlorite, muscovite and sericite.
Secondary processes present	Kaolinization, chloritisation, sericitization, albitization.	
RADIOACTIVE MINERALS PRESENT	Thucholite type in lodes.	Thucholite type in dump (country rocks).
ORE SHOOTS	Discontinuous	Continuous
WALL ROCK ALTERATION	Limited (a few inches wide on either side of lode). Pyroxene (contact metamorphism).	Extensive.
LODE DIMENSIONS		
Total length extent	2816 m.	1036m.
Length of individual lodes	304 to 914 m.	100 to 884 m.
Depth extent of lodes	695 m.	850 m.
Width of lodes	3 to 7·62m.	0.61 to 9 m.
Strike of lodes	30 degrees	90 to 120 degrees
Dip of lodes	40 to 65 degrees NW	75 degrees

and a pegmatite assemblage is absent, except for minor pegmatites. Jack considered that 'the Wallaroo Lodes were formed at a slightly later time, or, at a lower temperature, and/or more probably at a greater distance from the source,' in contradiction to McBriar (1962). The last stage of mineralisation was marked by the introduction of a carbonate gangue, e.g. calcite, dolomite and siderite; and was possibly contemporaneous with the introduction of the zinc-blende and galena.

3.4. GEOCHRONOLOGICAL DATA IN THE WALLAROO-MOONTA PROVINCE

The geochronological data is presented here to facilitate the correlation of the mineralisation with geology, compiled from various sources, (Figure 3.3). Recent Rb/Sr determinations were made by Webb (1972 and 1978b).

The earliest isotopic data is for the granitic gneiss and granite (augen gneisses) from Corny Point and West Cape in Yorke Peninsula, where an Rb/Sr age of 1810 Ma and a K/Ar age of 1406 Ma was given for the former area. The Rb/Sr total rock analysis for the granites of the Sir Joseph Banks Group, based on Spilsby Island core, produced an isochron of 1425 ± 60 Ma, and the line of maximum slope is 1580 Ma (Webb, 1978b), comparable with the Rb/Sr age of 1510 Ma for the Parara pegmatite, (Compston, et al., 1966).

The Wardang Island volcanics, continental porphyritic rhyodacites, which were compared lithologically with the Moonta Porphyry, have an Rb/Sr isochron of 1735 ± 42 Ma for an initial ratio of 0.70 ± 0.004, (Bone, 1978). This is older than previous ages for the Moonta Porphyry, (1511 ± 195 Ma) and agrees with values for the Hutchison Group (metasediments from Coffin Bay, 1773 ± 25 Ma and the Cook Gap Schist from Mangalo Creek, 1688 ± 76 Ma, Webb, et al, in press). The age of these acid volcanics corresponds to the major phase of metamorphism of the Hutchison Group (1688 ± 76 Ma) and with the McGregor Volcanics (previously named Moonabie Volcanics) of the Moonabie Range, (1615 ± 29 Ma). This data suggests that these volcanics or their equivalents may be present within the Doora Schists, and should not be correlated with the younger Moonta Porphyry.

K/Ar determinations of biotite and hornblende in schists from W.M.C. and N.B.H.'s DDH 1, 55, 78, 98, 124, 131 and 135; hornblende - scapolite rock from Doora Mine, and amphibolite and schist from Point Victoria, range between 1631 and 1430 Ma. The minimum age was obtained from the Doora Mine. The maximum age given for the calc-silicate rock from DDH 135 is 1631 Ma and the hornblende analyses from DDH 131 range between 1545 and 1523 Ma. Therefore, the minimum age of these metasediments is 1540 Ma, and presumably the metamorphism occurred before 1500 Ma, since biotites sampled from adamellites intruding the schists have minimum ages of 1490 to 1520 Ma (Webb, 1978b). The Moonta granite, from DDH 33 and 147 gave K/Ar ages from biotites between 1517 and 1477 Ma, and pegmatites from the Arthurton and Parara Mine, gave K/Ar ages on muscovite and biotite between 1459 to 1421 Ma.

Rb/Sr whole rock determinations for pegmatite core from DDH 23, 91, 100, 114, 118, 124 and 130 provided an isochron with a slope equivalent to 1400 ± 64 Ma (Webb, 1978b). This indicates a very comparable age for all these pegmatites, and is slightly earlier than Compston, et al's. estimate for the Parara pegmatite.

Rb/Sr analyses for the Tickera Granite, based on adamellites near Point Riley, adamellites and granites from DDH 33, 57 and 103, show an isochron age of 1282 ± 179 Ma for samples from DDH 33 only and 1223 ± 58 Ma for all samples, (Webb, 1978b).

The last metamorphic recrystallising event at 1220 Ma is restricted to this Province, based on a limited sample distribution. These later ages were considered by Webb (1972) to relate to the emplacement of the 'Moonta Porphyry', Tickera and Arthurton granites. Thomson (1973a) interpreted 'this event to reflect the intense feldspathisation and some recrystallisation.' Evidence from the Arthurton-type granite, showing variable chloritised biotite, and a comparable isochron age 1220 ± 27 Ma, suggests that this isochron probably corresponds to the regional hydrothermal mineralisation event, the scapolitization and metasomatic alteration, and the penecontemporaneous intrusion of the granite. The areal envelope of these 1200 Ma events shows a distinct zone centred over this Province, (Figure 3.3). However, more data points are required to verify this hypothesis.

3.5. RELATION OF BASE METAL MINERALISATION TO LITHOLOGY AND STRUCTURES

The major copper mineralisation can be divided into four main groups in relation to lithology. The first group, the Moonta Lodes are associated with pegmatites and are confined within the Moonta Porphyry to fracture zones. Local pegmatitic veins intruding the metasediments in the Kadina area contain some pyrite and minor chalcopyrite.

The second group, the Wallaroo Main Lode, Matta Mine, Devon and Doora Mines, all have a strong fracture control, are near and associated with the magnetite-rich Doora Schists. The biotite-hornblende-rich rocks, quartzite, porphyritic material of possible volcanic origin, and thin bands of dolomite within mica schists, may be important stratabound units influencing the mineralisation, which at Bingo occurred within an amphibole rock considered to be a metamorphosed limestone in metasediments (Dickinson, 1942b). At the Vulcan Prospect, the copper mineralisation is in a dolomite unit within the schists and quartzites. The presence of diorite in a belt containing the Wallaroo Main Lode, East Matta and Bingo Mines may not be a coincidence. The Wandilta Mine also contains diorite.

The third group, the Kurilla and Duryea Mines contain mainly schists and quartzite, associated with some porphyritic material and minor diorite. They have a similar fracture control to those in group two, but occur with non-magnetic metasediments. The tonnage extracted from these two is considerably less than that taken from the Wallaroo Main Lode and Matta Mine.

The fourth group of lower economic importance relates to the pyritic-rich bands and possible volcanics (pyroclastics) within the metasediments, associated with the Doora metasedimentary sequence. These bands are thin, contain up to 2% Cu, and appear to be stratiform and/or stratabound primary mineralisation, and were mapped using geochemical and I.P. methods.

Other important features are zones of alteration, namely zones of intense scapolitisation, feldspathisation, and sericitisation, combined with zones of brecciation. These may be important guides for the mineralisation outside the Kadina and Moonta areas.

Two geological models have been proposed for this area by the exploration companies and each model may be partially correct.

First, the Sedimentary Model (based on the W.M.C., 1965) represents a sedimentary-volcanic sequence, (using current terminology developed in this thesis) in which the lodes are associated with a lode 'horizon'. Figure 3.4 represents an overall fold model, based on the distribution of the major magnetite-rich units, electrical and geochemical anomalies. Two magnetic units are assumed, the Doora Schists and the Warburto Belt. The latter belt forms a closed fold with a NE-SW axial plane, surrounded by a continuous sigmoidal-shaped series of magnetic anomalies, which include the Moonta Porphyry and the West Weetulta Complex. The principal lodes are confined to the Kadina-Doora-Tiparra magnetic belt, which shows a distinct fold system, with an E-W axial direction.

The second is the Porphyry Copper Model, proposed by Lynch in 1974 (pers. comm.). Figure 3.5 shows the Moonta Porphyry as a large batholith. The Warburto and Doora Belts form a contact zone at the edge of the batholith, containing copper, lead and zinc mineralisation, implying a zonation.

Both models are good, interpretive and possible; but are too simple for this complex area. A new model proposed in this study is basically a combination of these models, reverting to Jack's original concept of a large batholithic body, (the Arthurton Granite) and more recently the Tickera Granite Complex, to the north. The sedimentary model is satisfactory for the Kadina (Wallaroo Mines) and the copper porphyry model may explain the Moonta Mines, with some reservations. The latter could be explained by a cauldron subsidence model, (Chapter 7). However, a better model may be the combined model representing two ages, the older sedimentary - volcanogenic model for

Wallaroo, and a Butte-Boulder Batholith model for the later Moonta mineralisation. The geophysical concepts for this model are discussed in other chapters.

3.6. URANIUM MINERALISATION IN THE PROVINCE

The uranium potential of this Province was assessed from 1945 to 1957. The main geophysical sampling was done by Fenner, and was summarised by Woodmansee (1957) and Dickinson *et al*, 1954. Since 1957 both Government and company exploration has been directed towards the copper potential. Using a gamma-ray spectrometer, the author investigated some gamma log anomalies associated with the Penang Mine, North Kadina drill holes and some company mineralised drill cores within the Moonta and Kadina Areas and recorded a distinct uranium response generally associated with K^{40}. The Th response was generally weak, except for a pegmatite near Alford, which had both a U and Th response, (J. Lynch, pers. comm.). A thick uranium ore intersection, identified by chance by the author, was initially ignored but was later assayed for uranium after the discovery of the Roxby Downs copper-uranium-gold deposit. Subsequently numerous cores have been resampled by J. Lynch and results summarised by Plimer (1980). The uranium potential was given a low priority due to environmental and political problems.

3.6.1. RADIOACTIVE MINERALS AT THE MOONTA AND WALLAROO MINES

The radioactive hydrocarbon, thucholite, was first observed as a minor constituent of the copper lodes at Moonta by Radcliff (1906), in his search for radium. It is related to hypogene-metasomatic alteration based on its mode of occurrence (Whittle, 1955). Radcliff tested concentrates from the Treuer's and Taylor's Shafts at Moonta, and found the black ore from Treuer's Shaft assayed 58.5% Cu with 4.74% U_2O_5, 16.4% S, and an undetermined 11% of C, H_2O, Zn and Pb. A chalcopyrite sample with minor lead and possibly carnotite in quartz contained 1.9% U_2O_5. The radioactive ore from Taylor's shaft had an S.G. of 1.55, contained 20% Cu, 10% fixed carbon, 13% hydrocarbon, 5% water and 17.8% insoluble residue, which contained some pitchblende. The radioactive hydrocarbon was thucholite, (S.G. 1.78).

The only other report of in situ uranium occurrences in the Moonta Mines, was by Mawson (1944) who inspected two different radioactive locations in 1907, as follows:

(i) "Treuer's Shaft, Moonta: where the uraniferous vein was in a cross-course, 2-6 inch wide, separated from the main copper lode, within felsitic quartz porphyry and schists. The uranium occurred as covellite, with quartz associated with minor thucholite. A yellow carnotite-like mineral encrustation was also present". Two different occurrences were reported within this shaft at different mine levels and in different cross-courses and appear from the text to cut the principal copper lode.
(ii) "Taylor's Shaft at Moonta: Thucholite with tiny yellow spots of a secondary uranium mineral", (not specified by Mawson, but probably either carnotite or autunite).

Mawson compared the occurrences with data from Canada and Scandinavia, but gave no other details.

3.6.2. SIGNIFICANCE OF THUCHOLITE

Ellsworth (1928) originally defined this radioactive hydrocarbon, by using the chemical symbols of the five main elements present in naming Th-U-C-H-O-lite for this urano-organic complex, although thorium was frequently absent or nearly so. Sulphur may be present in appreciable amounts, (noted by Ruzicka and Steacy, 1976, from Elliot Lake, Canada). Steacy and Kaiman (1978) stated that thucholite is frequently encountered in pegmatitic and vein-type uranium deposits. In pegmatite, thucholite locally pseudomorphs uraninite, and its uranium content and manner of association is variable, in different occurrences. In some thucholite occurrences, e.g. gold veins at the Box Mine in the Beaverlodge area, Saskatchewan and at Madoc, Ontario, the uranium was traced to finely divided grains of uraninite, whereas in others, e.g. thucholitic partings in Ordovician sandy dolomite near Ottawa, Ontario, (Steacy et al., 1973) the uranium is present in the urano-organic complex. Thorium present, is associated the uraninite and thorianite, (Steacy and Kaiman, 1978).

The occurrences of thucholite are summarised by Nininger (1954) who states:

"It is usually found embedded in feldspar, quartz, or mica, where it may replace uraninite and has been identified in pegmatites at Parry Sound, Ontario, and at Buckingham, Quebec. Thucholite also occurs in an unusual manner at the Black King and White Spar properties near Placerville, Colorado, in vein-type deposits associated with copper, lead, and zinc sulphides.

It is probable that thucholite is associated with a variety of occurrences of uranium minerals that contain hydrocarbons, particularly the carnotite-asphaltite deposits at Temple Mountain, Utah; the pitchblende deposits at Lake Athabaska, Saskatchewan, Canada; and the uraninite-bearing Witwatersrand gold ores in South Africa".

Thucholite is possibly a mixture of hydrocarbon and uraninite containing 2-8% U_3O_8. It has possibly been found in the alum shale beds of southern Sweden, a black hydrocarbon called Kolm, resembling thucholite and contains 0.5% U_3O_8, (Nininger, 1954).

The low percentage of uranium recovered from the gold production from the Witwatersrand and Orange Free State Gold ores, South Africa, is uraninite with minor thucholite associated with gold grains in relatively thin but very extensive conglomerate beds (Nininger, 1954). The pebbles in the ore-bearing conglomerates are composed mainly of vein quartz, with basement rock types. The most abundant constituent of the matrix is quartz, which occurs with sericite, pyrophyllite and minor chlorite, chloritoid and tourmaline. The main sulphide is pyrite, but pyrrhotite, arsenopyrite, galena, chalcopyrite, sphalerite, marcasite, cobaltite and linnaeite, may be present, (Von Backstrom, 1976). The conglomerates are reworked older basement, and this type of occurrence is classified as pyritic-quartz-pebble conglomerates, or (stratiform sandstone - conglomerate deposits).

The origin of thucholite is not yet fully resolved, but it is generally believed to form either by polymerization of fluid hydrocarbons exposed to radioactive emanations, or, by precipitation of urano-organic complexes, (Steacy and Kaiman, 1978). A botanical origin was proposed for its presence in the Witwatersrand deposits, (Hallbauer, 1975) and an organic origin was postulated for thucholite in ore from Elliot Lake, Canada, (Ruzicha and Steacy, 1976). 'Its presence should always be suspected in permeable radiometric horizons of sedimentary formations', (Steacy and Kaiman, 1978).

This discussion shows that the presence of thucholite in a mineralised zone should be considered with caution in any classification of uranium mineralisation or comparison of the Wallaroo-Moonta uranium mineralisation with other occurrences, without additional geological data.

3.6.3 URANIUM EXPLORATION IN THIS PROVINCE (PERIOD 1945 to 1957)

From 1945 to 1957 as part of an Australian uranium exploration programme the S.A.D.M. assessed the uranium potential of South Australia. Previous mining in South Australia was at Radium Hill, 1906-1931, and Mount Painter, where primary radium was produced for medical purposes, 1923-1937 and uranium, 1944-1945. Radium Hill was re-opened in 1954. Crockers Wells Uranium Deposits were found in 1952-1953, and the Mount Victoria Uranium Deposit in 1954. Exploration was continued at Mt Painter between 1945-1955. Other areas investigated were the Barossa Complex, Houghton Inlier; the Wallaroo-Moonta district; and numerous minor uranium prospects in the Port Lincoln region and Cleve Uplands of the Gawler Craton.

Uranium exploration in the Wallaroo-Moonta Province commenced with radiometric tests on samples (Fenner, 1948d) discussed in Chapter 4. Tests on 82 samples showed that 76 samples were less than the mean value of 187 ± 95 cpm, for a background level of 168 cpm. This standard deviation value of 95 cpm, probably coincides with the error or reproducibility of these older instruments taken over a 5 minute period, and the radioactive samples showed differences in repeated readings of this order. 31 of these samples which were above the background value, are discussed in relation to the particular mining area. The major radiometric responses were as follows:

MOONTA MINES	cpm	WALLAROO MINES	cpm
Radioactive ore (thucholite)	811-870	Pyrite	200
Chalcopyrite 'peacock ore'	370-417	Fluorite	344-547
Bornite plus chalcopyrite	302-328	Smaltite	197
		Sphalerite	322-342

The ores between the background level and mean sample values from the Moonta Mines area are quartz and vein material with chalcopyrite, associated with hornblende in country rocks; and with atacamite, hematite and molybdenite. The latter minerals are probably within the magnetite-hematite halo (Chapter 7) associated with the lodes or within the Moonta Porphyry itself.

In the Wallaroo Mines, samples within the same radiometric range are associated with the low grade ores with preference to scheelite, pyrite, smaltite, tourmaline and apatite. The remaining data is based on one sample only: chalcopyrite, covellite, chalcopyrite and atacamite, cuprite with native copper, chalcopyrite with pyrrhotite, hematite, quartz, calcite and some country rock. In this mine most copper minerals showed no radioactivity, indicating no distinct Cu-U association, whereas, all the Moonta samples had greater than background radiometric values.

Further sampling was taken in situ near the shafts and dumps (Fenner 1948d), on the slime, mullock and slag dumps, by Schleiss in 1948; who identified thucolite, torbernite and uraninite (Woodmansee, 1957). This was followed by numerous total count radiometric surveys. A problem is that no radiometric data within the old workings was recorded, except for Mawson (1944), as these mines were flooded after mining, and no core over the mineralised zone was preserved.

The radioactive minerals were investigated by Whittle, Stillwell and Edwards, (Dickinson, <u>et al</u>, 1954); and later by Whittle, (1955). Other details from northern Yorke Peninsula were summarised by Woodmansee (1957) and Hiern (1959) for the Dead Horse Bay Uranium Deposit, Hillside and Hart's Copper Mines. Dickinson, <u>et al</u>, (1954) reported pitchblende, uraninite, thucholite, autunite (derived from thucholite), and torbernite in the Moonta Mines. Davidite has not been observed in the Province.

3.6.4. DISCUSSION ON A POSSIBLE COPPER-URANIUM ASSOCIATED IN PROVINCE BASED ON DATA TO 1957

A summary of the uranium and thorium occurrences, (Table 3.2) shows the limited amount of information. Woodmansee (1957) reported 'narrow zones of radioactivity, possibly caused by pitchblende' in North Kadina DDH3 and 6,

TABLE 3.2

PRINCIPAL URANIUM MINERALS IN WALLAROO-MOONTA PROVINCE

DEPOSIT	URANIUM MINERALS	THORIUM MINERALS	TYPE OF MINERALS	ASSOCIATED MINERALS	ASSOCIATED BASE METALS	COUNTRY ROCKS	REFERENCES
MOONTA MINES							
Treuer's Shaft	covellite thucholite carnotite	-	secondary & primary	quartz		feldspar quartz porphyry & schist	Mawson, 1944
Taylor's Shaft	thucholite covellite or autunite	-	primary & secondary	-		feldspar quartz porphyry & schist	Mawson, 1944
MOONTA MINES (generally)	uraninite associated with thucholite	-	primary		chalcopyrite, covellite and chalcocite		
	pitchblende (Whittle) torbernite metatorbernite gummerite beta-uranolite		primary secondary) secondary) secondary) secondary)	after uraninite			Woodmansee, 1957
	autunite meta autunite torbernite* metatorbernite	-))))	secondary				Whittle in Dickinson et al., 1954
	*Torbernite, found at Hancock Shaft, Hancock Lode, Moonta (Woodmansee, 1957)						
WALLAROO MINES	autunite meta autunite torbernite metatorbernite	-))))	secondary				Whittle in Dickinson et al., 1954
Dead Horse Bay Uranium Deposit	-	thorium) brannerite) absite)	primary	Fe minerals zircon, tourm- aline, rutile (minor)		metamorphic rocks intruded by granite and kaolinised aplite (brecciated)	Hiern, 1957
					orthoclase-microcline-albite-quartz-sericite -muscovite (chloritised) rock (host rock granite or pegmatite)		
Hillside Copper Mine	pitchblende torbernite	-	primary secondary	associated with calcite & repl- aces sulphide esp. covellite	pyrite, chal- copyrite bornite (ex- solved), cov- ellite	siliceous & argill- aceous rock	Hiern, 1957 Woodmansee, 1957
Hart's Copper Mine	*[1]	-	-	ferruginous rocks	possible Cu-U assoc- iation	porphyritic rocks	Hiern, 1957
	*[1] Radioactivity 175cps and in shaft 25 to 30 cps - background less than 25 cps						
Penang Copper Mine	torbernite very radioactive dump				possible U-Cu association	pegmatite (plus mica), granite & hematite	Woodmansee, 1957
Parara Copper Mine	*[2] No data *[2] No radioactive response				copper		Hiern, 1957
Parara Pegmatite	No data						

discussed later. He stated

'radiometric investigations of the mine dumps in the Moonta-Kadina copper mining district and of 17 other known copper prospects on northern Yorke Peninsula revealed .... anomalous radioactivity associated with much of the copper mineralisation throughout the region. Although this radioactivity is largely weak and in general lacks concentration to suggest ore grade uranium mineralisation, surface indications at three widely separated copper workings justify subsurface exploration;' and from surface radiometric studies, the response over 'the Kadina area is similar to those over the Moonta Mines, but the overall intensity ... is apparently weaker'. The anomalous radioactivity in the Moonta Mines 'is not necessarily related to the copper mineralisation, but seems to be largely a "mass effect" characteristic of the "Moonta porphyry", the host rock for copper mineralisation, with local concentrations of uranium minerals probably along favourable structures'.

Woodmansee reporting on Whittle's petrology considered the U-Cu assemblage was relatively constant. The primary uranium oxides were uraninite, pitchblende and their alteration products. In the Moonta Mines, the uraninite in the copper sulphide ores is associated with thucholite as inclusions within it, surrounded by chalcopyrite, covellite and chalcocite, and within the limonitic copper gossan, with malachite colouring. The secondary uranium minerals are torbernite, metatorbernite, gummite and beta-uranotil, after the uraninite. At the Hillside Copper Mine, the pitchblende in the copper ores is associated with calcite, and replaces the copper sulphide minerals, especially covellite. The primary sulphides are pyrite, chalcopyrite, exsolved bornite and covellite, with quartz and calcite gangue.

He considered based on the ore-grade uranium distribution that

'the uranium minerals occur in concentrations in places along the copper lodes, but no information is available regarding the degree of concentration or the mode of occurrence of these uranium minerals in relation to the copper minerals in the lodes', ... and 'may occur thinly distributed throughout a lode system or ... be confined to a particular zone in the system'. He concluded 'there is no evidence to support the possibility that uranium minerals occur in mineable quantities in any part of the region,' but recommended diamond drilling at Hillside Copper Mine, Hancock Shaft and Penang Copper Mine, with the objective 'to obtain information on the occurrence of uranium minerals in place in the copper lodes'.

A hole sited to intersect 12 m beneath the Hillside Copper Mine was drilled to 80 m in 1955. No lode or copper sulphides were encountered, and the radiometric log showed no anomalous zones, and no intensity changes at lithological boundaries (Min. Rev. 103 p. 34). The marble and amphibolitic marbles in places were calcite-veined, brecciated and contained hematite staining. The other holes were not drilled.

This radiometric exploration phase up to 1957, did not delineate any economic uranium mineralisation, nor establish the proposed copper-uranium association, which would have helped in the search for copper mineralisation. However, numerous proposed origins were advocated by some geologists, or indirectly through possible copper conceptual models.

3.6.5. PREVIOUS IDEAS ON THE ORIGIN OF THE MOONTA URANIUM MINERALSATION

As stated previously the occurrence of thucholite cannot be used to classify the type of uranium mineralisation or evaluate its origin. McMillian (1980) in his clasification of important Canadian uranium deposits placed carbon in two genetic types of deposits, Detrital placer, (pyritic quartz pebble conglomerate types) and Hydrogenic, syngenetic and epigenetic or the two combined, (unconformity vein type). The one comparable with the Province is the epigenetic-classical vein type. He gave examples of Beaverlodge, Saskatchewan; Port Radium, Northwest Territories and Schwartzwalder, Colorado.

Jack (1917) considered the Moonta copper and radioactive mineralisation were of hydrothermal origin, with the copper ± uranium being within the schorlaceous pegmatite vein-type deposit. Woodmansee (1957) considered the uranium was not associated with the copper.' Dickinson, et al., (1954) considered the pitchblende-uraninite - thucholite assemblage to be of either hypogene or metasomatic origin. Crawford (1965) considered the granitic intrusions associated with feldspathisation and metasomatisum were the source of the uranium.

Previous discussions on the origin of the uranium mineralisation were related to the Moonta Mines, and are still based on Jack's original concept of a copper-uranium-tourmaline pegmatite. The principal minerals are uraninite-pitchblende-thucholite-cyrtolite in pegmatite assemblage, possibly associated with copper mineralisation (bornite-chalcopyrite-pyrite - pyrrhotite with minor magnetite, specularite, etc. based on McBriar, 1962).

3.6.6 URANIUM ASSOCIATED WITH PEGMATITES IN THE PROVINCE

The widespread occurrences of granite, aplites, pegmatites, and the local areas of varying intensity of granite-pegmatite-aplite intrusions with feldspathisation associated with metasomatism (Crawford, 1965), were considered as a possible uranium source. Jack (1917) states'

'torbernite and autunite have been reported as occurring in pegmatite dykes in South Australia, so that its presence in the lodes of Moonta cannot be regarded as abnormal'.

Mawson (1944) referred to radioactivity in 'veinstuff', and in narrow cross-course, associated with smokey quartz (thucholite-covellite-quartz with possible carnotite). Fenner (1948 b, e), considered 'the radioactivity .... is associated with the lode minerals other than the copper.'

The author's appraisal of the 1954 to 1961 petrological data on pegmatites and granite-aplites showed the pegmatites have two mineral assemblages.

(i) orthoclase-quartz ± albite ± microcline ± opaques.

(ii) quartz-feldspar (microcline-albite-perthite) - muscovite - tourmaline ± biotite ± apatite.

The Parara Pegmatite has the latter composition, but no reported radioactive minerals. In the Parara Copper Mine, the pyrite post-dates the tourmaline, and where the tourmaline pegmatite has intruded the country rocks, tourmaline and muscovite were introduced. The source of this pegmatite was considered by Whittle in 1959 to be derived from an adamellite or granodiorite.

The pegmatised zone in DDH JJ1/2 shows minor mineralisation but no distinct increase in radioactivity, and a similar geophysical response (gamma log) was found associated with a pegmatite containing pyrite and chalcopyrite in DDH CC 1.

Whittle in 1955 identified zircon associated with cyrtolite as an accessory mineral in granite-aplite (P367/54). A similar rock type containing 0.005% U_3O_8 derived from cyrtolite was found in bore hole samples in Section

6, Hd. Warrenben. The following minerals were present in all samples: feldspar, quartz, iron oxide, zircon, cyrtolite and rutile; with biotite carbonates and amphiboles occurring in 80% and apatite in 60% of the samples. Although limited in number and distribution, this data shows that the assumption that the widespread distribution of the pegmatites and aplitic dykes in both the metasediments and intrusions could provide the uranium mineralisation, (Woodmansee, 1957), is not a valid generalisation, as the purpose was only to identify the uranium minerals.

The radiometric (total count) gamma logs from Balgowan holes show that in DDH 1, the response is associated with pink gneissic granite (a medium-grained quartz-orthoclase granite) and sometimes with pegmatised gneiss. The pegmatites are generally not radioactive. A radioactive response is associated with a concentration of magnetite at 112.8 m, and elsewhere is associated with chlorite-pyrite veins. In DDH 2, between 103 and 121.5 m, is a radioactive zone, correlating with an orthoclase-quartz granite with some pegmatitic zones, which contain 5% pyrite. This indicates a possible uranium association with magnetite and pyrite in a particular gneissic granite, which may be a favourable horizon within the metamorphic sequence. No uranium assays are available.

The data indicates a possible uranium pegmatite association, and a uranium granite association. Local residents from near Alford, reported to the author an undocumented ground follow-up survey within their properties over numerous quartz-rich pegmatites by the B.M.R. in 1952. Investigations by N.B.H. over these pegmatites, showed a radiometric uranium and thorium response, (J. Lynch, pers. comm.).

Petrological data during this research indicates granites, which based on their mineral assemblages could be classed as alaskites, are present in this Province. This granite rock type is known to be associated with uranium in the Broken Hill Province, eg. Mundi Mundi Granite (Rayner, 1958, 1960) and with Rossing Deposit, Namibia, (Von Backstrom, 1970 and Martin, 1978). An appraisal of the petrological data and further studies of the granites in the Wallaroo-Moonta Province are warranted to test this hypothesis.

3.6.7. URANIUM MINERALISATION IN THE WALLAROO MINES AND WITHIN METASEDIMENTS

Past discussions on the uranium mineralisation were related to the Moonta Mines, and little importance has been given to the Wallaroo Lodes, the Doora Schists or other metamorphic rocks.

McBriar (1962) reported monazite crystals, associated with chalcopyrite, molybdenite and quartz in a dolomite gangue in the Wallaroo Main Lode. Also country rocks in the Wallaroo area show allanite and haloes within micas and amphiboles, giving evidence for radioactivity. The uranium mineralisation in the Wallaroo Mines has two assemblages, a monazite-allanite-chalcopyrite-molybdenite-quartz in a dolomite gangue, and a uraninite-sulphide association. The main sulphide is pyrite with minor chalcopyrite. The relationship between these two associations is unknown.

Plimer (1980) stated that minor uranium, possibly uraninite and secondary minerals were found at Doora Mine, and the West Doora-Martins prospect (DDH 19 and 198) showed minor uranium associated with copper, with minor traces of apatite, fluorite, Fe-Ti, Co and Ni minerals. He stated the uranium occurrence at West Doora and in the Wallaroo Main Lode, might have a close resemblance to the massive sulphide deposit at the Phillips Mine, Westchester County, New York, (Grauch, 1978) where the uraninite occurs locally around the Proterozoic Phillips deposit.

In the North Kadina Areas, Whitehead (1973a) found allanite in North Kadina DDH 5 at 95.4 m, (P847/72) in magnetite-bearing hornfels metasediments, having a mineral assemblage of oligoclase-potash feldspar-magnetite with minor quartz, biotite, chlorite, sphene and rutile, and traces of carbonate, apatite, tourmaline and zircon. Migrating solutions containing molybdenite, magnetite and tourmaline, with minor pyrite, chalcopyrite and allanite were evident. The magnetite contains about 50% titanium oxide. In other holes Whitehead (1973a) and Whittle for N.B.H. confirmed the molybdenite-magnetite-tourmaline with minor pyrite-chalcopyrite-allanite assemblage possibly associated with feldspathisation and granite intrusions. Lynch reported that Mo-Cu assemblage associated with magnetite, and a quartz-orthoclase-minor tourmaline assemblage with a possible uranium association (uraninite) was accompanied by feldspathisation. Local allanitic and/or chloritic zones were slightly radioactive, which Lynch (pers. comm.) suggested were due to uraninite.

In the Alford and Alford West uranium-molybdenum-copper prospects, (Chapters 10, 16 and 17), some uranium mineralisation is restricted to the water table, (Plimer, 1980). The U-Mo mineralisation is associated with a major fracture zone, and has a possible areal extent of 10 km by 1 km, south and including the North Kadina Areas, (Chapters 10 and 16). The nearby diorite and granite plutons, interpreted from petrological data, J. Lynch's company reports, and this geophysical study, were interpreted by Plimer, (op. cit) to have provided the hydrothermal mechanism for the redistribution of the uranium within the metasediments and metavolcanics, and reprecipitated the uranium at a suitable redox barrier, such as the magmatic-meteroic/connate fluid interface, or, in the carbonaceous thermal metamorphic carbonate rocks at Alford, i.e. the uraninite zones is in a thermal metamorphic aureole.

3.7. COMPARISON OF THE WALLAROO-MOONTA URANIUM MINERALISATION WITH OTHER AREAS IN SOUTH AUSTRALIA AND NEW SOUTH WALES.

Outside the Wallaroo-Moonta Province, uranium in South Australia occurs in minor quantities in the Gawler Orogenic Domain, in Eyre Peninsula and in the Barossa Complex (Houghton Inlier) within the Adelaide Fold Belt, and at Roxby Downs in the Stuart Shelf. Major deposits are at Mount Painter; Radium Hill, Crockers Well, Mount Victoria in the Olary Subdomain and in the Broken Hill Subdomain, both within the Willyama Orogenic Domain. The Tertiary sedimentary uranium deposits of the Lake Frome area are not discussed.

The following domains are compared with this Province.

3.7.1. GAWLER OROGENIC DOMAIN

Numerous minor uranium prospects occur in the Lincoln Complex of Eyre Peninsula. In the Port Lincoln region, the Hospital, Lomax, Hargistrom and Ainslee prospects contain pitchblende with secondary minerals, uranophane and gummite, in hornblende granitoid gneiss in narrow shear zones within metasediments and amphibolite, (King and Woodmansee, 1956). Some disseminated uraninite is present in the Ainslee South Prospect, (Johns, 1961). The pitchblende and uraninite, the pyrite-chalcopyrite-magnetite association, brecciation, and fracture control compares with those in the Wallaroo-Moonta Province. Major differences are the host rock and age of the hornblende granitoid gneiss (1810 Ma.), within the Cape Donnington Granite Suite (R. Flint, pers. comm.), and the sodic metasomatism (King and Woodmansee, 1956). In the Wallaroo-Moonta Province, potassium metasomatism is dominant but sodic metasomatism is minor.

The minor uranium occurrences in the Cleve Uplands Area have a uranium - thorium - copper ± silver association, in quartz pegmatites within mica schists and slates, (Dickinson, et al, 1954). In the Calcookra Copper Mine, 0.7% U_3O_8 was found in copper samples, and assays values showed 0.2%V; 0.7%U and 0.12% Th, (Moulton, 1969). Elsewhere uranium is in brecciated fault zones, enriched with manganese and iron, and is associated with either pyritic-graphite units or dolomite, or gneissic metasediment. In 1967, Ellsworth noted the similarity between these uranium occurrences to those at Rum Jungle, N.T., where the deposits occur in an Early Proterozoic sedimentary and volcanic rocks in association with dolomite and black shale, (Moulton, 1969). Uranium exploration in the Gawler Orogenic Domain is currently using the Archean-Early Proterozoic conglomerate - unconformity conceptual model combined with the uranium vein-type fracture control deposit, as developed in the Pine Creek Geosyncline. This concept is being applied to the posible Early-Middle Proterozoic unconformity in the Wallaroo-Moonta Province.

The individual minor uranium deposits have structural, mineralogical and lithological similarities, and based on geophysical interpretations are controlled by E-W fractures and retrograde zones.

3.7.2. STUART SHELF REGION

The regional distribution of base metals and geology of the Early-Middle Proterozoic rocks of the basement underlying the Stuart Shelf is relatively unknown, as this area is concealed by thick relatively unmineralised Adelaidean sediments. This area contains the Olympic Dam copper-uranium-gold deposit, discovered by W.M.C. in 1975. The regional setting of this deposit, the Roxby Province is geophysically similar to the Wallaroo-Moonta Province having a comparable aeromagnetic pattern, but the Roxby Province is at a deeper depth. An interpretation of the gravity data in both areas indicates large granite batholiths surrounded by numerous basic bodies (high density with moderate magnetic susceptibility), and numerous circular structures interpreted as either calderas or granite plutons. Interpreted seismic sections show steep dips, comparable with the slopes of stratavolcanic centres. Geophysical computer modellings, using aeromagnetic and gravity data indicates that volcanic cone models, in some cases with overlying calderas, give good curve matchs. Detailed 2 dimensional modelling of ground geophysical data, (by C. Anderson and the author, unpublished), controlled by published W.M.C. drill hole data showed a saucer-shaped hematite copper-uranium ore zone, with a 1 to 2.5 km thick section, confined on either side by vertical faults in granite, with a deep seated magnetic source below, (an andesite core zone of a stratovolcano). This compares with the cauldron subsidence model for the Moonta Porphyry (Chapter 7) but the hematite mineralised zone is missing. Subsequent geological data shows in 3 dimensions a possible graben, filled with at least a 1 km section, trending NW with a strike length of 6 km and width of 0.7 km, (Roberts and Hudson, 1982). The sides are granite, but the basement to the Olympic Dam Graben and the deep seated magnetic source beneath are unknown. These two concentual models, the Olympic Dam Graben (cauldron) and the Moonta Caldera are part of the same concept, but at different levels of a possible stratovolcano-caldera model, being separated vertically by 2-3 km. The Moonta model is beneath. There is little porphyritic material intruded into the Olympic Dam breccias except for altered veins of questionable material (B. Dalgarno pers. comm.).

In the Olympic Dam Deposit there are two phases of copper mineralisation, (Roberts and Hudson, 1982). The older phase is stratabound, within hematite breccia, has a bornite (chalcocite) - chalcopyrite-pyrite assemblage with uranium, rare earth elements and hematite. The gangue minerals are hematite, quartz, sericite and fluorite. The sulphides show a vertical zonation, but an indistinct lateral zonation. The Moonta Porphyry shows hematite and local breccia zones containing copper mineralisation, (J. Lynch, pes. comm.), but its uranium content is unknown.

The second copper phase is transgressive, consists of chalcocite-bornite with minor hematite and fluorite in veins parallel to the long axis of the graben, interpreted as epigenetic in origin, (Robert and Hudson, 1982). These veins have alteration haloes, sericite-quartz or chlorite. There is a lateral change along strike of the lodes. "Hematite-chalcocite-bornite veins in the main linear zone appear to grade laterally into hematite-chalcopyrite veins away from the main zone", (Roberts and Hudson, 1982). Minor gold and silver are present. This copper mineralisation, the alteration zones and the overall lode dimensions, are similar to the Moonta mineralisation, but in Olympic Dam the individual lodes are smaller and discontinuous (B. Dalgarno, pers. comm.), and the uranium is associated with bornite.

The uranium mineralisation is a pitchblende-uraninite-coffinite-brannerite assemblage, associated with sulphides, sericite, hematite, fluorite with minor chlorite, and the rare earths are associated with stratabound copper mineralisation. This could not be observed at Moonta, based on the two level hypothesis.

This discussion, based on geophysical data, mineralogy (Roberts and Hudson, 1982) and the Moonta mineralogy (McBriar, 1962), has provided a conceptual comparison. It may explain the problems of identifying the source of the radioactivity at Moonta in the 1950's, as two uranium-rich models, one stratabound (flat lying) on the 'upper' surface of porphyry, but now only remnants, cf. mass effect of the porphyry itself, (Woodmansee, 1957) and the observation of Mawson (1944) of the sporadic responses in the lodes, eg. the bornite-uranium association. The bornite is sparse outside the main lodes, which were mined out at the time of his observations.

The major uranium prospect in the Province, (Alford-Alford West, uranium-molybdenum ± copper) is associated with an E-W fracture zone, has interpreted dimensions similar to the Olympic Dam Graben, contains small isolated hematite breccia plugs(?) and has a near surface chalcocite blanket in a geochemical anomalous argillised zone to the west, (Lynch, 1974). This belt has some similarities, but requires more data.

3.7.3. MOUNT PAINTER BLOCK

The principal uranium deposits are just above the unconformity between the Radium Ridge Beds and the Mount Painter Complex, and within the Radium Ridge Beds. They are associated with NE and NW fractures. The Mount Painter Complex (1900-1480 Ma), composed of granite, schists, gneisses and quartzites, contains monazite-bearing schists and gneiss with traces of allanite and brannerite, (Youles, 1975). This age range is comparable to the Doora Schists in the Wallaroo-Moonta Province. These deposits arranged stratigraphically above the unconformity are:

NAME OF DEPOSIT	URANIUM ASSEMBLAGE	LITHOLOGICAL UNIT (HOST ROCK) RADIUM RIDGE BEDS
Hodgkinson	uraninite-pyrite-silica	arkosic and brecciated granitic rocks.
Radium Ridge, Armchair and Streitburg	uraninite-chlorite-hematite	breccia layer with a conglomerate sequence.
Mt. Gee	uraninite-hematite	basal hematite breccia layer of unit.
	UNCONFORMITY	

The Alford-Alford West prospects are probably located within the lower two horizons of this sequence, and the unconformity is interpreted to be at depth.

These deposits are possibly the conglomerate-sandstone type at an unconformity, associated with NE, NW, N-S and E-W fractures. They are comparable with the Pine Creek Geosyncline uranium occurrences. A hydrothermal origin is possible for some mineralisation as there is a possible association with Early Ordovician pegmatites, which contain fergusonite, brannerite, allanite, and monazite. Although no uraninite or pitchblende has been identified in these pegmatites, it is present in the hematite breccias. Radiogenic lead data on samarskite from the Radium Ridge Deposit was dated at 400 ± 50 Ma, (Kleeman, 1946) indicating some uranium within the breccias are of Early Palaeozoic age, (Coats and Blissett, 1971 and Lambert et al., 1982), and some have Tertiary ages. This age range within a uranium province is as expected by the rejuvenation and redistribution of the uranium, (Adamek and Wilson, 1979 and Dahlkamp, 1980).

Nearby are minor copper mines, with a uranium-copper assemblage, but the major copper mines are within the overlying Adelaidean sediments.

Although the mineral assemblage is unknown at the Alford prospects in the Wallaroo-Moonta Province, (Chapter 10), both contain trace elements of Cu, Mo and Mn, and minor magnetite. The main exception is the cerium group. Both are associated with major fractures and contain hematite breccia zones. Some are interpreted as plugs, possibly comparable with the inverted cone of breccia at Hodgkinson Prospect, which contains a similar alteration zone. Both are near granite batholiths and thermal metamorphism zones. Considerably more hematitic breccia zones within granitic rocks are present in drill holes in this Province than originally described.

The unconformity concept could be applied to the unconformity between the Devon Group and the Wilkamulka metasediments, (Chapters 9, 15 and 16) and numerous conglomerate zones are present in drill cores in this Province within the Devon Group. No gamma logs are available.

3.7.4. THE WILLYAMA OROGENIC DOMAIN

This section compares the uranium mineralisation in both the Olary and Broken Hill Subdomains, and the distribution of the uranium and base metals, which have a similarity to the Wallaroo-Moonta Province. The uranium mineralisation is inter-related and possibly has a common origin in the evaluation of these polymetallogenic provinces.

3.7.4.1. Olary Subdomain

In the Olary Block, the uranium mineralisation and associated rare earth mineral deposits are primarily hypogene deposits, associated with granite and granitoids, as pegmatites or aplites, with minor stock work-type deposits of pneumatolytic and hydrothermal deposits, (Campana and King, 1958). There are three main types of uranium mineralisation, which have similar radiometric uranium/lead ages, representing the primary Middle Proterozoic epigenetic event, with a later remobilisation and redistribution event in Early Cambrian times: (i) pegmatites and aplites, (ii) the Crockers Well type and (iii) the Radium Hill and Mount Victoria type.

(i) Pegmatites

These fall into two groups, similar to the Wallaroo-Moonta Province.

(a) equigranular feldspar-quartz ± magnetite ± rutile related to granites and migmatites, with discontinuous and gradual boundaries with the granitoids.

(b) discordant pegmatite swarms, younger in age than the former. These are zoned, and contain the complex uranium and rare earth minerals. They occur either in non-zoned areas of the pegmatite vein, or, are marginal to the central quartz core of massive zoned pegmatites. The Crockers Well Uranium Deposits fall into this group.

The Crockers Well Deposit Type

This type contains uranium-thorium mineralisation (absite and absite - davidite deposits) associated with rare earth minerals, within granite. The lodes are fracture-controlled, associated with sodic metasomatism (albitisation), with abundant beryl, tantalite, columbite, and rare phosphates, (Campana and King, 1958). This mineral assemblage is not known in the Wallaroo-Moonta Province.

The Radium Hill and Mount Victoria Deposit Type

These are uranium hydrothermal deposits with minor associated copper within paragneiss and amphibolites. The lodes occupy steeply dipping shear zones. The main mineralisation is davidite and iron-titanium minerals with a magnetite - pyrite halo, containing no davidite or biotite. The chalcopyrite - bornite - covellite - pyrrhotite is associated with the davidite and with the magnetite-pyrite vein. Molybdenite is rare.

The main similarities with Wallaroo-Moonta is the epigenetic age, two pegmatite types, the copper-uranium association, shear zones, the magnetite-pyrite halo and copper assemblage. The main differences is the lack of davidite in the Wallaroo-Moonta Province.

3.7.4.2. Broken Hill Subdomain

In the Broken Hill area, numerous radioactive occurrences were discovered in the 1950's, and several deposits were mined for other minerals with minor uranium (Barnes and Stevens, 1974). Traces of uraninite and hydrocarbon are present in parts of the Broken Hill Lode, (Rayner, 1960) and at Great Western Mine (Broken Hill-type deposit), where 0.05% U_3O_8 was found associated with galena. In the Thackaringa Ag-Pb lode type, the Hen-And-Chickens deposit, within leucocratic granite gneiss, contained minor uranium in secondary lode material.

The major uranium deposits occur in the Thackaringa Davidite Belt, and the Mundi Mundi, Brinkworth Well and Eldee prospects in the Mount Robe and Mundi Mundi-Mount Franks Areas. They are near and east of Mundi Mundi Fault, within the metamorphic facies Zone A of Binns (1964), and are associated with extensive zones of potash feldspathisation and pegmatisation, possibly related to the Mundi Mundi Granite rock type. The Great Western and Copper Blow Mines, which contain minor uranium, are in Binns' Metamorphic Zones B & C, of higher metamorphic grades.

The Thackaringa Davidite Belt (Rayner, 1958) contains primary davidite, and brannerite, is approximately 1.5 km wide and 9.7 km long, contains three Prospects and forms an arcuate zone, north of the Thackaringa - Pinnacle Shear Zone. The davidite occurs within pegmatites, and later uranium mineralisation is within shear zones in aplite and granite. These have been compared with the Radium Hill lode, (Rayner, 1958, 1960). This belt is comparable in size, with the possible extent of the Alford uranium zone, which is also associated with a major tectonic zone.

The Mundi Mundi, Brinkworth, Eldee No. 1 and 2, and Mount Franks No. 1 and 2 prospects, contain predominantly secondary autunite associated with limonite within schists, with pegmatites and the Mundi Mundi Granite-type (alaskite), and with shear zones. The Mundi Mundi Granite, a leucocratic, muscovite-microcline granite, (alaskite) contains tourmaline, apatite, zircon and sometimes, sericite and biotite, (Rayner, 1960).

Other radioactive minerals occur in pegmatite, aplitic granite, quartz veins and sheared gneiss. Some autunite, (associated with iron oxides) occurs in retrograde schist zones in areas containing alaskites.

A U-Fe association 0.1 to 0.3% U_3O_8 occurs in ironstone in the Warren Open Cut. A similar association was reported by Karkhanavala (1958) in uranium-bearing iron oxides from the Singhbhum Shear Zone of Bihar, India, which contains rich deposits of copper sulphides, apatite - magnetite and uraniferous mineral veins. The secondary minerals are associated with hematite. This is a possible explanation of the Copper Blow U-Fe prospect in the Broken Hill Province, and is equally applicable to the Wallaroo-Moonta Province.

Multichannel radiometric data studied by Khan (1978) over the Mundi Mundi Granite showed distinct U, Th and K^{40} anomalies, with a distinct K^{40}, and minor U anomaly pattern, but when normalised by the K^{40} channel. This granite shows a distinct U signature. The pegmatites, with a feldspar-quartz ± muscovite ± garnet ± tourmaline assemblage showed a K^{40} response only and were slightly magnetic.

The Mundi Mundi Granite-type an unstressed alaskite, is found in small bosses, sills and dykes near some uranium deposits, and is related to the uranium mineralisation in the Broken Hill Province, (Rayner, 1957). Alaskite is found at Boolcoomata near Radium Hill, Crockers Well and Mt. Victoria in South Australia; and in the Templeton Granite in the Cloncurry-Mt. Isa Province.

The major granulite facies metamorphism and deformation of the Broken Hill Province was about 1700 Ma, (Shaw, 1968), defined in South Australia as the Olarian/Kimban metamorphism. The Mundi Mundi and Binberrie Granites have an Rb/Sr age between 1450 and 1550 Ma, (Pitt, 1981), and the lower amphibolite grade retrogression occurred 500 Ma, (Richards and Pidgeon, 1963). These retrograde rocks are essentially restricted to transgressive shear zones, (Plimer, 1977). These late tectonic granites are comparable in age to the Moonta and Tickera granites, but no massive alaskites were reported in this Province, until the petrology for this study. The only age data known in shear zones in the Wallaroo-Moonta Province is that they are post the recrystallisation event, which has an Rb/Sr age of 1220 Ma.

3.7.4.3. Uranium associated with base metals and metamorphic rocks.

The distribution of known base metal mines and prospects in the Wallaroo-Moonta Province and the two subdomains in the Willyama Orogenic Domain is comparable. Mineralisation in the Plumbago-Glenorchy area in the Olary Block, showed a marked zonation which is closely related to the lithology and to the degree of granitisation and pegmatisation. Campana and King (1958) grouped the zoning as monazite-cyrtolite, uranium-thorium, uranium, and copper-cobalt-tungsten, but some overlap of these zones occurred in the Crockers Well and Mount Victoria Areas.

In the Olary Block the principal base metal is copper, associated in different proportions with Co and W, W and Ni with W. The main copper deposits are stratigraphically controlled, eg. the copper-cobalt-tungsten deposits (Ethiudna Mine) in calc-silicate rocks and graphite units of the Ethiudna Group, which are tremolite-diopside-garnet skarn rocks overlain by massive quartzite. Scheelite is present with magnetite-copper ± Fe sulphides and is associated with pegmatites. Other copper deposits have similar associations to Wallaroo namely, epidote-actinolite quartzite, magnetite-pyrite-actinolite rock, amphibolites (Mutooroo Copper Mine) which was considered as the pyritic mineralisation associated with aplite in the Pinnacles Group in the Broken Hill Province,' (Campana and King, 1958). Superimposed on these syngenetic deposits is a uranium-copper association derived from pegmatites and granitoids.

The Olary Block is dominantly Cu-U-Co-W-Ni province, with no economic Pb-Zn-Ag mineralisation. However, company exploration in the Kalabity and Mutooroo regions has outlined the Broken Hill Mine sequence. This concept of a dominantly copper-uranium province may be comparable with the Devon Group in the Wallaroo-Moonta Province.

In the Broken Hill Subdomain, the Broken Hill Area is dominated by Broken Hill Type (Pb-Ag-Zn sulphide concentrations in quartz-gahnite and/or garnet-quartz rich horizons) which are generally not radioactive except for pegmatised gneiss in the wall rock of Lead Lode No. 18 of the Zinc Corporation Mine, which contained uraninite and hydrocarbon (thucholite). A trace of uraninite is present in the Broken Hill South Mine, (Rayner, 1960). Another radioactive occurrence in the Broken Hill Type is within the upper oxidised portion of the Great Western Lode, (a Ag-Pb-Zn deposit) associated with galena within the sulphide zone. This minor radioactivity is comparable to the amount present in Wallaroo Mines.

The other silver-lead mines, (Thackaringa ore type); show a radioactive association in the sulphides zones, mainly between uranium, iron and possibly manganese, ie 0.1% U_3O_8 at the Hen and Chicken Lode, (Rayner, 1960); and a uranium-copper-iron association within a shear zone in quartz-biotite-sericite ± magnetite schist at Copper Blow. This mine near the Thackaringa-Pinnacles

Shear Zone, contains torbernite and meta-torbernite, (0.1 to 0.3% U_3O_8). The sulphide dumps showed 0.05% U_3O_8, associated with chalcopyrite, pyrite and magnetite. The primary ore is magnetite-pyrite-chalcopyrite.

The uranium in the Thackaringa area is associated with the major shear zone, and minor subparallel shears in the Pb-Zn deposits. Local pegmatites and alaskite bodies occur near these deposits (Rayner, 1958, 1960).

The numerous subeconomic base metal deposits outside the Broken Hill Mine area, outlined by Barnes (1980) are stratiform and stratabound Cu-Au, Pb-Ag-Zn ± W, W, Co, and Cu deposits, and hydrothermal vein deposits of Cu, F, Pb-Ag-Zn, Ag, Pb and U. The former contain some Pb-Ag-Zn occurrences of Thackaringa ore type. These base metal deposits are broadly zoned in a north-south to northeasterly arc centred around the principal Pb-Zn Mines, outlined by the numerous copper occurrences, with the uranium occurrences outside this arc, and minor Pb-Ag-Zn deposits inside. The copper and uranium mineralisation is near the outer marign of the central zone of intense metamorphism, and is to some extent marginal to the sillimanite-garnet isograds, (Rayner, 1960), and within metamorphic facies Zone A and B, (Binns, 1964).

In the Wallaroo-Moonta Province, most copper occurrences are west of a steep irregular magnetic gradient which outlines the near surface extent of the Devon Group. The copper mines and occurrences form a semi-circular pattern around the main subeconomic Pb-Zn prospects to the east, within the Smithams sequence and Willamulka metasediments and volcanics. The main U-Mo occurrences, the Alford prospects, are north and outside the copper zone and on the opposite side to the Pb-Zn.

The metasediments contain stratabound Cu-Ni-Co mineralisation mainly south of the principal mines at Tiparra and Weetulta. Major N-S faults or lineaments offshore, (Chapter 6) may compare with the distribution of the uranium mineralisation associated with the Mundi-Mundi Fault, and numerous east-west possible retrogressive shear zones are comparable to those in the Broken Hill Province, (Chapters 16 and 17).

More fundamentant data is required on the presence of uranium in the Wallaroo-Moonta Province, the metamorphic zones, the amount of Pb-Zn-Ag present in the Devon Group, Pb-Zn present in the Smithams sequence, and on the economic distribution in the offshore portion of this Province.

The following main similarities between this Province, and the Gawler and Willyama Orogenic Domains are outlined, but require additional information.

(i) The uranium is associated with pegmatites. Are these related to alaskite granites?

(ii) The uranium is associated with zones of extensive feldspathisation and in major shear zones. Sodic metasomatism has been reported. What is its distribution and is there a U-Fe association within the shear zones?

(iii) Minor uranium is associated with carbonaceous-rich metasedimentary units. These are thin, but present in the Wallaroo-Moonta Province, but no gamma logs or uranium assay data is available. The East Kadina and Willamulka metasediments contain relatively thick sequences of this type.

(iv) The association of minor uranium with Cu-Co-Ni $\pm$ W and Ag-Pb-Zn assemblages are worthy of further study, especially in the Tiparra-Weetulta areas.

The main difference between this Province and the Willyama is the lack of davidite and its association with the rare earth minerals, which are generally restricted in distribution, and therefore could have been missed in the exploration of this Province.

3.8. BASE METAL-URANIUM ASSOCIATION - WORLD WIDE

World uranium - base metal associations are discussed in relation to host rock-types and placed into three groups: i) uranium dominant over the base metals in pegmatites, alaskites and acid volcanics, ii) uranium subordinate to the base metals in porphyry copper deposits, iii) either uranium or the base metals dominant in sedimentary rocks. The Wallaroo-Moonta Province may be in the second or third category. The following discussion is mainly restricted to the Proterozoic, with some references to the Archaean and younger deposits, but not to the Tertiary roll fronts.

3.8.1. URANIUM (DOMINANT) ASSOCIATED WITH PEGMATITES AND ALASKITES

Namibia deposits, Africa

Within the highly metamorphosed (amphibolite facies) Damaran Mobile Belt, Namibia, there are two pegmatite suites, one of which is mineralised, containing the Khan Copper Mine with minor zinc and the Henderson Mine with copper and minor gold (Wagner, 1916).

The Khan Mine was compared by Jack (1917) with the Moonta Mines. Also possibly related to this mineralised suite is the Rossing Uranium (uraninite) Mine, (Von Backstrom, 1970), which was suggested by Martin (1978) and Wilpolt and Simov (1979) to be related to an alaskite, which is associated with uranium and copper, (IUREP, 1980). This uranium-minor copper mineralisation is relevant to the Mundi Mundi Granite rock type in the Broken Hill and Olary Sub-domains, and presumably to the Wallaroo-Moonta Province.

Aitik deposits, Sweden

In the Aitik Copper Deposit, 'uraninite, scheelite and molybdenite occur now and then as isolated grains in the pegmatites' (Zweifel, 1976). These pegmatites relate to the Lina granite (alaskite), having an Rb/Sr age of 1545 ± 809 Ma, younger than the copper mineralisation, which is compared with the Wallaroo-Moonta Province in Chapters 1, 16 and 17.

3.8.2. URANIUM (DOMINANT) ASSOCIATED WITH ACID VOLCANIC ROCKS

The presence of uranium in the rhyolite, rhyodacite and dacite units within the Wallaroo-Moonta Province has not previously been suggested. Studies of the uranium content of minerals in acid rocks, South California Batholith, (Larson and Gottried, 1961) showed that 68% of the total uranium was contained in the plagioclase, orthoclase and quartz, and 35% in the mafics, hypersthene, biotite, augite, muscovite and hornblende. These minerals contain the highest leachable uranium compared to other rocks. A summary is given by De Voto (1978). Research on Tertiary volcanic glass in Trans-Pecos, Texas, (Walton, *et al*, 1981) showed the uranium may be released during diagenesis into the surrounding sediments, or may be locally redistributed by hydrological fluids. The U content in groundwater (20-200 ppb) in tuffs and tuffaceous sediments is high, and finely grained U in other volcanic rocks, is 1.5 to 2 times the background of the plutonic equivalents.

The uraniferous stratiform epigenetic deposits in the basal Permian sandstone in the Lombard Basin, Italian Alps, namely the Val Rendena, Val Daone, Val Pescara deposits in Italy, and Zirovski Vrkin Deposit in Yugoslavia are related to the Permian volcanics. They occur at the facies change between these volcanics and the marine shale, sandstone and volcanics with additional uranium from the basement platform (Mittempergher, 1974).

De Voto (1978) stated:

'uranium with associated Mo, Hg, F and Se concentrations, combined with porosity-permeability control in volcanoclastic sediments, pumice-lithic ash units, contact zones, fracture and fault zones and subjacent rocks, combined with exhalative gases are important in the concentration of uranium in the development of caldera'. He gave 'the Pena Blanca, Chihuahcia, Mexico epigenetic uranium' as an example of this type. 'The mineral assemblage is uranophane, uraninite, carnotite, autunite, with abundant Mo and Hg, with the uranium'.

Some deposits in the western United States; Pocos de Caldos, Brazil and the Baker Lake region of northern Canada are possible volcanogenic uranium deposits (Page, et al, 1979).

A trace element geochemical study of radiometrically anomalous tuffaceous rocks occurring in conformable lenses in a volcano-sedimentary sequence of Neogene age, northwest Iran, (Beeson, 1980), showed statistically these rocks were enriched in U and Th. A zone of kaolinization contains increased levels of U, Th, Pb and Sr relative to the unaltered country rock, and nine other elements were depleted in the zone. He considered these changes were due to hydrothermal activity within the tuffs and black shales, with potential for a Tertiary deposit of syngenetic and hydrothermal orign.

The Laura Jean, uranium-fluorite deposit and the Maureen uranium-fluorite-molybdenum prospects in Georgetown, Queensland, (Withnall 1978 and O'Rourke 1975) are Australian examples of uranium mineralisation associated with acid volcanics and cauldrons. The Moonta cauldron model (Chapter 7) and the Alford uranium molybdenum prospect (Chapters 10, 16 and 17) are comparable.

The Duobblon occurrence, in northern Sweden within the Arjeplog-Arvidsjour-Sorsele uranium ore province is a stratabound uranium mineralised zone within rhyolitic ignimbrites. Its age is between 1625 and 1750 Ma, (Lindroos and Smellie, 1979, Adamek and Wilson, 1979). The ignimbrites and an underlying basal breccia lie unconformably on a deeply weathered granite basement, about 1790 Ma, and are overlain by thick red-bed type conglomerates and sandstones, which are overlain by acid to intermediate terrestrial volcanics. The ignimbrite unit is 60 m thick, and has a strike length of 4 to 5 km. The richest uranium concentration, on average 200 to 300 ppm U, occurs in several 1 to 25 m thick and 1 km horizons within lithophysae-bearing parts of the unit. The fine grained mineralisation consists of pitchblende and complex uranotitanates, within the chlorite-sericite groundmass. The highest U enrichments are generally associated with high Pb, V and Mo, (Lindroos and Smellie, 1979). In Wallaroo-Moonta, numerous volcanic units, including possible welded tuffs were found within the metasediments and Moonta Porphyry. Multi-channel spectrometer tests have shown there is some uranium present, possibly associated with copper and molybdenum. However, no red beds are known as in the Duobblon occurrence, but hematite-conglomerates referred to as a possible red bed facies are present near Alford, (B. Coles, pers. comm.).

In the USSR, uranium occurrences were classified as hydrothermal deposits, with the andesite-rhyolite association, and separated into two types, by Kazansky and Laverov (1977): (i) Fluorite-uranium deposits in superimposed volcanic caldera depressions, associated with acid volcanics and sediments; (ii) Arsenic-uranium deposits in erosional-tectonic basins which have similar relationships to granitoid basement and contain conglomerates, volcanics and red beds, and are associated with carbonates. Both these models compare with the Olympic Dam Deposit and may be applicable to the Alford deposit and the Moonta Porphyry.

Possible circular structures (Chapters 16 and 17) and an undersaturated rock in West Weetulta Granite Complex (Chapter 14), may be associated with uranium. In this case, the conceptual model of C-09 Uranium deposit at Campo de Cercado, Brazil (Santos, 1981) may apply if the area is an alkaline volcanic complex.

3.8.3. URANIUM (MINOR) IN PORPHYRY COPPER DEPOSITS, BOULDER BATHOLITH, MONTANA, U.S.A.

Beyschhag et al., (1909) grouped the Moonta Mines with the porphyry copper, Butte Mine, within the Boulder Batholith, Montana. Numerous small uranium shows have been discovered since 1949, in hydrothermal veins within the northern part of the batholith, and a few are near the Butte Mine (Wright and Shulhof, 1957). Lead, zinc, gold and silver are the main deposits in the uraniferous areas which lack copper. In the Butte Mine, only minor uranium occurs. The Lone Eagle Mine, the only uranium producer amongst the base metal veins, is a steeply dipping fracture-controlled lode in a biotite-quartz monazite host rock. The lode contains sparsely distributed pitchblende, with pyrite, sphalerite, galena, and minor chalcopyrite and argentite in a quartz, calcite - siderite gangue. Deposition of quartz and sulphides was followed by extensive brecciation, prior to the introduction of the quartz, pitchblende and minor sulphides, similar to the siliceous reef and Butte Mine alteration zones (Wright and Shulhof, 1957).

The West Wilson deposit is another minor uranium producer where the uranium ore occurs as pods along a sulphide-bearing hydrothermal vein deposit (Wright and Emerson, 1957).

This shows that the uranium post-dates the lead-zinc mineralisation and may be related in time to part of the Butte porphyry copper mineralisation. A porphyry copper model has been suggested for the Wallaroo-Moonta Province and could be applicable to the Tickera Granite Complex, where the uranium is most likely to be associated with Pb, Ag and Au with minor Cu away from the major copper mines. The Moonta Mines produced extractable Mo and Au, and the Wallaroo Mines produced some Mo, Au and Ag with minor Pb, Zn, W and traces of Ni and Co (Jack, 1917).

3.8.4. URANIUM - BASE METAL ASSOCIATIONS IN SEDIMENTARY ROCKS

In this section, either uranium or base metal deposits can be the dominant economic deposit, as Pb-Zn-Ag is in the Broken Hill Province, U with minor Cu in the Olary Province and copper with minor Pb-Zn and U in the Wallaroo-Moonta Province.

3.8.4.1. Pine Creek Geosyncline, Northern Territory

The Pine Creek Geosyncline is divided by the South Alligator Hinge Zone, (Stuart-Smith *et al.*, 1980) into two metamorphic provinces. Province I, to the northeast, is an area of medium to high grade regional metamorphic rocks, Nanambu Complex (Archaean), and contains the Range, Jabiluka, Koongarra uranium deposits (Proterozoic unconformity related deposits) ie U, U-Au stratabound within the Masson and Cahill Formations, close to the Archaean-(2400 Ma) - Early Proterozoic unconformity. Province II, west of this Hinge Zone, contains low grade regionally metamorphosed sediments and volcanics, with hornfels facies rocks developed around the late-orogenic high-level granitoid plutons (approximately 1800 Ma), locally superimposed on a contact metamorphic zone. These aureoles range up to 5 km wide, but are generally less than 1 km. This province II contains widespread stratiform or stratabound mineralisation within the Goodparla Group, which shows both lateral and vertical variations in the mineral assemblages. In the Rum Jungle area, the Masson Formation contains Cu-Pb-Zn, with hydrothermal U, Co and Ni veins. Eastwards towards the South Alligator River area, the same formation contains Ag-Pb-Zn mineralisation, with the Stage Creek Volcanics being host to Cu-U mineralisation. The overlying South Alligator Group, rests unconformably on both the Goodparala and Mount Partridge Groups. This unconformity marks a period of basement uplift and possible movement along the South Alligator Hinge Zone. The South Alligator Group, near and east of Rum Jungle contain U, which traced eastwards changes laterally into an Au, Cu, U, Fe assemblage in the Koolpin Formation, U-Au deposits in the Gerowie Tuff and Au, Ag-Pb-Zn, and Cu-U mineralisation at the base of the Kapalgo Formation, (Needham and Roarty, 1980). The early Middle Proterozoic granites introduced vein type deposits of Au, Sn, Ag-Pb, W, Ta, Cu and Bi into the system.

The broad similarities between this province and Wallaroo-Moonta, are:

(i) The South Alligator Hinge Zone is a N-S geophysical lineament, eg. South Alligator River - Bamyili gravity lineament, associated with granitoids, and is interpreted (Tucker, et al., 1980) as a lateral change in structure and composition at depth shown as a gravity gradient. It is reflected in the aeromagnetic and magnetic basement depth contours as a N-S fault coincident with the eastern boundary of the South Alligator Trough. It corresponds with a rapid change in metamorphic isograds, ie actinolite to biotite and to almandine-kyanite-staurolite, eastwards based on Needham, et al., (1980), and with lines separating folds with different orientations and styles. To the west are open tight folds and east multiple isoclinal folds. In the Wallaroo-Moonta Province, the style and direction of fold axis change along a NE-SW line separating the Warburto and Kadina provinces, based on J. Lynch (pers. comm.) and interpreted data in Chapters 16 and 17. Another NNE hinge zone separates the Wallaroo-Moonta Province from the Orontes Structure. The evolutionary cross section of the Pine Creek Geosyncline, (Stuart-Smith, et al., 1980, fig. 3 stages 2 and 3) show some comparison with both NS and EW cross sections across this Province based on the geophysical interpretation, (Chapters 16 and 17). The metamorphic isograd geological model is a solution discussed for the modelling of the Tickera Gravity Traverse, (Gerdes, 1974) ie. deep seated granulite facies for the N-S Bouguer Gravity Anomaly along the eastern side of Yorke Peninsula.

(ii) Period of uplift between two major stratigraphic sequences. There is geophysical evidence, with some geological control for major uplift pre the Smithams sequence and the Willamulka metasediments (Chapters 15 and 16).

(iii) West-East lithological and mineralisation lateral facies changes are evident between the Smithams and Pridhams sequences, eg Pb-Zn to Cu, within metasiltstones containing carbonate facies. There is geochemical evidence for a Cu to Cu + Pb ± Zn lateral facies change with the Doora Schists, along the West Doora to Southeast Doora trend, (J. Lynch, pers. comm.). This is subparalleled by the loss of pyrite and possibly pyrrhotite in an overlying carbonaceous-graphitic unit.

(iv) Tuffaceous and volcanic units are present in all stratigraphic units. Some show a slight Cu-U association and others a possible Pb-Zn above background level, as in Smithams. (cf. the Gerowie Tuff lateral change Ag, Au, Pb-Zn, Cu, U in the west to U, Au in the East).

(v) Evaporitic sequences are evident in both provinces, (Pine Creek Geosyncline, (Crick and Muir, 1980 and S. Whitehead pers. comm.).

Differences are:

(i) No known Archaean or Archaean domes are known in the Wallaroo-Moonta Province.

(ii) The Pine Creek Geosyncline is slightly older than this Province.

(iii) There is a scale problem. The Wallaroo-Moonta Province is small compared with the Pine Creek Geosyncline by a factor of 5.

3.8.4.2. Mount Isa Belt, Northwest Queensland

The Mount Isa Block has radiometric ages between 1870 and 1470 Ma, Middle Proterozoic, (Plumb, 1983) which compares with the metamorphic age of the Devon Group and possibly the depositional age of the Willamulka metasediments in the Wallaroo-Moonta Province. The Mount Isa Mines, a Cu-Pb-Zn-Ag deposit, is within the western trough, (Warren, 1972) and has numerous U deposits in the north, Calton Hills and Paroo Creek. The copper stratabound mineralisation within the Urquhart Shale, having a depositional chalcopyrite-pyrite-pyrrhotite assemblage, is stratigraphically equivalent to Ag-Pb-Zn bearing volcanic and dolomitic shales in this unit. The major copper deposits were formed by redistribution into zones of deformation, probably related to axial zones of major folds, (Bennett, 1965), and relatively unmetamorphosed zones associated with major faults or shear zones in the copper province northwest of Mt Isa, (Brooks, 1965). Generally the lithology of some metasediments and volcanics in the Mount Isa-Cloncurry Province, is comparable with the Wallaroo-Moonta Province. Similarly the copper deposits in this Province, the West-Doora-Martin prospects are in the deformed axial zone of the Kadina fold, and the other mines of the Wallaroo group are associated with fractures.

There are two copper provinces, one is to the northwest of Mt. Isa and separated from the western trough by the Mount Gordon Fault, and the other, east of the unmineralised N-S Median Welt (Nicholson Domain), is within the eastern trough, the Cloncurry copper-uranium province.

The northwestern copper province contains the Mt. Oxide, Mammoth and Lady Annie Mines, which are minor deposits compared with Mt. Isa. The copper mineralisation occurs in relatively unmetamorphosed sandstones, conglomerates, dolomitic shale and siltstones of different stratigraphic ages, is associated with brecciation and is controlled by faults striking from 015° to 045°, and from 090° to 120°. The former is subparallel to the Mt. Gordon Fault. These sediments are interpreted as platform sediments and further NE contain the Lawn Hill Ag-Pb-Zn Mines. The Pridhams prospect in the Wallaroo-Moonta Province has some lithological and structural similarities to the above province.

The eastern province, the Cloncurry province, contains copper, cobalt, gold, minor lead-zinc deposits and the major uranium occurrences at Mary Kathleen. The Wallaroo-Moonta Province has some similarities with the Cloncurry province. Both are copper provinces, with minor lead-zinc deposits, and cobalt. The cobalt in Wallaroo-Moonta is associated with copper and nickel in some rocks, whereas it is not known if the Wallaroo-Moonta Province is geosynclinal.

The distinct N-S fracture system, with the mineralisation controlled by

NNE fractures are similar in both areas. They are equal in size, shape and the whole of the Mt. Isa Belt could be superimposed over the eastern margin of the Gawler Block, Yorke Peninsula and Spencers Gulf. Geophysically, based on the gravity data, the distinct high-low density striation, comparable structures are present along the eastern sides of Eyre and Yorke Peninsulas, (Orontes Structure).

Other similarities occur in specific mines, eg. the Duchess Copper Mine, (Broadhurst, 1953) contains scapolite metasomatism, and has similar mineralisation to the Wallaroo-Moonta Province, except the ore bodies are concentrated near faults and shear zones on the contact of the granites with basic intrusions. The Trekelano Copper Mine, (Shepherd, 1953) which has cobalt, copper with minor Au and Ag is analogous to the copper-cobalt-nickel in the metasediments at Weetulta and Tiparra, which are also scapolitised. Red feldspar and red scapolite in hornblende schists and scapolite granulites within shear zones have not been observed in the Wallaroo-Moonta Province. Small uranium occurrences with associated copper in the carbonaceous sediments, Kuridala Formation may be comparable to similar sediments within the Devon Group and Willamulka metasediments. In the Wallaroo-Moonta Province, carbonaceous sediments have not been thoughly tested for uranium.

3.8.4.3. Africa

The U-Au deposits of the Witwatersrand, Ventersdorf and Transvaal sub-basins, classified as auriferous quartz-pebble conglomerates, are older than the rocks in the Wallaroo-Moonta Province, the youngest being between 2250 and 2000 Ma. The Elliot Lake Deposits of Canada also fall into this classification.

Syngenetic copper, cobalt and uranium mineralisation occurs near the base of the Katanga System in the Shaba Province, Zaire, Zambia Copper Belt and in northwestern Zambia. This system is mainly marine except for continental facies at the base with a depositional age between 1300 and 850 Ma which is younger than Wallaroo-Moonta Province. Remobilisation and redistribution of the syngenetic mineralisation by orogenic and metamorphic events (550-600 Ma, Meneghel, 1979) have produced vein type uranium deposits. The Delamerian Orogeny may have had a similar effect on the uranium mineralisation in the Wallaroo-Moonta Province. The uranium vein deposits are broadly associated with the syngenetic base metals. In the Shada Province, the syngentic mineralisation is in an arcuate belt 300 km long which forms three distinct mineral zones. The inner arc to the south contains U + Cu + Co + Ni mineralisation which includes numerous mines eg the major Shinkolobwe Mine. The central zone is Cu - Co ± U rich and the outer zone to the north contains minor Cu - Co. Within the Devon Group in the Wallaroo-Moonta Province there are Cu, Co, Ni above background geochemical values with anomalous uranium in the metamorphic units eg. in the Balgowan, Weetulta and Tiparra areas. The mineral zonation in the Shada Province may be present in Wallaroo-Moonta, but on a smaller scale, or represents a cross-section of an arc.

Cu-U mineralisation occurs in the Domes Area, northwestern province of Zambia which contains basement domes. Dome-like structures are present within the Wallaroo-Moonta Province surrounded by metasediments. The Cu-U mineralisation is within lower schists and quartzites above a basal conglomerate and minor U occurs higher in the sequence. Cu is in dolomite-rich sediments. Carbonaceous siltstones containing Cu in the Willamulka metasediments rest unconformably on the Devon Group, but no conglomeratic facies has been identified.

Elsewhere in the Katanga System in the intra-cratonic Franceville Basin, eastern Gabon, uranium occurrences are in marginal marine clastic sediments near Early Proterozoic granitic basement, and also in conglomerates and sandstones, commonly carbonaceous. Pyritic carbonaceous metasediments are present within the East Kadina metasediments and the Williamulka metasediments. The U potential is not known except in Alford West Area.

Compared to other parts of the world eg. in Sweden, uranium is within Cu-Co-Ni-Bi-U veins at Los (age 1690 Ma) and in the Norrbotten district Cu, Ni-Cu-Co and U ore are present. The Aitik deposit is on the southern fringe of this district. Other examples of this Cu-Co-U association are present in

Finland, U.S.A., and Canada.

In conclusion, the Wallaroo-Moonta Province has both base metal and uranium potential, and similarities to other deposits. The closest base metal comparison on current research is to the Broken Hill and Olary Provinces, the Aitik copper deposits, Sweden; the Butte deposit Montana; and the Kuroko type deposits, Japan, (Chapters 15, 16 and 17). The magnetic-apatite rocks have some similarity with the Kiruna-type deposits, Sweden. The Cu-U-Fe-Co-Ni association has similarities with the Shada Province, Zaire; the Cloncurry, Olary and Broken Hill Province. U-Mo±Cu±F association has similarities to the Laura Jean and Maureen Deposits, Queensland; the Duobblon Deposit, Sweden and the Olympic Dam Deposit. The potential for the occurrence of major uraniferous pegmatites associated with alaskites should not be dismissed. The problem is that the age of the major uranium-rich alaskites is 550 to 510 Ma (Cambrian) and rocks of this age have not been identified in this Province or in the Stuart Shelf.

The most probable conceptual model for a major uranium deposit, apart from the Alford-Alford West prospects, will be a conglomerate-vein type deposit related to an unconformity, based on the age range of the rocks in the Province, between 1700 and 1200 Ma, Middle Proterozoic, similar to those in Pine Creek Geosyncline, or the Rum Jungle type of a later Late Proterozoic age. The other possibility is a stratabound uranium deposit associated with volcanics and tuffaceous metasedimentary units.

Future research and exploration in this Province should be compared or incorporated in terms of the geological development of the Gawler Orogenic Domain, including the Stuart Shelf, Mt. Painter and the Willyama Orogenic Domains, based on the concept of the evaluation of a metallogenic province, similar to the Athabasca region, N. Sackatchewan, (Dahlkamp, 1979) and the Arjeplog-Arvidsjaur) uranium province in Sweden, (Adamek and Wilson, 1979) and its association with other polymetallogenic provinces. This type of study combined with all the geophysical data is beyond the scope of this thesis, and should be jointly studied using all the disciplines by numerous researchers or an exploration team.

CHAPTER 4

BRIEF HISTORY OF GEOPHYSICAL EXPLORATION OF THE WALLAROO - MOONTA PROVINCE

Geophysical methods were first applied in this area in 1930, seven years after large scale mining had ceased. Most of the subsequent ground geophysical surveys did not extend very far eastwards; (Figures 4.1 and 4.2). The 1930 locations of the I.G.E.S. geophysical traverses are too small to be shown at this scale. The electrical traverses (equipotential method), 2.4 km east of Moonta, covered 4.5 km^2 over the mineralised lodes. The five vertical magnetic traverses, covering 0.0162 km^2, were surveyed 3.2 km east of Kadina, over a magnetic anomaly found by the Government Astronomer of South Australia, (Mr. G.F. Dodwell) in 1929. Results and interpretations of the surveys are briefly outlined in chronological order.

4.1 PRELIMINARY GEOPHYSICAL EXPLORATION

PERIOD 1930 - 1939

In 1930, during the International Geophysical Experimental Survey, electromagnetic, electrical resistivity and ground magnetic methods were used at the Moonta and Wallaroo Mines. Edge and Laby (1931) concluded that "the results of the electromagnetic methods were unsatisfactory and impractical in the Moonta area", and that "the frequencies (10-80 kHz) used for the electromagnetic system were too high". The electrical tests with a frequency of 500 Hz were unsatisfactory due to the highly conductive saline clay layers between the surface and the bedrock.

A 60 foot shaft sunk on a magnetic anomaly of 5 000 nT. amplitude, encountered ferruginous mica schists, magnetite, and no mineralisation. Therefore the hypothesis for a copper - magnetite association for the mineralisation was discounted and so the area was relinquished.

PERIOD 1940 - 1947

In 1942, the Commonwealth Department of Supply and Shipping, undertook a preliminary survey mainly electromagnetic, using a lower frequency (500 Hz) than that used by the I.G.E.S (Thyer, 1943). This survey included magnetic, self potential and potential - ratio methods. The electromagnetic results showed numerous conductors, often having the same orientations as the known lodes. Drilling did not discover any significant mineralisation.

Later experimental surveys (Fenner, 1948a) used resistivity profiles. A line of drill holes was sited parallel to four of the sub-parallel electromagnetic conductors, outlined by Thyer (1943). Fenner showed that these conductors were within a clay layer and were perhaps channels of high salinity water. In addition, holes sited on particular EM anomalies intersected a very weak zone of alteration, with no copper mineralisation.

4.2 THE ADVENT OF NEW EXPLORATION TECHNIQUES, PERIOD (1947-1949)

From 1947-1949, Zinc Corporation Ltd. which held S.M.L. 14 in the Wallaroo Mines area, commenced an extensive and systematic approach by combining a number of methods, (i) A variation of the electrical resistivity technique, (ii) radiometric methods, (iii) geochemical methods, and (iv) systematic magnetic methods.

4.2.1 ELECTRICAL METHODS

Resistivity and self potential methods were used in preference to the electromagnetic technique. To determine if the depth of penetration could be increased, and to overcome the saline clay conductive effect, Gustavson and Oscar Weiss suggested lowering the electrodes into drill holes within the bedrock. The results indicated no appreciable difference, as most of the current was channelled through the surface clay layer. The self potential profiles with the electrodes at the surface, and concealed in drill holes on the bedrock surface showed no significant differences for this method to be of any use in this environment, (Fenner, 1948a).

The resistivity traverse measurements, using a D.C. source, recorded for both Wenner and Lee configurations, were also unsuccessful due to the high conductivity. Edge and Laby (1931) had reported from the Moonta Test Pit, a 2.74 m hole, 1.16 m of 'brown clay (decomposed porphyry gradually passing into solid feldspar porphyry)' which had a resistivity range of 1.87 to 3.20 ohm.m. (mean value 2.71 ohm.m.); and from DDH1 in the Moonta Area, 3.35 m of 3 ohm.m. surface clay and a groundwater sample at 8.53 m gave a value of 0.44 ohm.m. Thyer (1943) and Fenner (1948a) gave no further resistivity values on these conductive clays. The V.E.S. curves produced by W.M.C. show resistivities of this order. Gerdes (1974) from V.E.S. in the Tickera-Alford-Port Broughton areas interpreted resistivities between 1.8 to 9.1 ohm.m., with conductive areas having values less than 1 ohm.m., using A.C. frequencies of 3, 0.3 and 0.1 Hz in progressively more saline areas, to obtain reliable measurements for the V.E.S.

The self potential measurements on several traverses were tried, but the results were not significant due to noise, i.e. telluric earth currents. The magnitude of the telluric earth currents varies with time and contains a wide frequency range of signals, which may cause unrepeatable readings over different survey periods. The earth currents would also be channelled in near surface conductors and show some distortion due to topographic and weathering variations of the resistivity basement surface. This produces noise in the S.P. measurements which may be comparable in magnitude with the S.P. effect. The S.P. theory assumes that the orebody is both above and below the water table. In the Wallaroo-Moonta Mines area the water table is shallow, which implies that most of the primary ore zones are below the water table, with the non-sulphide supergene deposits above.

The S.P. results did show some response over the Wallaroo Main and Duryea Lodes, coincident with relatively low conductivities, and a large variation over the Stirlings Lode. Weiss (1948) considered that these results should be treated with caution, as the disturbed ground and contamination near the old workings may produce anomalous effects.

A number of resistivity and additional tests with constant spacing intervals along traverses and expanding depth profiles, were unsuccessful in delineating any conductive zones within the basement.

4.2.2. RADIOMETRIC METHODS

Radioactive minerals were already known at Moonta based on thucholite, (Radcliff, 1906), covellite with quartz associated with minor thucholite, and possible carnotite or autunite, (Mawson, 1944). The significance of these, and the identification of other minerals were included after 1947 in an evaluation of the use of radiometric data to outline copper mineralisation. The possible close association of radioactivity with the copper mineralisation might have provided a means of prospecting for copper occurrences.

This concept provided the stimulus for a joint Zinc Corporation and S.A.D.M. radiometric study in 1948, and was continued by the S.A.D.M. until 1957, with the help of W.C. Woodmansee, seconded from the U.S. Atomic Energy Commission to the S.A.D.M. in 1955. He summarised the seven years of geophysical exploration and mineralogical data, (Woodmansee, 1957). The geophysical study in 1948 was performed in three parts:

(a) laboratory studies on museum ore and mineral specimens, and some country rocks collected by Jack from different mines and shaft levels from the Wallaroo and Moonta Mines, were suggested by Dr. C.F. Davidson (Geological Survey of Great Britain) who had found that the bornite from the Wallaroo Mines was faintly radioactive. Fenner (1948d) studied Jack's specimens, and found that out of 82 samples, only one was strongly radioactive (ore containing thucholite from Moonta Mines, 811-870 cpm). Chalcopyrite 'peacock' ore and bornite with chalcopyrite from the Moonta Mines had radiometric values between 302 to 420 cpm. Fluorite and sphalerite from the Wallaroo Mines had values between 322 to 550 cpm. As only two of these were copper ores, and their location in the mines was unknown, further sampling was required, which was done on water samples and from different levels in numerous shafts, recording both beta and gamma counts, (Fenner, 1948d).

The results showed a greater variation with the beta counts, and Fenner suggested this method could be applied to exploration. The gamma ray counts were just over background ± 20 cpm, except for a sample from the dump near

Smith's Shaft, Moonta. Samples containing torbernite from the Moonta Mines showed low radioactivity.

(b) Concurrent sampling of the slime, mullock and slag dumps were recorded by Schleiss of the Oscar Weiss organisation, (Woodmansee, 1957).

The radioactivity showed between 2 to 3 times background over the dumps, and a few isolated samples of possible ore grade, 4 times background, are shown as 1% U_3O_8 sample, in Table 4.1 based on Woodmansee (1957). The background radioactivity ranged from 10 to 20 cps. The other uranium prospects outside the principal mining areas are shown for comparison.

A significant radiometric source of possible extraneous dumped material occurred near the Hancock Lode, Moonta East Mine.

TABLE 4.1

RADIOACTIVITY ASSOCIATED WITH THE MINE DUMPS

Uranium Associated with Copper Mineral Fields	Name of Mine/ Lode	Radioactivity of Mine Dumps
Wallaroo Mines Area (Kadina)	Wallaroo Main	100 - 200 cps
	Stirling	100 - 200 cps
	Devon	100 - 200 cps
	Halls	1% U_3O_8 sample*
	Duryea	100 - 200 cps
	Doora	100 - 200 cps
Moonta Mine Area (Moonta)	Hancock	1% U_3O_8 sample*
	Yelta Main	100 - 200 cps
	McDonnell	1% U_3O_8 sample*
	Taylor	100 - 200 cps
	Treuer	1% U_3O_8 sample*
	Musgrave	100 - 200 cps
	Beddome	1% U_3O_8 sample*
Outside Major Copper Mineral Fields		
Penang Mine		1% U_3O_8 sample*
Kulpara (Copper Hill) Mine		100 - 200 cps
Old Cumberland Mine		50 - 100 cps
Jerry Mine		50 - 100 cps
Hillside Copper Mine		1% U_3O_8 sample*
Hart Copper Mine		50 - 100 cps
Dead Horse Bay Uranium Prospect		1% U_3O_8 sample*

*Sample of ore grade (greater than 200 cps) based on Woodmansee (1957).

(c) To verify the possible copper-uranium association, numerous radiometric test surveys were performed. Fenner (1948d) found from radiometric data that the Moonta ores were more radioactive than the Wallaroo ores, and that the underground radiometric readings in the Moonta shafts to 70 feet, showed a distinct increase by a comparison of both gamma and beta counts, possibly a solid angle effect. The beta counts were considered as a better exploration parameter than the conventional gamma measurements. Fenner (1948d) showed, using both gamma and beta instruments, that the Moonta Porphyry in the areas around the East Moonta DDH1 and 2, drilled to test and evaluate Thyer's electromagnetic anomalies, were slightly radioactive. Fenner (1948e) recommended a study of the porphyry using both instruments to define the background level of the whole porphyry, and to evaluate whether or not the mineralised zones were significantly radioactive compared with the main porphyry body.

Fenner (1948e) surveyed some experimental radiometric traverses across the Wallaroo Main Lode, comparing simultaneous gamma and beta counts within a trench near Office Shaft, a surface traverse near the same shaft and near the Taylors Shaft. His results were inconclusive in defining any significant radiometric anomaly associated with the copper lode. He considered the negative results were due to:

(i) inconsistencies due to no drift correction being applied for the various instruments used, which had different sensitivites and calibration contrasts.

(ii) possible contamination due to the near surface workings and dumped material.

(iii) inconsistencies produced by radon emmissions.

(iv) inconsistencies in results on different days, i.e. the anomalies were not repeatable.

(v) Two thick an overburden. If the lode was concealed beneath 4 to 5 feet, the radiometric response would not be detected.

Fenner (1948c) selected the Wandilta Lode, and Stirling Lode near Stirling Shaft as shallow lode sources, and using two meters, one roving and the other stationary, found no anomaly over the Wandilta Lode, but identified a possible anomaly, which subject to possible surface contamination, was coincident with an S.P. anomaly over the Stirling Lode. Fenner (1948a, c) concluded

"the radioactivity in this district is associated with the lode minerals other than the copper" and "it is doubtful if the method can be used in areas having greater than 4 to 5 feet of clay over the lode cap", (Fenner, 1948c).

The samples that Fenner tested and the radiometric traverses were inconclusive in evaluating the possible copper-uranium mineralisation. One of the major problems was the samples tested, were not representative ore samples, and using comparable instruments, when compared with similar data from uranium-rich deposits in South Australia, (reported by Pegum, (1954b) and given below).

Radium Hill ore	1800 cpm
Houghton ore	1450 cpm
Crockers Well ore	2100 cpm
Moonta radioactive ore (thucholite)	811-870 cpm
Moonta bornite ore	302-328 cpm

Even with these discouraging and unsatisfactory results, a number of radiometric surveys were made, (Figure 4.1), using aerial scintillometer (Knapman, 1951) and vehicle-mounted scintillometer (Figure 4.3), (Knapman, 1954). The 1951 airborne survey showed disappointing results. It outlined anomalous dump material, 4 times background and the signal from the copper lodes was within the background noise. In addition, the copper lodes being 2-3 ft. wide could not be registered at 200 ft. agl with an aircraft speed of 80 m.p.h.

This data over part of the Moonta Porphyry showed an anomalous area associated with the mining operations, and areas of possible contamination. Some linear radiometric responses suggested by Knapman to be investigated, fell on roads, and are probably produced by radioactive material used for road metal, as previously identified elsewhere by Fenner (1948c, d). Knapman (1954) used the airborne scintillometer (2 inch Thallium activated sodium iodide crystal) with the detector mounted on a jib about 12 feet agl behind and fixed to the vehicle. He traversed numerous mine areas, over the lodes, but most were associated with dumps. The background increased by 3 to 4 times, but he was unable to find a known lode with no surface contamination. His interpretation, based on significant anomalies above the local geological background noise (statistic geological envelope), showed that the Moonta Porphyry was generally slightly radioactive. He resolved another possible 'porphyry' body, verified by drilling DDH JJ1/2 (Kerr Grant, 1952; Knapman, 1953a), but did not solve the problem of the possible copper-uranium mineral association. He considered areas with twice background levels should be further evaluated, combined with other methods e.g. S.P., magnetic gravity and geochemical surveys. One radiometric anomaly investigated in this way, (Knapman, 1952) east of the Duryea Lode within the Eastern Shear Zone, was on a regional magnetic gradient, accompanied by sharp S.P. lows, and was the site of DDH K (Knapman, 1953a). No mineralisation was intersected. Other holes, CC1, JJ1/2, MG1 and MG2a showed that particular lithological units and perhaps porphyry units have possible radiometric ranges which could be used for stratigraphic correlations.

Pegum (1953) in the vehicle mounted scintillometer at Radium Hill and Crockers Well, a year later, showed that background noise of the scintillometer was produced when the engine was running, possibly due to:

(i) vibrations of the equipment and mountings of the scintillometer,
(ii) the effect of the ignition on the scintillometer circuit, which required modification and suppression of the ignition, and
(iii) the inability of the instrument to repeat readings.

There is no way of knowing if these effects were present in the Moonta survey, but these possible errors should be considered in data of this vintage.

A detailed total count radiometric ground survey for uraniferous lodes associated with the Eastern Shear Zone was made to determine if 'a spatial relationship existed between the uranium mineralisation in the lode structure and the Eastern Shear Zone,' (Webb, 1954). The highly radioactive dump between the Elder's and Stirling Shafts on the Wallaroo Main Lode and Stirling Lode was outlined. Here, the radioactivity was produced by thucolite and uranium decomposition products.

The radiometric contours of this survey (Figure 4.4, after Mumme, 1954a), coincides with the lodes, dumps and shafts and the associated contamination from the dumps. Two linear discordant trends of radiometric responses, A and B, striking at 160° and 130° respectively, were suggested as possible uraniferous lodes or contamination, produced by infilled drains associated with the mining operations.

There was also a possible radiometric anomaly within the shear zone. No verification was given, and presumably the unsuccessful drilling within a shear zone, DDH K possibly explains why no further evaluations were made.

A radiometric study of the dump, south of Gurners Shaft, Hall's Lode, Kurilla Mine, (Mumme, 1954b) containing thucolite and uranium decomposition products, (samples containing between 0.04 to 0.42% U_3O_8) showed that the major contamination was outlined by the greater than 35 cps contour. This was confined to the dump and had a wider zone of 25-35 cps associated with areas of minor contamination and shaft material. The contamination zone surrounding the dump is estimated to extend for at least 35 m, and after this distance, significant anomalies may be resolvable from the background. This shows that the responses outlined by Mumme (1954a) may be real, based on the above estimate, provided that the groundwater movement is similar. Therefore the uranium responses, shown by the radiometric contours greater than 35 cps, (Figure 4.4) are possibly both subparallel to, and form discrete anomalies, coincident with the Wallaroo Main Lode, and do not have any distinctive strike extent. The discrete nature of the radiometric contours is present in the Dead Horse Bay Uranium Prospect, (Mumme, 1955b) and perhaps in the cliff section of Harts Copper Mine, based on radiometric contours, after Mumme (1955a).

All these radiometric tests and surveys show that no major uranium responses were detected in the Wallaroo-Mines area, comparable with those resolved in the Barossa Complex, associated with the Houghton 'diorite' in the Houghton and Inglewood areas, (McPharlin, 1950; Knapman, 1951), and in the

Olary and Mt. Painter areas. The geophysical evaluation of the possible copper-uranium association is inconclusive, except there is a possible association which cannot be applied generally to the mining areas, (Fenner, 1948d). This association is discussed in Chapter 3.

Further ground exploration for uranium in the mining areas is hampered by the general contamination, dump material, and concealment. Future studies should be aimed at providing multispectral data from the available core samples, from radiometric logging of drillholes, and possibly the use of track etch methods, using parameters set out by Hogg and Fisher (1977).

4.2.3. GEOCHEMICAL METHODS

Advances in analytical techniques and the increasing knowledge of the dispersion and translocation of metals, had led to the evolution of the geochemical prospecting method, which was developed in Scandinavia, Russia, and America, (Sokoloff, 1948). At this time, geochemical prospecting was in its infancy. The Wallaroo Mines area was used for a test site by Sokoloff, who found the narrow width of the lodes, the relatively thick overburden, (between 3 to 6 m thick), the concealment of the ancient soil profile by poorly permeable calcrete layers, and 2 feet of tailings containing less than 1% Cu over the lodes, and its associated contamination in a poor drainage system, were major exploration problems in obtaining the geochemical haloes associated with the Wallaroo-type copper lodes. He solved the problem of the tailings by removing them from a 3.35 m^2 pit at 50 and 100 ft. intervals along traverses across the lodes. He then drilled through the calcrete to obtain the lithological variations and geochemical data of the underlying soils. He subdivided the lithological logs including the surface soil and calcrete into ten units. He found that the reddish-brown clay (soil unit 4) was part of the 'B' horizon - the subsoil, and outlined the complex distribution of units 4 to 10.

He semi-qualitatively assayed each unit for extractable Cu, Ag and Au. By allowing for errors produced by contamination due to the local absence of the calcrete layer, he showed that both the variations in copper and sometimes silver in unit 4, and the total copper for units 4 to 10, showed a comparable and realistic profile of the supergene copper distribution. He assumed 'a vertical translocation of the copper minerals rather than lateral'.

The results of the traverses across the principal lodes are given in Table 4.2. The width of the geochemical anomaly varies between 75 m for a single peaked response to between 150 and 425 m for a multiple peaked response. The multiple peak over the Wallaroo Main Lode has a projected strike length of 240 m beyond the known lode and the silver anomaly is coincident with the copper anomaly.

These results were encouraging and showed that the geochemical profile between approximately 2 to 3 m b.g.l. correlated with known copper lodes deeper in the section. In some cases the anomalies were coincident with the lodes, and in others were displaced to the south.

Although the geochemical reconnaissance traverse, conducted in a three month period were orientated to investigate a cross section from the Doora to the Wallaroo Main Lode, he did resolve and recommend two distinct copper zones, Anomaly H43-49, (a mutliple peak anomaly) midway between the Doora and Duryea Mines associated with a magnetic anomly, and the anomaly WR4-8 (Bacon's Find) and the Newtown anomaly immediately east. He outlined another anomaly on traverse C. These were later the sites for DDH H49 and DDH WR8.25 (1) and (2) and C14, which intersected minor pyrite and chalcopyrite mineralisation.

Sokoloff recommended 'that these geochemical anomalies should be evaluated with magnetic data and other geophysical methods,' and 'other elements such as silver and gold should be assayed as specimens containing traces of gold were found later to contain 2.5 gr. per ton'. Based on his 'imperfect tests for other elements' and 'on the atomic radius of copper', after Fersman data in 1936, he suggested that 'assays should be taken on elements with similar atomic dimensions which may be associated with the Cu ore Zn, Mn, Co, Cd, Pb, etc.). A possible copper association with U and Th may exist'.

TABLE 4.2

GEOCHEMICAL ANOMALIES OVER PRINCIPAL LODES

	Equivalent ppm Cu*	
WALLAROO LODE	>1.7	Coincident multiple peak (2 peaked) with coincident Ag anomaly. Background 0.08 to 0.2 equivalent ppm Cu.
STIRLING LODE	0.8 to 1.1 and >1.7	On either side of Lode.
WANDILTA LODE	0.8 to 1.1	Coincident peaked anomaly. No Ag anomaly.
KURILLA LODE	0.5 to 0.8	Anomaly displaced south.
DOORA LODE	0.08 to 0.2	Anomaly displaced south.
DURYEA LODE	0.8 to 1.1	Anomaly displaced south (possible Ag anomaly and trace of Au).

* relative values based on analytical method used by Sokoloff (1948).

These values are the extractable, semiquantitative copper values given in microgram Cu per aliquot, with the corresponding ppm. Cu in soil, dry basis.

4.2.4. MAGNETIC METHODS

Previous magnetic data revealed nothing useful, except that the I.G.E.S. had established that large anomalies existed. The aim of the survey by Wegerle (1948), was to resolve the faults and shear zones, by tracing the displacement of magnetic key horizons, or, by sudden changes in magnetic intensity along strike, and to compare the relationship of the old mines to these anomalies.

This survey initially consisted of a detailed grid of 4 square miles, with traverses spaced at 500 ft., sampled at 100 ft. interval, and laid out approximately perpendicular to the strike of the Wallaroo Lodes. After this grid area was completed, the grid was extended to cover a larger area for better control of the displacements, and road traverses were recorded outside this grid to obtain a regional coverage, (Wegerle, 1948).

Vertical magnetometer stations numbered 9433, were recorded as follows:

Main Kadina Grid	7340
Detailed data within Main Grid	916
Road Traversing (Regional)	1177

Wegerle stated that

'Although the magnetic survey showed an interesting pattern of linear anomalies, the method could not be used directly to define copper targets of the Wallaroo Main Lode type, as these were in relatively non-magnetic areas'.

The magnetic contours were published by Dickinson (1953, fig. 10).

Weiss (1948) suggested two possible interpretations for the anomaly pattern around the Wallaroo Mines area:

(i) 'The anomalies are the results of magnetite introduced selectively in certain rock types and in certain structural conditions. The pattern indicated a pitching fold with a magnetite concentration towards its nose'.

(ii) 'The high amplitude anomalies indicated the positions of shear zones, in which magnetite mineralisation was concentrated'.

Weiss considered the latter the most probable, but made no suggestion of the magnetite being within the original sediment as either a precipitate or detrital grains. However, Bacon (1948) reported magnetite bands within the metasediments in Devon DDH 1 and 2.

Weiss interpreted a "possible fault" oriented between Wallaroo Main Lode, Stirling Lode and just east of Devon, Hall's Duryea and Doora Lodes, to explain the easterly termination of the Devon and Doora magnetic anomalies. This structure coincides with the Eastern Shear Zone of Dickinson (1942a), and is oriented nearly parallel to the principal Moonta Lodes to the south. Both features were considered to dip westwards.

Fenner (1948f) investigated the magnetisation by recording the deflection of a Watts vertical magnetometer, using a sensitivity of approximately 60 to 20 nT per scale division. The rocks were collected from different mine shaft levels, and from Devon DDH 1. He concluded that:

"should these figures be representative in this distict, where large anomalies occur un-associated with copper mineralisation, it is questionable, whether there is any chance of finding a direct anomaly associated with copper mineralisation. The only exception occurred in the core of Devon DDH1 which contains heavily magnetized rocks that would produce an anomaly at the surface. Presumably the magnetic content in this core is either pyrrhotite or magnetite".

These minerals were not recorded in the geological log.

4.2.5. DISCUSSION OF EXPLORATION DATA

The Zinc Corporation's investigation was divided into three exploration phases, all of which show no additional economic mineralisation, but show an integrated exploration philosophy as follows:

PHASE 1 Three drill holes were sited to further test:

(a) previously obtained copper showings north of the Wallaroo Main Lode.

(b) possible western extensions of the Morphett's Lode, Kurilla Mine.

PHASE 2 Geophysical investigation recommended by Oscar Weiss; and simultaneous relogging of old cores, geological inspections of old dumps and a serious investigation of historical aspects.

The historical researches (Benedict, 1948a) showed:

'an underestimation of the amount of previous prospecting already performed in the area; and the value of the possible prize had decreased through a better understanding of the low profit margin which the mines had experienced'.

The investigation would have been terminated at this stage, except for the arrival of Sokoloff from America.

PHASE 3 Geochemical research under Sokoloff and the drilling of Bacon's Find, DDHZ4 sited on a geochemical anomaly.

From 1900 to 1948, 157 diamond drill holes were sited, mostly by the S.A.D.M., but no new ore body was indicated. After S.M.L. 14 was relinquished, the S.A.D.M. intended to drill a second hole at Bacon's Find Prospect.

The concealment, thick conductive overburden, and the narrow width of the known lodes posed a major exploration problem, (Bacon, 1948; Benedict, 1948b). Benedict also reported that over the most thoroughly prospected areas, the results were modest or negative, and these contributed to their discouragement.

Zinc Corporation's exploration programme was unsuccessful. However, they introduced two new important concepts into the area: regional magnetics and geochemistry, and had also explained the problems associated with the electrical and electromagnetic methods in this concealed area.

The original Oscar Weiss data is reinterpreted in Chapter 8.

4.3 THE IRON SEARCH PERIOD (1949-1960)

In 1949, the Broken Hill Proprietary Company at the request of the South Australian Government considered an aeromagnetic survey of both the Middleback Ranges and the Wallaroo - Moonta areas, in the iron ore search.

The first aeromagnetic survey of the Wallaroo - Moonta area was proposed by the S.A.D.M. in 1950, to try to solve the critical copper position in Australia. It was to be flown over Wallaroo and Moonta with a flight line spacing of $1/2$ mile , at an altitude of 500 or 1000 ft. a.g.l. and over Maitland at 1000 ft. a.g.l., with a flight spacing of 1 mile. All northern Yorke Peninsula was flown in 1952 by the B.M.R. along N-S lines, at an altitude of 500 ft. a.g.l., with a flight line spacing of $1/2$ mile. The areas covered were Wallaroo, Moonta, Tiparra, Maitland and part of Wardang. No survey report was issued. This data was contoured with an interval of 200 nT for Wallaroo, Moonta and Maitland, and a detailed contour interval 50 nT for the eastern side of Maitland and Moonta.

In 1955, Adastra Huntings Geophysical Ltd. flew the remainder of Yorke Peninsula for the S.A.D.M., at an altitude of 1500 ft. a.g.l. This data was intially contoured at 200 nT in 1956 and later recontoured at 10 nT in 1970 and republished in 1976. During this survey numerous very sharply defined aeromagnetic anomalies were discovered. Kerr Grant (1953) suggested that a number of ground vertical force magnetic surveys should be conducted over these anomalies, to define their extent, to investigate the possible copper magnetite association, and for iron ore. The areas of greatest magnetic disturbance were given first priority for possible iron ore deposits. Four separate aeromagnetic anomalies using both magnetic and gravity methods with a follow-up diamond drilling programme, were investigated, namely: Balgowan, (Crawford, 1955); Weetulta, (Crawford, 1957); North Kadina, Areas 1, 2 and 3 (Pegum, 1954a); and Currumulka, (Seedsman, 1957). These results were difficult to interpret (Pegum, 1954a), owing to (i) the lack of detailed geological knowledge, (ii) the wide variety of magnetic rocks, and (iii) the lack of mathematical models. The first three anomalies were reinterpreted, and are presented later.

In 1960, the B.M.R., whilst survey flying BURRA and CHOWILLA, (Wells, 1962), reflew the land areas of Wallaroo, Broughton, Wandearah and Whyalla. The latter flight lines were oriented east-west and flown at 500 ft. a.g.l. with a line spacing of 1 mile. This data was contoured at 50 nT.

4.4 THE RECONNAISSANCE EXPLORATION PERIOD (1960-1965)

The previous experimental tests had shown that:

(i) Ground magnetics could be used for delineating fold and fault structures, (Weiss, 1948).

(ii) In the experimental geochemical techniques, (Sokoloff, 1948) analyses of auger chip samples resolved significant responses over the known orebodies, whereas surface geochemical sampling was dependant on particular lithological horizons for significant results.

During the period of iron search, 1950-1959, two significant advances relevant to the exploration problems of Wallaroo-Moonta had evolved, as follows:

(a) The ground geophysical investigations of the aeromagnetic anomalies of Balgowan, North Kadina and Weetulta, and the subsequent drilling had suggested a possible stratigraphic correlation with the Middleback Sub-Group, (Whitten, 1955; 1966a,b).

The copper assays from the numerous drillholes sited to investigate the sources of these magnetic anomalies, showed values between 0.01 to 0.10% Cu, with considerable depth variations, which when plotted against the percentages of total iron (Fe_2O_3 + FeO) and magnetic iron from these drillholes showed no direct correlation, (Whitten, 1955; 1957). He considered there was no direct correlation between the copper values and the highly magnetic horizons, and states "the copper mineralisation appeared to be independent of the magnetic material".

(b) Overseas developments in the field of Induced Polarization, (Bliel, 1953; Hallof, 1957; Marshall and Madden, 1959), the experimental successes in U.S.A. (Hallof, 1960; Seigel, 1962) and Canada; and tests at Cobar and Broken Hill, New South Wales, by Broken Hill South Ltd., illustrated the potential of the frequency domain, induced polarization technique for the discrimination of conductors.

The combination of these four factors contributed to the reconnaissance exploration, initiated by Gold Mines of Australia Ltd., (a subsidiary of W.M.C.), over 4350 km^2 defined between latitudes 33°30'S and 34°35'S; and longitudes 183°2'E to the coast line in the west.

4.4.1 THE EXPLORATION OF GOLD MINES OF AUSTRALIA LTD.,

From 1960 to 1963, Gold Mines of Australia held four successive Special Mining Leases (Nos. 36, 37, 38 and 42) in the Wallaroo-Moonta region. In 1960 they conducted a number of magnetic traverses (142 line km.) and an experimental I.P. study, (52 line km) south and southeast of Wallaroo.

The I.P. method (frequency domain), using a dipole-dipole configuration, responded well over the known mineralised areas, and it was expected that this method would be successful in the surrounding areas. Woodall (1961) stated that some trouble was experienced in areas of low ground resistivities near the coast. Power line and earth-return currents caused local difficulties.

The initial reconnaissance area investigated, outside the known mines area was 24 km southeast of Moonta and east of the Weetulta investigations. The I.P. and magnetic data covered 174 and 512 line km. respectively (Triglavcanin, 1962). Tiparra DDH 1 and 2, drilled to depths of 230 and 428 m. respectively over two P.F.E. anomalies, intersected sulphide mineralisation, (Larsen, 1963).

Triglavcanin used the aeromagnetic contours to select the direction of the I.P. traverses, either north-south or east-west. He experimented over a promising P.F.E. anomaly in Tiparra area, to select the best dipole spacing to clearly resolve a source buried beneath 76 m of overburden. A dipole spacing of 300 ft. using frequencies of 0.25 and 2.5 cps. gave the best resolution. He also found the I.P. equipment was unsuitable in low apparent resistivity areas, less than 1 ohm. m. Comparable low resistivity overburden has been reported in the Kalgoorlie area, Western Australia, as shown by the I.P. pseudo-sections given by Hallof (1968). Baird (1972) referred to it in discussing the signal attenuation due to electromagnetic coupling and masking of conductive overburden. Pridmore and Lindman (1981) referred to this coupling problem in the exploration of the Pincher Well-type mineralisation (a Cu-Zn with minor Pb and Ag occurrence within an acid to intermediate volcanic lava and pyroclastic sequence), within the Kalgoorlie region.

The relationship of the I.P. (P.F.E.) anomalies with the magnetic profiles was subdivided into three group (Types A,B,C) by Triglavcanin:

A. Anomalous I.P. (P.F.E.) centred below the apex of a magnetic anomaly.

B. Anomalous I.P. (P.F.E.) in apparent resistivity low areas, and centred on the inflexion point of the magnetic anomalies.

C. Anomalous I.P. (P.F.E.) which did not correlate with magnetic anomalies of significant magnitude i.e. independent of any magnetic source.

The significance of these groups are of considerable interest and are discussed throughout later chapters.

A large scale (blanket) geophysical programme, using both magnetics and I.P. methods, was conducted from 1961-1964, to cover S.M.L. 42. This programme involved geochemical auger testing for copper over P.F.E. anomalies, followed by diamond drilling of target areas. About this time Western Mining Corporation, Broken Hill South Ltd. and North Broken Hill Ltd. formed a partnership to explore this area.

I.P. data was obtained using a co-linear dipole-dipole configuration with an electrode spacing of 200 feet. The station interval for the vertical magnetic data was 300 feet. By the end of 1964, the total line mileage covered by the ground magnetics and I.P. traverses was 3943 and 1304 line km. respectively, auger hole sampling, and seven diamond drill holes, having a total metreage of 2454 m.

On the 22.1.64, Gold Mines of Australia Ltd., transferred the lease to Western Mining Corporation Ltd.

4.5 THE EXTENSIVE COPPER SEARCH PERIOD (1965 to PRESENT)

The geophysical exploration in this period has been restricted to detailed surveys of local prospects in areas of anomalous P.F.E. Geochemical augering was used to determine what extent the P.F.E. response could be attributed to copper or base metal mineralisation. In areas of sufficiently marked geochemical anomalies, which coincide with P.F.E. anomalies, diamond drill holes were sited to test the basement for mineralisation.

Figure 4.5 shows two main phases of geophysical exploration from 1960 to 1978, separated by a period 1966-1968, in which extensive vertical electrical soundings (V.E.S.) were applied in the Moonta-Kadina and Tiparra (Weetulta) area, to determine the resistivity basement configuration, and the real surface layer resistivity characteristics, for the I.P. interpretation. In addition to V.E.S., a total of 195 line km. of resistivity profiling was undertaken, mainly between Moonta and Kadina.

The significance of the interpreted results of the V.E.S. data and similar data in the Tickera-Alford-Port Broughton area, (Gerdes, 1974), is discussed later.

In 1968, the S.A.D.M.E. held E.L. 87 and 207, with the purpose of investigating the basement-cover relationships at the edge of the Gawler Block, between the metamorphic basement and the Adelaidean in the Bute, East Bute and Tickera-Broughton areas. Most of these geophysical investigations were planned and made by the author, supplemented by surface float mapping in the Bute area, and auger and stratigraphic drilling. Subsequently N.B.H. leased a portion of E.L. 87 as E.L. 248. Geoex flew a detailed aeromagnetic survey of the Bute area for N.B.H. in 1976, and Geoterrex flew an aeromagnetic and INPUT survey over the East Kadina area in 1975.

In MAITLAND, B. Riseley and the author tied in most of the previous gravity data to a new network connected with the Australian Gravity Network, and D. Roberts recorded numerous additional stations for the standard 1:100 000 computation. Between 1974 and 1979, two aeromagnetic surveys of the Maitland (E.L. 181) and Price areas (E.L. 180) were flown by Geometrics for Aquitaine Australia Minerals Pty. Ltd. The magnetic data was analysed using Geometrics' compudepth computer programme in their search for Cambrian stratiform lead-zinc deposits. Some possible targets were resolved, which were defined by I.P. (time domain) traverses. Subsequent drilling found no significant mineralisation.

4.6 SUMMARY

The geophysical exploration history of the different periods of commodity search in the Wallaroo-Moonta Province (Figure 4.5), shows the extent of geophysical methods tried, both successfully and unsuccessfully in the different periods between 1930 to 1980 after the mines closed in 1923. The major geological and geochemical contribution from government agencies, company exploration and university research are included as these are important in any case history study of a metallogenic province.

The feasibility period between 1930 to 1947, a period of copper search, saw the introduction of geophysical methods into Australia, with the I.G.E.S. (Edge and Laby, 1931) and in 1942 the experimental Commonwealth Department of Supply and Development survey, (Thyer, 1943) in the search for additional copper lodes. The three major geological contributions were from Jack (1917) and Dickinson (1942a), on the basement geology and structures of the lodes, and from Jones (1940), who provided detailed petrology of the Tickera Batholith.

The two early geophysical experimental surveys, combined with the contribution from the Oscar Weiss organisation for Zinc Corporation, and the concurrent radiometric surveys by the S.A.D.M. in the search for uranium between 1948 to 1955, provided the basic exploration method in the search for copper and later iron ore, between 1950 to 1960. The I.P. method was tested in 1961 and used predominantly by W.M.C. from 1962 to 1970, combined with geochemistry for locating possible mineralised targets.

Detailed airborne radiometric methods were introduced into the area in 1951 for the uranium search, and regional aeromagnetic and airborne radiometrics surveys were flown for the iron ore search in 1952. Detailed aeromagnetic surveys were not used by the joint venture partners until 1974, as they considered that the reconnaissance blanket vertical magnetic traverses surveyed by W.M.C. between 1961 to 1969 were adequate for their requirements, as their prime exploration methods to delineate targets were auger geochemical sampling combined with I.P. (frequency-domain), ground magnetics and diamond drilling. The 1974 East Kadina aeromagnetic survey introduced the INPUT-electromagnetic method into the Province, and, combined with a review of the I.P. data, (Smith, 1976), did not really influence and stimulate N.B.H. to test other recent geophysical electrical and electromagnetic techniques.

However, I.P. (time domain) was tested successfully by Aquitaine Australia Minerals Pty. Ltd. in their Maitland exploration licence, and recently M.I.P. has been successfully tested by Jododex in the Alford region in the northern part of the Province. A discussion of these two methods is not given as the I.P. (time domain) method was applied in the search for stratiform Pb-Zn in the Cambrian limestones, and the Jododex data is confidential.

In retrospect, in a concealed area like the Wallaroo-Moonta Province, should the target drilling exploration philosophy be accepted, or, should an integrated philosophy be adopted to obtain a regional stratigraphic and structural picture, and then use conceptual models in the selection of exploration targets? The target drilling philosophy, or anomaly philosophy in this Province was successful in defining some of the sub-economic ore deposits by 1970, but at that stage did not provide the regional geological or structural picture. An attempt was made by Wright and Lynch (1973), which incorporated some of the author's initial geophysical interpretations, and Lynch (1976 and 1977a-c). These compilations were made 56 years after Jack's mapping of the Wallaroo-Moonta Mining districts, although attempts were made by Benedict and Bacon (1948), Crawford (1965) and Callen (1966).

The copious geophysical data could have been used to obtain the regional structural configuration of the basement rocks. Some interpretations have been made of local prospects, and interpretations of the earlier geophysical data, Thyer (1943), Wegerle (1948) and Weiss (1948) showed the way, combined with the factual geological compilation of Benedict and Bacon in 1948. It would have been possible in the late sixties to have developed regional and integrated exploration philosophy, using interpretive methods developed by the B.M.R., and from overseas studies, e.g. Domzalski (1966), Boyd (1970) and Richards and Walraven (1975). Note that the reconnaissance W.M.C. contoured data provided the distribution of the major magnetic units, but is unsatisfactory for any detailed study, due to the way the contour cuts were taken, and should either be recontoured or reflown by a detailed aeromagnetic survey.

The forthcoming chapters are a new interpretation of the Wallaroo-Moonta Province, which will contribute towards a regional understanding of the major geological structures in this concealed complex area.

CHAPTER 5

PETROPHYSICAL PROPERTIES OF ROCKS IN THE WALLAROO-MOONTA PROVINCE AND SURROUNDING AREAS

Petrophysical properties of the basement and cover rocks is highly desirable and in part is essential for qualitative interpretation. More attention should be given to this fundamental data for model studies. The data required is density, magnetic susceptibility, remanent magnetisation, and to a minor extent, resistivity and velocity data, for electrical and seismic correlation.

Previous magnetic investigations in this Province relied on density and susceptibility data, from lists in standard text books, from iron ore studies, e.g. Middleback Subgroup, or, from values derived from similar rocks overseas. Also, the theoretical rock density may be obtained from silicate analysis calculations, a widely used method in the U.S.A. for studies of igneous complexes. Few such analyses have been made on this area.

Petrophysical data originally in other chapters, were combined for simplicity to form part of this chapter. The geological discussion explains the importance of particular sections, especially associated with exploration. These lithological and stratigraphic concepts are assumed and are required as background information in later chapters.

The expected magnetic anomaly, estimated from an intersected magnetic unit within a drillhole, is presented in terms of vertical field intensities, as most data interpreted in the later chapters is of this type. If it is total field data, it is specified. The amplitude is estimated using a vertical dyke model, based on Gay (1963), assuming the source depth corresponds to the drill hole intercept depth, or the vertical depth. If numerous drill hole intersections are present, correction for the dip is specified where known. In some cases, the depth to width ratio is estimated as unity, if the width is unknown. Other interpretational details are given in Appendix 1.

5.1 REVIEW OF PREVIOUS PETROPHYSICAL DATA OF PROTEROZOIC ROCKS

South Australia lacks Proterozoic petrophysical data, except for local detailed studies of iron formations. The few petrophysical investigations of Proterozoic rocks nearby are summarised, as equivalent rocks may occur in the Wallaroo-Moonta Province. During this research, a few surface and systematic core samples were also measured from Proterozoic rocks. Since the discovery at Roxby Downs, companies have provided some additional data.

EARLY PROTEROZOIC

A summary of Mumme (1963) and Gunn (1967) for the Middleback Ranges is given in section 5.2. (Tables 5.1 and 5.2 respectively). Whitten & Riseley (1968) provided data for the Warramboo area in KIMBA. The author, sampling at 1 foot intervals, measured some cores within the Gawler Block, as background data for this study, but this data is not presented, because the research showed the Wallaroo-Moonta Province contains mainly late Early to Middle Proterozoic rocks. Reference is made to some of this data in the regional study, Chapter 6.

MIDDLE PROTEROZOIC

Petrophysical data is limited to Mumme (1963, Table 5.1) and Riseley (1968, Table 5.3) in PORT AUGUSTA. Some estimates from Roopena DDH 1 and 2 (Gerdes, 1972) show the mean susceptibility of the Roopena Volcanics is 0.4 x 10^{-3}cgs units, with some lower values correlating with oxidised samples and andesites (Table 5.4).

Mumme's susceptibility results show the Corunna Conglomerate has a value less than 0.04 x 10^{-3}cgs units and the Moonabie Porphyry, (renamed McGregor Volcanics, Parker, 1980b) and Gawler Range Volcanics have maximum values of 3.53 and 1.34 (x 10^{-3}cgs units). The values reported by Mumme for the Gawler Range Volcanics in PORT AUGUSTA, from either the rhyodacite or dacite, are higher than the susceptibility values measured on fresh surface geochronological samples, from the Kokatha area, GAIRDNER. Although these values from dacite, rhyodacite, tuffs and welded tuffs show a wide variation, they are all less than 0.28 x 10^{-3} cgs units. The andesite and vesicular basalt, (lower units of the Gawler Range Volcanics) have values of 0.33 and 0.51 (x 10^{-3}cgs units) respectively, and a flow banded obsidian,

TABLE 5.1

MAGNETIC PROPERTIES OF ROCKS IN THE MIDDLEBACK RANGES AREA (Mumme, 1963)

Rock Type	No. of Specimens	Permanent Movement (x 10^{-3} cgs units)	Susceptibility (x 10^{-3} cgs units
Hematite Quartzite	54	0.07 to 154	0.13 to 134
Hematite Ore	16	0.48 to 13.2	0.10 to 2.14
Gawler Range Porphyry	15	0.36 to 6.71	0.29 to 1.34
Granite (TOR) (Charleston Granite)	9	0.31 to 26.7	1.91 to 3.20
Moonabie Porphyry	3	2.49 to 9.46	1.89 to 3.53
Amphibolite	8	0.02 to 0.16	0.02 to 0.13
Corunna Conglomerate	6	0.004 to 0.02	0.01 to 0.04

TABLE 5.2

MAGNETIC SUSCEPTIBILITIES OF METASEDIMENTS IN THE SOUTH MIDDLEBACK RANGES

(based on Gunn's 1967 data)

Lithology	Magnetic Susceptibility (x 10^{-3} cgs units)	Koenigsberger Q Ratio
Dolomite	0.120	-
Chlorite Amphibolite	0.112 to 0.370	12.6 to 15.7
Amphibolite	0.68	16.0
Amphibolite Schist	0.44	68
Amphibolite Chlorite Schist	2.40	63
Magnetite amphibolite Schist	18.5	2.7

(prepared by R.A. Gerdes, 1983)

TABLE 5.3
SPECIFIC GRAVITIES OF SURFACE SAMPLES COLLECTED IN PORT AUGUSTA
by RISELY (1968)

Formation Name	Lithology	No. of Samples	Specific Gravity Range	Mean	Standard Deviation
Roopena Volcanics	Fresh basalts	17	2.61-3.35	2.818	0.165
	(weathered)	1	-	2.42	-
	combined	18	2.42-3.35	2.796	0.186
Moonabie Formation	Quartzite	4	-	2.637	0.017
Pandurra Formation	Quartzite	1	-	2.44	
	Gabbro	1	-	3.07	
Gawler Range Volcanics	Porphyry	1	-	2.62	
	Granophyre	1	-	2.57	
	Combined	2	2.57-2.62	2.595	0.035

TABLE 5.4
MAGNETIC SUSCEPTIBILITY OF THE ROOPENA VOLCANICS

	OVERALL RANGE ($x10^{-3}$ cgs units)	No. of Samples	Mean	Standard Deviation
All samples (1)	0.031 to 0.86	14	0.387	0.208
Samples neglecting low values (2)	0.13 to 0.86	11	0.407	0.195

All values are x 10^{-3} cgs units

(measured by R.A. Gerdes, 1983)

and a rhyolitic agglomerate (possible welded tuff) have susceptibility values of 0.28 and 0.107 (x 10^{-3}cgs units) respectively. An interpretation of a linear magnetic anomaly trending at 045° in GAIRDNER coincident with the contact between the rhyolite (middle unit) and overlying rhyodacite-dacite (upper unit), has a susceptibility contrast of 0.92 x 10^{-3}cgs units, which compares with this surface susceptibility data, thereby confirming these lower values.

Mumme's data on the Charleston Granite, (Table 5.1) show abnormally high susceptibility values, and may explain some of the features described by Roberts (1978).

LATE PROTEROZOIC - ADELAIDEAN

Petrophysical data on the Fold Belt was discussed in a palaeomagnetic study by Briden (1967). Tucker (1972) studied the Tindelpina Shale Member and measured densities, using surface and core samples, with some density estimates from gravity profiles.

Most sediments in the Stuart Shelf and Adelaide Fold Belt are non-magnetic (less than 100 x 10^{-6}cgs units). Volcanics are few, except for the Beda Volcanics on the Stuart Shelf, at Depot Creek and River Broughton, and Wooltana Volcanics in the Adelaide Fold Belt and Mt. Painter area. Ironstones are present in the Sturtian tillites as the Braemar and Holowilena Iron Formations. The Tindelpina Shale Member (Tapley Hill Formation) is magnetic. The major magnetic marker beds (Table 5.5) are shown with their observed magnetic anomaly amplitudes. Other minor magnetic units are the Pepuarta Tillite, the Bethel Shale Member (Saddleworth Formation), the Rhynie Sandstone (Algate Sandstone in ADELAIDE), and a unit near the Minburra Quartzite in ORROROO. The petrophysical data is limited on these units, due to the surface weathering, the development of a Tertiary calcareous or siliceous crust, and the lack of drill core. In general, drill holes within the Adelaide Fold Belt are shallow (less than 200 m), relate to mineral prospects and do not provide reliable petrophysical data representative of the stratigraphic unit outside the local prospect area. The susceptibility and specific gravity data in the Adelaide Fold Belt is summarised in Table 5.6.

TABLE 5.5
MAJOR MAGNETIC MARKER BEDS IN THE ADELAIDEAN SYSTEM

Wilpena Group	Ulupa Siltstone	600 nT.	Tucker (1972)
Umberatana Group	Tindelpina Shale Member.	500 nT.	Tucker (1972)
	Braemar Iron Formation	2500 nT.	Gerdes (1973)
	Holowilena Ironstone	1500 nT.	
	Appila Tillite	20-150 nT.	Gerdes (1973)
Burra Group	Minburra Quartzite (eastern side of ORROROO)	100 nT.	Tucker (1972)
Willouran	Roopena Volcanics	500-1500 nT	Risely (1968)
	Wooltana Volcanics	500-2000 nT	(Young and Gerdes (1966)

(prepared by R.A. Gerdes, 1983)

TABLE 5.6

PETROPHYSICAL DATA OF ADELAIDEAN ROCKS IN THE FOLD BELT BASED ON DRILL HOLE DATA

*Based on Tucker (1972)

GROUP	FORMATION	MAGNETIC SUSCEPTIBILITY (x 10^{-3} cgs units) No. of Samples	Range	Median	Mean	S.D.	SPECIFIC GRAVITY No. of Samples	Range	Median	Mean	S.D.
UMBERATANA GROUP	Appila Tillite*	11	0-0.18	0.075	0.70	-	-	-	-	-	-
	Holowilena* Ironstone	4	0.15-58.0	-	-	-	-	-	-	-	-
	BRAEMAR IRON FORMATION										
	Population A	58	0-26.0	18	8.138	4.085	55	2.9-3.3	3.1	3.12	0.13
	Population B	6	34-54.0	40 approx.	43.636	3.636	20	3.8-5.0	4.1	4.10	0.25
	Tindelpina Shale* Member	26	0.025-3.00	0.05	0.75	-	-	-	-	-	-
WILPENA GROUP	Ulupa Siltstone*	31	0.5-15.0	0.5	-	-	-	-	-	-	-
EARLY CAMBRIAN											
TRURO VOLCANICS) (surface samples)		23	0.092-0.268	0.16	0.1603	0.039	33	2.35-3.20	2.95	2.99	0.14
'Bendigo' Granite DDH(BD3)		44	0.07-7.48	0.7/1.8	1.121	1.464	71	2.51-2.84	2.65	2.64	0.07
(ORDOVICIAN AGE)											
	DDH(BD7)						41	2.39-2.72	2.66	2.64	0.06

(measured by R.A. Gerdes, 1983)

5.2 REMANENT MAGNETISATION

No remanent magnetisation data is available on the Wallaroo-Moonta Province, except for a study of Precambrian basic dykes near Point Victoria and Corny Point in lower Yorke Peninsula, (Giddings and Embleton, 1974); and Early Cambrian limestones in the Stansbury Basin, (Embleton and Giddings, 1974).

The dykes in the Point Victoria area, trend between 290° and 340°, except for a negative (reversed) polarised N-S dyke. In the foot of the Peninsula, they trend between 270° and 320° and show a unimodal distribution with the dykes further north. The remanent directions from these two locations show similar declinations and positive inclinations, (Table 5.7). A minor set with a negative polarisation direction, compares with those in Eyre Peninsula, (Giddings and Embleton, 1974).

The dykes between Point Neill and Cape Carnot on Eyre Peninsula have two orientations. The major orientation between 0° and 50°, is similar to an orientation in upper Yorke Peninsula, which is only evident as linear magnetic sources resolved in the East Kadina aeromagnetic data, (Chapter 15) and in the Cape Elizabeth-Agery area. The minor orientation in Eyre Peninsula, between 110° and 140°, is similar to the major dyke group in central and lower Yorke Peninsula.

These two groups of dykes, in Eyre Peninsula, have both positive and negative polarisations. Their group-means are not antiparallel and are interpreted to record two separate periods of dyke-intrusion, (Giddings and Embleton, 1974). Their geochronological ages are unknown, but based on comparable strike orientations, the NW-SE strike in lower Yorke Peninsula may be compared to the Gairdner Dyke Swarm, the assumed feeders of the Beda Volcanics, which have an Rb/Sr isochron age of 1076 ± 34 Ma., (Webb, 1978a).

The remaining dykes have similar palaeomagnetic inclinations and declinations to those reported by Facer (1971) for the Giles Complex and the associated dolerite dykes, which have an age of 1100 to 1000 Ma. This data suggest that the major intrusive event, represented by the Gairdner Dyke Swarm and the NW-SE dykes in southern Yorke Peninsula, have a common age with ultrabasic intrusions in the Musgrave Block.

TABLE 5.7

SUMMARY OF THE PALAEOMAGNETIC DATA FROM YORKE AND EYRE PENINSULAS

	N	R	D°	I°	Ags
*Eyre Peninsula (Basic Dykes)					
(a) positive group	9	8.389	270	+59	15°
(b) negative group	10	9.665	032	-49	9°
*Yorke Peninsula (Basic Dykes)					
(a) leg (Port Victoria)	5	4.768	275	+60	19°
(b) foot (Corny Point area)	8	7.379	275	+65	17°
+Iron Monarch					
(a) positive group	28	25.678	283	+63	8
(b) negative group	13	12.355	26	-58	10
+Iron Prince	22	20.660	63	-46	8
øGawler Range Volcanics (Kokatha area)	52	-	34.2	-48	5.2

Where N = number of dykes meaned in analysis.

R = resultant of N unit vectors.

D° = Declination.

I° = Inclination.

Ags = semi-angle of the cone of confidence at the 95% probability level. (Fisher, 1953).

* (Data based on Giddings & Embleton, 1974).

+ (Data based on Chamalaun & Porath, 1968).

ø (Data based on Chamalaun & Dempsey, 1978).

(prepared by R.A. Gerdes, 1983)

5.2.1 THE METASEDIMENTS IN THE YORKE AND EYRE PENINSULAS

As no remanent data is available in the Wallaroo-Moonta Province, an estimate based on data from Eyre Peninsula is required, as the order of the magnitude and/or intensity and remanent component direction is important for interpretation.

Studies of remanent magnetisation were made on the Middleback Subgroup, amphibolite and Corunna Conglomerate, (Mumme, 1963, Gunn, 1967 and Chamalaun and Porath, 1968); the Charleston Granite, porphyries of the McGregor and Gawler Range Volcanics (Mumme, 1963); and the Gawler Range Volcanics in the Kokatha area, GAIRDNER (Chamalaun and Dempsey, 1978).

Mumme (1963) measured the permanent magnetic moment per unit volume and susceptibility (Table 5.1), to determine the preferred orientation of the remanent magnetisation, using an astatic magnetometer. The stereographic equal-angle projection of the directions for the hematite quartzite, (Middleback Subgroup) showed a random orientation of both normal and reversed directions. Measurements of hematite quartzite from two drill holes between 16.5 and 134 m, showed a susceptibility range from 1.02 to 7.36 (x 10^{-3}cgs units), mean value of 4.22 ± 1.79 (x 10^{-3}cgs units). The permanent moment ranged from 0.14 to 0.668 (x 10^{-3}), with a mean value of 0.278 ± 0.19 (x 10^{-3} cgs units) per unit volume. These results show the Koenigsberger Q ratio is less than 0.24 for these hematite quartzites, i.e. the remanent component is small. Mumme found no marked magnetic increase with depth in the Iron Monarch area, as the holes were still within the weathered zone.

Gunn's (1967) results on the remanent magnetization of the Lower Middleback Jaspilite from the South Middleback Ranges showed that the directions of the permanent magnetic moments were random, after correction for the folding component. Gunn did not report A.C. washing procedures in his study.

Susceptibility and permanent moment measurements on core from the South Middleback Range, ranged between 60 and 200 (x 10^{-3}cgs units) with a mode, median and mean value of 130 x 10^{-3}cgs units. Gunn explained these values by magnetic anisotropy, due to demagnetization and the concentration of magnetite into bands. Rocks containing 20% magnetite by volume show susceptibility values measured along the layers are twice that recorded in homogeneous rock, and the susceptibility parallel to the bands or layers can be over twice that recorded perpendicular to these bands (Jahren, 1963). Therefore, this spread of susceptibility values for the Lower Middleback Jaspilite may in part be explained by these bands being folded to produce an overall random orientation with respect to the core barrel.

Gunn's estimates of the Koenigsberger Q ratio showed a large variation, with a possible grouping between 2 to 16, with a maximum of 730, indicating that the permanent moment is greater than the induced magnetic component for these jaspilites. Gunn also measured the susceptibilities and Q ratios of amphibolite and amphibolite schist, and found a similar remanent component to the jaspilites.

Hematite from Iron Monarch, Iron Prince and Iron Duke ore bodies, after alternating field demagnetization of the N.R.M. and thermal demagnetization to the Curie point, (Chamalaun and Porath, 1968), showed two distinct groups. The first group has a steep positive inclination and the other has a steep negative inclination for the Iron Monarch ore body. Iron Prince showed the major population has a negative inclination with the other group representing 12.9% having a positive inclination, (Table 5.7). Iron Duke showed a random direction for the distribution of the N.R.M.. Chamalaun and Porath interpreted these inclinations as either a reversal or a change in the dipole axis, indicating a possible time interval between these two palaeomagnetic events. The N.R.M. value from the North Wall amphibolite dyke coincides with the positive group and thermal demagnetization curves of the ore, and is interpreted as pre-ore, whereas, the Central Dolerite Dyke post-dates the ore.

5.2.2 INTENSITY OF MAGNETISATION OF IRON FORMATIONS

The T.R.M. intensity of remanent magnetization of 10^{-1} emu cm^{-3} recorded in a field of 0.6 oersted, showed the N.R.M. intensity lies between 10^{-4} and 10^{-2} emu cm^{-3}. This N.R.M. is related to the CRM, and may correlate with the replacement/origin of the hematite ore (Chamalaun and Porath, 1968).

Palaeomagnetic studies of the Gawler Range Volcanics, having a mean age of 1525 ± 15 Ma., show a distinct negative inclination, (Table 5.7) based on remanent component values after magnetic cleaning and thermal demagnetization, (Chamalaun and Dempsey, 1978). These results are comparable with the data for the negative inclination group of the iron formation at Iron Monarch and Iron Prince (Chamalaun and Porath, 1968) and the negative inclinations for basic dykes in Eyre Peninsula, (Giddings and Embleton, 1974).

The positive inclination is interpreted to represent the pre-iron ore concentration, corresponding to the palaeomagnetic field at the time of metamorphism, (Deformation D_2). The weaker negative inclination, represented by the later dyke intrusions, indicates igneous activity and hydrothermal fluids, both penetrating along structurally weak zones. By comparison with the paleomagnetic data for Gawler Range Volcanics, the possible period of iron ore processes was 1600 to 1500 Ma, (Chamalaun and Dempsey, 1978). These two inclinations are time equivalents to the possible metamorphism in the Kadina area, and the weaker corresponding to the possible emplacement age of the Moonta Porphyry. However, few negative polarized magnetic features have been identified in either Peninsulas to date. The later recrystallising and/or mineralisation event in Wallaroo-Moonta probably reached a temperature of 700°C (McBriar, 1962), thereby reaching the Curie point, and depending on the time period involved, would have caused readjustment and/or realignment to a 'new' magnetic field and direction. As the later field parameters are unknown, the qualitative interpretation of the Wallaroo-Moonta magnetic data was assumed to be produced by the present induced field, with no corrections for any remanent or demagnetization effect.

5.3 SUMMARY OF PETROPHYSICAL DATA FROM DRILL HOLES IN THE REGION AROUND THE WALLAROO-MOONTA PROVINCE

This data is concerned with important regional magnetic units near this Province. As estimates of magnetic basement depths show east and south of the Province numerous shallow magnetic sources, which appear to originate from within Tertiary and Cambrian sediments, a possible explanation is outlined.

The possible Tertiary magnetic sources originate from heavy mineral bands, and some very magnetite-rich lens were verified by drilling, in the Bute area, (Lynch, pers. comm.). The other sources are disseminated glauconite bands within the Port

Willunga Formation and Blanche Point Marls, in Barabba DDH3 (Figure 5.1). The results show the mean susceptibilities are 64 and 111 (x 10^{-6}cgs units) respectively, but the percentage of glauconite in each formation is unknown. The values from adjacent beds are low, generally less than 10 x 10^{-6}cgs units.

Similar magnetic responses in Early Cambrian limestones were due to glauconite-rich bands. Aquitaine DDH SYC610 contains up to 10% glauconite between 78-80 m. This glauconite-phosphate facies is 250 m thick in the upper member of the Kulpara Limestone in the Curramulka area. Some small isolated copper anomalies, with no Pb or Zn assays are associated within the central portion of the Kulpara Limestone, i.e. within the limestone-dolomitic limestone-glauconite limestone facies zone, (Lee, 1977). Susceptibility measurements verified these magnetic sources.

In Bute DDH2 values up to 400 x 10^{-6}cgs units were observed within the Kulpara Limestone, (Table 5.8). The Mt. Terrible Formation is non-magnetic. Depending on the proximity of magnetic basement rocks, some locally derived material within these transition beds are also weakly magnetic.

5.3.1 ADELAIDEAN SEDIMENTS

Petrophysical measurements from the Bute and Wokurna stratigraphic holes (Table 5.8) show Adelaidean sediments have a mean susceptibility less than 100 x 10^{-6}cgs units, except for the shale and dolomitic-siltstone sequence (Woolcalla Dolomite equivalent) in the Tapley Hill Formation, which has mean values of 195 and 332 (x 10^{-6}cgs units) in Bute DDH3. These units in Wokurna DDH2 are less than 60 x 10^{-6}cgs units, indicating local facies variations. The other exception is the Appila Tillite, which has a mean value of 50 to 60 (x 10^{-6}cgs units), and has a thin magnetic unit, (4 m thick in Wokurna DDH4) which has susceptibility values from 4500 to 13450 (x 10^{-6}cgs units), and a mean value of 7620 x 10^{-6} cgs units. This unit is correlated with the Braemar Iron Formation, (R. Coats, pers. comm.).

The S.G. data repeatably indicates that most of the Adelaidean sediments on the Spencers Shelf are more dense than the assumed mean density of 2.67 gm/cm^3 for those in the fold belt. This may reflect a local facies variation due to the close proximity of basement rocks, i.e. locally derived material. This 2.67gm/cm^3 value

TABLE 5.8

MAGNETIC SUSCEPTIBILITY AND SPECIFIC GRAVITY DATA OF SHELF CAMBRIAN AND ADELAIDEAN ROCKS IN THE SPENCER & STUART SHELVES

(BASED ON SAMPLES FROM DRILL HOLES)

TIME UNIT	MAGNETIC SUSCEPTIBILITY ($x10^{-6}$ cgs units) No. of Samples	Range	Mean	S.D.	SPECIFIC GRAVITY No. of Samples	Range	Mean	S.D.	DRILL HOLE SAMPLED
CAMBRIAN									
para Limestone	5	0-400	150	210	6	2.80-2.86	2.82	0.03	Bute DDH2
	2	350-420	390	50	-	-	-	-	Bute DDH2
nt Terrible Formation	1	-	0	-	1	2.62	-	-	Bute DDH2
IDEAN SYSTEM									
oona	-	-	-	-	-	-	-	-	
nens Quartzite Member (Equiv.)	-	-	-	-	-	-	-	-	
raberra Sandstone M.	13	4-6	5	1	75	2.04-2.85	2.53	0.03	Woomera Bore
lana Shale M.									
omera Shale M.)	4	70-100	80	14	195	2.44-2.76	2.65	0.05	Woomera Bore
llah Siltstone M.	25	20-240	86	54	25	2.67-2.84	2.76	0.04	Wokurna DDH6
omera Shale Equiv.)									
china Formation	52	20-500	99	69	52	2.24-2.91	2.70	0.12	Wokurna DDH6
caleena Formation	30	0-80	25	25	30	2.64-2.71	2.67	0.01	Wokurna DDH6
cliff Sandstone M.	43	0-210	53	40	43	2.60-2.82	2.66	0.05	Wokurna DDH6
nella Siltstone M.	20	50-110	74	15	20	2.64-2.78	2.74	0.03	Wokurna DDH6
alla Sandstone	3	-	7	0	86	2.14-2.65	2.42	0.10	Woomera Bore
lochra Subgroup									
nit A. Maroon Shale	15	0-93	56	24	15	2.67-2.77	2.71	0.03	Wokurna DDH3
nit B. Feldspathic/Calcareous Sandstone	45	0-80	53	20	46	2.60-2.78	2.73	0.04	Wokurna DDH3
epena Formation	36	20-60	41	13	36	2.49-2.79	2.64	0.08	Wokurna DDH5
Willochra Subgroup)									
epena Formation									
nit 1. Shales	94	30-82	60	11	93	2.49-2.82	2.73	0.06	Wokurna DDH3
nit 2. Dolomitic Sandstone	92	30-95	63	15	92	2.53-2.93	2.78	0.04	Wokurna DDH3
ghton Limestone	33	10-50	32	7	33	2.55-2.85	2.75	0.06	Wokurna DDH5
erbanded Brighton Lst. & apley Hill Fm. (Transition Beds)	8	30-50	44	7	8	2.64-2.74	2.70	0.03	Wokurna DDH5
oley Hill Formation	61	0-80	61	20	61	2.60-2.82	2.72	0.03	Wokurna DDH
oley Hill Formation									
Unit 1	14	40-75	60	11	11	2.40-2.68	2.57	0.09	Wokurna DDH
Unit 2	37	0-90	45	31	31	2.56-2.87	2.69	0.07	Wokurna DDH
oley Hill Formation	4	0	0	-	3	2.74-2.75	2.74	-	Bute DDH2
oley Hill Formation									
Unit A. Shale Sequence	4	135-286	196	68	4	2.68-2.72	2.70	0.02	Bute DDH3
oley Hill Formation (Woocalla Dolomite Equiv.)	4	53-96	66	20	4	2.45-2.60	2.53	0.06	Beda Bore
ocalla Dolomite	4	25-50	41	11	119	2.65-3.09	2.81	0.10	Woomera Bor
ocalla Dolomite	5	0	0	-	2	2.76-2.89	2.83	0.09	Bute DDH2
ocalla Dolomite	5	266-542	332	122	5	2.81-2.87	2.86	0.03	Bute DDH3
ocalla Dolomite	8	20-65	40	16	8	2.80-2.98	2.89	0.05	Wokurna DDH
Leay Beds (Transition)	9	10-45	34	13	9	2.72-2.84	2.76	0.03	Wokurna DDH
oila (Sturt) Tillite	28	22-180	60	36	-	-	-	-	Bute DDH1
oila (Sturt) Tillite	50	5-55	41	14	50	2.67-2.90	2.78	0.04	Wokurna DD
oila (Sturt) Tillite	87	10-180	53	26	93	2.22-2.86	2.67	0.09	Wokurna DDH
oila (Sturt) Tillite (Braemar Equivalent)	5	500-13880	7623	5676	-	-	-	-	Wokurna DDH
rra Group (Skillogalee Dolomite)	125	10-175	53	32	113	2.55-2.86	2.67	0.06	Wokurna DDH
rra Group (Emeroo Quartzite Equiv.)	82	0-150	50	22	76	2.46-2.94	2.66	0.08	Wokurna DDH
ynie Sandstone (Emeroo Quartzite Equiv.)	51	0-63	28	21	51	2.69-2.96	2.79	0.07	Wokurna DDH
ynie Sandstone									
Unit A	129	10-80	42	12	48	2.15-2.72	2.52	0.12	Bute DDH6
Unit B	117	10-105	45	19	40	2.50-2.84	2.71	0.13	Bute DDH6
da Volcanics	10	1015-7480	3752	2783	10	2.65-2.99	2.81	0.13	Beda Arm DI
da Volcanics	1	238	-	-	1	2.88	-	-	PP6 (Pirie)
da Volcanics									
Population A	13	70-130	94	17	-	-	-	-	SAS C3
Population B	10	400-1200	869	274	-	-	-	-	SAS C3
da Volcanics									
Population A	107	0-380	127	77	-	-	-	-	SAS 1
Population B	53	410-880	638	124	-	-	-	-	SAS 1
Population C	55	900-3824	1422	626	-	-	-	-	SAS 1
cky Point Beds	5	57-108	92	23	5	2.58-2.60	2.59	0.01	Pirie (PP
ndurra Formation	6	10-15	13	3	196	2.34-2.77	2.56	0.07	Woomera Bo

was confirmed as a realistic mean value, based on a few hundred measurements of surface rocks from different stratigraphic units around the Adelaide - Mannum pipeline in ADELAIDE, by Adelaide University students, during a gravity terrain correction project in 1971, supervised by the author.

The major magnetic unit at the base of the Burra Group, the Beda Volcanics, is widespread on the Stuart Shelf and has been intersected by N.B.H. drilling (PP6) in the Pirie Area, just north of the Wallaroo-Moonta Province. Susceptibility measurements on Beda Arm DDH2, and Australian Selection Pty. Ltd. DDH SASC3 and SAS1 show a wide range of susceptibility values. The histogram shows three median values of 60 to 120, 600 and 1250 (x 10^{-6}cgs units) respectively. Correlations between the lithological (Mason, 1977) and susceptibility data from SAS1, shows that the highest group coincides with magnetite hematite-rich units, containing 10 to 30% Fe. The intermediate group represents the basaltic sequence, whereas the lower group correlates with varying degrees of epidotisation and carbonatization. Susceptibility variations are independent of grain size and are inversely proportional to the vesicle percentage. The susceptibility log indicates at least 10 petrophysical units. Some correlate with individual flows, whereas others are diachronous. These rocks within the Torrens Hinge Zone were subjected to considerable alteration.

5.3.2 MIDDLE PROTEROZOIC (1800-1400 Ma)

The volcanics, gently folded sediments and metasediments were previously ignored in the Wallaroo-Moonta Province and Gawler Platform, as they are concealed beneath Adelaidean sediments. Current exploration in the Gawler Block and Stuart Shelf has provided evidence for their existence, and possible transgressive relationships between these sedimentary and volcanic sequences were outlined (S. Daly and H. Blisset, pers. comm.). Tentative stratigraphic correlations were made with those in the Wallaroo-Moonta Province by Parker (1979).

Petrophysical data from stratigraphic holes intersecting the Myall Creek Volcanics, the Roopena Volcanics, Corunna Conglomerate and Willamulka metasediments and volcanics are summarised. No data is available on the Myola Volcanics.

5.3.2.1 The Myall Creek Volcanics

This sequence intersected in D.D.H. RC1, was interpreted by H. Blissett (1981) comm.) to be part of an upper sequence of the Gawler Range Volcanics. In the lithological and in situ geophysical logs (Figure 5.2), the upper porphyritic rhyodacite-dacite (welded ash flow) is possibly equivalent to the "Nonning Rhyodacite" (informal name), which rests on an altered basalt sequence, consisting of three units or flows, (Figure 5.3). These overlay a thick composite sequence of porphyritic rhyodacites which grade into dacite at depths between 89 and 248 m, and are interpreted to be two welded ash flow tuff sequences, separated by a thin porphyritic rhyolite and bedded tuff mudstone unit.

The units beneath 254 m are composed mainly of a porphyritic (welded ash flows) dacite grading into rhyodacite. The units between 254 and 510 m form three main cycles, based on in situ petrophysical correlations, and characteristic negative neutron and point resistivity responses coincident with positive S.P. and density responses. These thin bands correlate with hematised breccia zones which represent a part of each pulse of volcanic debris. Cycle 1 is characterised by a thin and repetitive sequence of these pulses. Cycle 2 shows thicker pulses and Cycle 3 is one large pulse, with a distinct matrix change from the other cycles. Cycle 3 and the upper part of Cycle 2 contains granitic inclusions with an increase in K_{40} associated with granite lower in Cycle 2. Some uranium is present in Cycle 3, and there is a significant Zn response in Cycle 2. Cycle 1 shows a greater degree of hematisation than the other cycles, and may be an important event in the mineralisation on the Stuart Shelf. No significant copper anomalies were reported.

The petrophysical logs show this sequence is subdivided into twelve petrophysical units, and the histogram parameters are given in Table 5.9. The thin magnetic units coincide with basalt, and their low susceptibility values show they are within the weathered zone. The density data over this basalt shows three subunits, and only the lower one is significantly magnetic. Giles and Teale (1979) and H. Blissett (pers. comm.) using silicate analysis data suggested a similarity with the Roopena Volcanics. The other minor magnetic unit H contains a minor pyrite and is beneath the geochemical zinc anomaly.

TABLE 5.9

PETROPHYSICAL UNITS OF THE MYALL CREEK VOLCANIC SEQUENCE

UPPER GAWLER RANGE VOLCANICS (DDH R.C.1)

DEPTH RANGE (in metres)	UNIT	SPECIFIC GRAVITY No.	Median	Mean	S.D.	MAGNETIC SUSCEPTIBILITY ($x10^{-6}$ cgs units) No.	Median	Mean	S.D.
13 to 44	A	32	2.57	2.54	0.05	32	300	309	78
45 to 89	B	88	2.61/2.70	2.63	0.08	80	100	171	82
		9	-	2.75	0.06	9	-	3225	1741
	(Basalt)	RANGE 2.69 to 2.85							
		M.S. Ranges from 1000 to 5500 x 10^{-6} cgs units							
89.5 to 108	C'	43	2.64	2.63	0.03	42	90/180	133	517
108.5 to 175	C	91	2.62-2.64	2.63	0.02	91	80/110	121	36
176 to 189	D	21		2.61	0.04	21	50	53	26
	rhyolite	6	2.60	2.57	0.05				
	wedded tuff	-	2.63	-	-	-	50	-	-
189 to 248	E	70	2.67	2.66	0.05	70	250	256	92
249 to 315	F + F'	67	2.69	2.69	0.04	67	110/150	134	36
	F	36	2.68	2.68	0.05	36	150	148	37
	F'	31	2.69	2.70	0.02	31	110	117	26
316 to 390	G	75	2.66	2.66	0.02	75	100/230	197	74
390 to 435	H	45	2.67	2.68	0.02	45	250	434	460*
	*Large S.D. due to 8 values greater than 600 x 10^{-6} cgs units								
	** Median value is a better estimate of the susceptibility of this unit								
436 to 492	I	57	2.68	2.68	0.03	57	150	175	62
493 to 518	J	26	-	2.69	0.04	26	110	116	15
519 to 539	K	21	2.73	2.70	0.04	21	80	86	19
539 to 551.34	L	13	2.71	2.70	0.01	13	130	137	27

TOTAL DEPTH OF HOLE 551.34 m

mean overall	16 units		2.65	0.05	15 units		172	96

(measured by R.A. Gerdes, 1983)

In summary, the susceptibility data indicates that this sequence is relatively non-magnetic, increases in density with depth, and is petrophysically weathered to 90 m. Some units show variation in density and susceptibility with depth, which may reflect grain size associated with the welding processes.

These subunits are important and provide fundamental data for the subdivisions of the Middle Proterozoic, but more data is needed. These rocks and those below may be equivalent to those in the Wallaroo-Moonta Province, i.e. Willamulka metasediments and volcanics and perhaps the East Kadina metasediments, and to the Myola Volcanics in Eyre Peninsula.

5.3.2.2 Roopena Volcanics

A petrophysical study of Roopena DDH 1 to 4 inclusive, (Table 5.10) shows the volcanics have a mean susceptibility of 85 x 10^{-6}cgs units from DDH1, which is a factor of 10 less than the value reported previously, and is based on different samples measured between 131 and 140 m. Table 5.10 also shows susceptibilities of the Corunna Conglomerate, Gawler Range Volcanics and Moonabie Formation, which are generally less than 50 x 10^{-6}cgs units, except for some values from the Corunna Conglomerate, which are 78 x 10^{-6}cgs units, probably correlating with part of the upper units in Uno DDH AUU6.

5.3.2.3 Corunna Conglomerate

Nissho Iwai Co. investigated the uranium potential of these sediments within the Uno Syncline. Their deepest hole selected for a susceptibility study contains numerous lithological units (Table 5.11), and represents a good cross section of the rock types. The mean susceptibility values for the whole sequence is 56 x 10^{-6}cgs units. The most magnetic rock types occur as thin bands within the two upper units, and the upper sections of the unit above 198 m have mean values between 61 and 91 (x 10^{-6}cgs units). Four bands show a characteristic linear increase in susceptibility with depth, from approximately 50 x 10^{-6}cgs units at the top to 146, 164, 110 and 190 (x 10^{-6}cgs units) respectively. These bands form four sedimentary cycles, and reflect either variations in grain size, heavy mineral content or disseminated ferromagnetic minerals. Pyrite has been observed within the upper part of this sequence, with the greatest concentration in the first cycle.

TABLE 5.10

MAGNETIC SUSCEPTIBILITY AND SPECIFIC GRAVITY DATA ON CORE SAMPLES FROM ROOPENA DDH1-4 inclusive

STRATIGRAPHIC UNIT	NUMBER OF SAMPLES	MAGNETIC SUSCEPTIBILITY (10^{-6} cgs units) MEAN	S.D.	NUMBER OF SAMPLES	SPECIFIC GRAVITY MEAN	S.D.
(Middle Proterozoic) Roopena Volcanics	10	85	22	7	2.79	0.22
(DDH1 only) (one value of specific gravity of 3.274) & remainder (minus higher value)				6	2.71	0.05
Corunna Conglomerate	58	36	31	33	2.74	0.14
Range 0-45 x 10^{-6}	41	18	11	-	-	-
Range 50-110x10^{-6}	17	79	20	-	-	-
Gawler Range Volcanics	22	54	26	3	2.70	0.02
Moonabie Formation	51	27	19	25	2.70	0.10

(measured by R.A. Gerdes, 1983)

TABLE 5.11

MAGNETIC SUSCEPTIBILITY DATA OF THE CORUNNA CONGLOMERATE UNITS FROM THE UNO AREA, WADE DAM. DIAMOND DRILLHOLE AUU6

DEPTH INTERVAL (in m)	THICKNESS (in m)	LITHOLOGY	MAGNETIC SUSCEPTIBILITY ($\times 10^{-6}$ cgs units) No. of Samples	Mean	Standard Deviation
66.75 to 129.54	62.79	Grey-green interbedded sandstone and mudstone	148	91	34
129.54 to 192.63	63.09	Grey-green bedded sandstone	131	87	31
192.63 to 243.23	50.60	Grey sandstone	91	61	32
243.23 to 282.55	39.32	Black shales plus calcareous bands	63	34	18
282.55 to 290.17	7.62	Greenish calcareous mudstone - laminated	15	44	7
290.17 to 353.87	63.70	Laminated black shale plus calcareous bands	194	49	13
353.87 to 395.63	41.76	Greenish quartzite plus shale bands (irregular)	136	25	9
395.63 to 416.97	21.34	Quartzite - iron stained, haematite clay layers	55	42	11
416.97 to 445.92	28.95	Granular quartzite - with conglomerate bands at base, iron stained.	67	25	14
445.92 to 448.06	2.14	Red finely cross bedded sandstone	8	76	29
66.75 to whole core	381.30	Total section of drill core. Corunna Conglomerate	915	56	34

(measured by R.A. Gerdes, 1983)

Two argillaceous siltstones from 142.65 m (P470/74) and 154.84 m (P471/74) with inferred glauconite, which was not confirmed, contain 40 to 60% chlorite with 25 to 30% quartz. Linear muscovite, 'glauconite', feldspar, opaques and sphene are the main accessories. The grain size indicates a slight increase in susceptibility, as a function of decreasing grain size for the ferromagnetic mineral. Some 'illite', an interlayered illite-like mineral with montmorillonite, may be a glauconite (type 3), (Moeskops, 1975), but it does not appear to have ferromagnetic properties.

The expected magnetic responses at the depth specified by this hole is less than 1 nT, even if these rocks crop out. Therefore, if present in the Wallaroo-Moonta Province, they would be unresolved. If metamorphosed, the 1 to 2% opaques would give a increased anomaly, but its magnitude would depend on the metamorphic grade.

5.3.2.4 Willamulka metasediments and Volcanics

These metasediments and volcanics in Bute DDH3, 5 and 6 and in Wokurna DDH4, are comparable with the low grade metasediments in N.B.H. DDH 207 to 210 inclusive, west of Bute. They are generally non-magnetic, except for the minor hematite-rich group, which has a mean susceptibility of 61 x 10^{-6}cgs units, and the minor interbedded amphibolites, which have susceptibilities between 200 and 1000 (x 10^{-6}cgs units). In Bute DDH5, the mean value, 547 x 10^{-6}cgs units, is representative of these amphibolites. No data is available on the dacites or rhyodacites within these metasediments. The histogram (Figure 5.4) shows no distinct difference between their densities. The Bute Amphibolite (Bute DDH2), has a comparable susceptibility value to the other amphibolites, but has a higher density.

The petrophysical data of the Tickera (Adamellite) DDH2, and the gabbro (Wokurna DDH1) is given in Table 5.12. This gabbro is probably a dyke, and younger than the amphibolites, interpreted from geological and detailed aeromagnetic contoured data.

TABLE 5.12

PETROPHYSICAL DATA OF THE WILLAMULKA METASEDIMENTS AND VOLCANICS BASED ON THE BUTE, WOKURNA & TICKERA STRATIGRAPHIC DRILL HOLES

DRILL HOLE	LITHOLOGY	MAGNETIC SUSCEPTIBILITY ($\times 10^{-6}$ cgs units) Number	Range	Mean	S.D.	SPECIFIC GRAVITY Number	Range	Mean	S.D.
Bute DDH2	Bute amphibolite	-	-	-	-	6	2.82-3.04	2.89	0.08
	GROUP I (Between 128 to 209 m)	45	0-326	72	61	-	-	-	-
	GROUP II (Between 209 to 215.5m)		117-654	327	169	-	-	-	-
Bute DDH3	Willamulka metasiltstones	10	0-317	209	110	10	2.75-2.83	2.78	0.02
	*with no zeros present in mean	8*	211-317	262	37	-	-	-	-
Bute DDH5	Willamulka metasediments and amphibolites	25	360-849	547	127	73	2.03-3.49	2.70	0.21
	*weathered samples to depth of 40.5m	(large no. of zeros for metasediments)			-	16*	2.11-3.49	2.25	0.21
	samples deeper than 41m	-	-	-	-	57	2.03-2.95	2.76	0.14
Bute DDH6	Willamulka metasiltstone & amphiblites	14	160-680	480	150	12	2.69-3.16	2.75	0.23
Overall Bute	(two distinct populations see figure 4)	TWO POPULATIONS (1) METASILT-STONES (2) AMPHIBOLITES				85	-	2.71	0.02
Wokurna DDH4	Low grade metasiltstones (haematite rich)	74	35-90	61	11	72	2.72-2.85	2.80	0.03
Tickera DDH2	Granite (Adamellite)	29	30-318	108	63	29	2.58-2.77	2.66	0.04
Wokurna DDH1	Gabbro	18	70-150	110	21	18	2.96-3.09	3.01	0.03
	(weathered gabbro)	10	20-100	66	24	10	2.47-2.76	2.57	0.14

(measured by R.A. Gerdes, 1983)

Gabbro intrusions related to the dyke intersected in Wokurna DDH1 were resolved near this hole (Chapter 16). As no age data was available, a comparison made with similar basic intrusions in Eyre Peninsula, namely the Inkster, Cungena and Ripon Aeromagnetic Anomalies, which showed from the isochron Rb^{87}/Sr^{86} plot for the gabbros, a maximum and minimum age of 1800 Ma and 1050 Ma, (Webb and Steveson, 1976). The K-Ar hornblende and biotite dates on the gabbros, granite gneiss and adamellite near these anomalies show a cluster between 1560 and 1620 Ma. Webb regards this as the minimum age for the gabbro intrusions in Eyre Peninsula. A similar age is therefore suggested for the gabbro in Wokurna DDH1, and the others nearby, verified by recent drilling.

Whitten (1963) reported specific gravity data on the Inkster (hypersthene gabbro and labradorite) to be 3.2 and 3.16 respectively and on Ripon (diorite) as 2.89. Later susceptibility measurements (Table 5.13) show a range of values, all less than 85 x 10^{-3}cgs units. The mean values for the individual gabbros, (Cungera, Inkster and Ripon) are 1.0, 70.5 and 19.5 (x 10^{-3}cgs units) respectively, indicating either different percentages of ferromagnetic minerals or varying grain size. The hypersthene gabbro (Inkster, IR6) has a mean value of 42 x 10^{-3}cgs units and the altered (uralitized) gabbros have very low values. The histograms show two distinct groups with median values less than 1.0 x 10^{-3}cgs units and 70 to 80 (x 10^{-3}cgs units).

5.4 PETROPHYSICAL STUDY OF THE MOONTA PORPHYRY

This study (Table 5.14) of Moonta Porphyry core provides:

(i) Specific gravity data for use in the density distribution within an interpreted gravity model,

(ii) Magnetic susceptibility data for estimating the expected magnetic responses over the Porphyry, (Chapter 7).

Most Moonta holes investigated the copper lodes: the Bennetts and Elders Lodes (Moonta East drillholes), the Yelta and Poona Lodes. Although the Poona Lode is outside the main porphyry mass, as defined by geophysical data, it was included for comparison.

TABLE 5.13

MAGNETIC SUSCEPTIBILITIES OF BASIC INTRUSIONS AND ASSOCIATED COUNTRY ROCKS IN THE GAWLER CRATON

AEROMAGNETIC ANOMALY NAME	DIAMOND DRILLHOLE REFERENCE	LITHOLOGY (ROCK TYPE)	NUMBER OF SAMPLES	MAGNETIC SUSCEPTIBILITY (in x 10^{-3} cgs. units) Range	Mean	$\pm$S.D.
CUNGERA	CR.1	Granitic gneiss	8	0.006-0.135	0.44	0.04
	CR.2	Gabbro	12	0.065-1.72	1.00	0.58
	CR.3	Uralitized gabbro	10	0.006-0.14	0.70	0.04
	Including 2 special in range		-	3.30-3.39	-	-
			12	0.006-3.39	0.62	1.22
INKSTER	IR.1	Labradorite	5	0.5-1.85	1.36	0.47
	IR.2	Gabbro	10	51.48-84.70	70.54	9.39
	IR.3	Uralitized gabbro	4	12.41-30.5	21.33	6.51
	IR.4	Granite (Leucocratic Adamellite)	3	0.396-0.402	0.40	0.00
	IR.5	Adamellite	7	1.54-2.69	2.41	0.40
	IR.6	Hyperthene gabbro	7	32.37-48.80	41.8	5.24
RIPON	DDH.1	Weathered gabbro	3	0.15-4.3	1.75	1.17
		Gabbro	11	11.9-28.2	19.51	5.36
	DDH.3	Diorite	13	2.71-7.67	4.92	1.51

(measured by R.A. Gerdes, 1983)

(Based on Diamond Drill Hole Core Samples)
(measured by R.A. Geddes, 1983)

LOCATION	DRILL HOLE NUMBER	LITHOLOGY	SPECIFIC GRAVITY RANGE	NUMBER OF SAMPLES	MEDIAN	MEAN	STANDARD DEVIATION	MAGNETIC SUSCEPTIBILITY ($\times 10^{-4}$ cgs. units) RANGE	NO. SAMPLES	MEDIAN	MEAN	STANDARD DEVIATION
MOONTA EAST	DDH 1	SCHIST	2.61 - 2.76	4	?	2.70	0.07	0.83 - 2.34	4	?	1.53	0.654
		QUARTZ MICA SCHIST	2.35 - 2.74	21	2.60	2.61	0.12	0.64 - 1.40*	20	0.8	0.903	0.230
								* One value of 15.3 x 10^{-4} cgs. units.				
MOONTA EAST	DDH 2	PORPHYRY	2.58 - 2.80	89	2.66	2.67	0.03	0.13 - 40.0	91	1.0	2.67+	5.33
		PORPHYRY (plus mica)	2.67 - 2.80	7	2.80	2.81	0.06	-	-	-	-	-
								+ Results associated with lodes - magnetic material introduced during mineralization.				
MOONTA EAST	DDH 4	PORPHYRY	2.61 - 2.80	51	2.67	2.66	0.03	0.13 - 2.2	49	< 1.0	0.996	0.565
MOONTA	DDHE1	PORPHYRY	2.62 - 2.89	89	2.71/2.74	2.72	0.09	0.27 - 25.64	89	0.05	3.80	5.80 (overall)
MOONTA	DDHE2	PORPHYRY	2.53 - 2.94	230	2.67	2.706	0.075	0.2 - 67.0	230	0.5	3.143	8.013 (overall)
						Population A.		0.2 - 8.74	210	0.5	0.909	0.992
						Population B.		10.4 - 67.0	20	20.0	24.752	7.876
MOONTA	DDHE3	PORPHYRY (above 94.5m)	2.52 - 2.81	95	2.64	2.65	0.062	0.2 - 6.03	95	0.5	0.894	0.696
		(below 94.5m)	2.35 - 2.97	78	2.72	2.75	0.062	0.46 - 2.50	77	1.0	0.965	0.481
POONA	DDH 1	PORPHYRY	2.55 - 2.76	45	2.69	2.69	0.052	0.08 - 22.1	46	0.5	4.41	6.21
	DDH 2	PORPHYRY	2.64 - 2.86	37	2.71	2.73	0.05	0.0 - 15.65	37	1.0	4.19	4.34
	DDH 3	PORPHYRY	2.10 - 3.04	47	2.68	2.67	0.16	0.0 - 25.4	48	0.5	4.31	5.19
	DDH 4	PORPHYRY	2.55 - 2.78	25	2.68	2.68	0.05	0.0 - 20.0	25	1.0	2.62	4.00
YELTA	DDH 2	PORPHYRY	2.53 - 2.71	28	2.62	2.62	0.043	0.0 - 7.68	31	0.25	1.643	2.51
	DDH 4	PORPHYRY	2.52 - 2.79	43	2.60/2.66	2.63	0.06	0.0 - 1.10	44	< 0.5	1.580	2.130
	DDH 5	PORPHYRY	2.51 - 2.79	41	2.69/2.73	2.68	0.06	0.1 - 61.0	41	< 0.1	6.454	11.778
						Population A.		0.1 - 9.1	35	-	2.458	2.25
						Population B.		10.3 - 61.0	6	-	29.763	17.646
	DDH 6	PORPHYRY	2.57 - 2.84	33	2.61	2.66	0.066	0.0 - 1.30	34	0.8	0.529	0.296
	DDH 7	PORPHYRY	2.45 - 2.85	37	-	2.64	0.086	0.0 - 6.20	36	0.4	1.813	1.931
								Higher values of 19.60 and 1060 x 10^{-4} cgs units recorded.				
	DDH 8	QUARTZITE	2.67 - 2.83	3	-	2.74	0.083	0.0 - 0.25	3	-	0.163	0.142
		MICA SCHIST (+felspar phenocrysts)	2.66 - 2.78	4	2.74	2.73	0.053	0.0 - 0.2	4	0	0.050	0.100
		PORPHYRY	2.47 - 2.86	41	2.62	2.64	0.078	0.0 - 16.2	41	< 0.1	2.0695	3.644 (overall)
						Population A.		0.0 - 4.8	39	< 0.1	1.3641	1.872
						Population B.		values of 15.45 and 16.20 x 10^{-4} also recorded.				

The petrophysical data of the country rocks in Moonta East DDH1 and Yelta DDH8, (Table 5.15), show the schists (mica and quartz-mica varieties) have higher susceptibilities than other metasediments. One sample of quartz-mica schists has a value of 1.53×10^{-3}cgs units. The distribution of these and other drillholes where petrophysical data was undertaken is shown in Figure 5.5.

5.4.1 DISCUSSION OF THE PETROPHYSICAL DATA FROM THE MOONTA DRILL HOLES E1, E2 AND E3

These vertical holes investigated EM anomalies, between the Hoggs and Taylors Lodes, resolved in the 1942 survey. As no mineralised lodes were intersected, these holes were assumed be a random sample of the unmineralised Moonta Porphyry.

5.4.1.1 Moonta DDH E1

The main foliation direction within the porphyry in this hole is steep, being at 70^{o} to the core axis. The dip of this foliation is similar to the inclination of the Moonta Lodes.

The lithological and petrophysical logs, i.e. S.G. and susceptibility, (Figure 5.6) show three lithological units: X, Y and Z. and their parameters are given in Table 5.16., but their histograms are not shown. The overall histogram of this hole compared with DDHE2 is shown in Figure 5.7.

The mean S.G. of units X and Z are the same. However, the mean susceptibility values are different, which reflects the varying amounts of magnetite (Table 5.17).

Units X, Y and Z correlate with the following lithologies:

Unit X - a mixture of massive 'porphyry' and porphyry with a predominant foliation (generally schistosic), between 12.2 and 39.6 m.

Unit Y - feldspar porphyry, between 39.6 and 56.4 m.

Unit Z - feldspar porphyry with chlorite and an increasing proportion of ferromagnesium minerals, between 56.4 m and 82.3 m.

The geophysical logs show an increase in magnetic susceptibility with depth, but no distinct increase in density, except for a slight change in the mean values, shown by a difference of 0.01 gm/cm^3 between units X and Z, (Figure 5.6).

Eight core samples investigated magnetic minerals. The results from unit X (3 samples), unit Y (2 samples) and unit Z (3 samples) show the main rock type is a meta-dacite with 5% plagioclase phenocrysts, (Radke, 1977). These rocks are not

TABLE 5.15

PETROPHYSICAL DATA OF METASEDIMENTS ENCOUNTERED IN MOONTA EAST DDH1 & YELTA DDH8

Lithology	Mean Specific Gravity	Range of Magnetic susceptibility ($\times 10^{-6}$ cgs units)
Quartzite	2.74	0 to 25
Mica Schist	2.70	83 to 234
Mica Schists (plus felspar phenocrysts)	2.73	0 to 20
Quartz-mica schist	2.61	64 to 140

(measured by R.A. Gerdes, 1983)

TABLE 5.16

PARAMETERS OF UNITS X, Y and Z in MOONTA DDH E1

UNITS	SPECIFIC GRAVITY				MAGNETIC SUSCEPTIBILITY (in cgs units x 10^{-6})		
	Number of Sample	Mean x	S.D. s	Range $x \pm s$	Number	Mean x	S.D. s
X	35	2.74	0.05	2.69-2.78	33*	61.2	34.2
Y	25	2.70	0.25	2.45-2.95	25+	269.6	288.8
Z	28	2.74	0.04	2.68-2.78	21^{X}	1141.6	622.3

* extraneous values of 524, 555 and 2564 x 10^{-6} cgs units are present in Unit X.

\+ range of susceptibility values in 70 to 1188 x 10^{-6} cgs units in Unit Y.

X susceptibility values less than an equal to 100 x 10^{-6} cgs units were rejected for the mean calculation for Unit Z, as these correlated with acidic intrusions e.g. pegmatite and quartz veins, which are not considered representative of the porphyry.

(measured by R.A. Gerdes, 1983)

TABLE 5.17

OPTICAL PERCENTAGES COMPARISON OF UNITS X,Y AND Z IN MOONTA DDHE 1

OPHYSICAL UNIT	X	X	X	Y	Y	Z	Z	Z
:trological Number	P470/76	P471/76	P472/76	P473/76	P474/76	P475/76	P476/76	P477/76
›pth (metres)	30.78	31.39	42.37	59.07	64.26	74.37	76.50	89.61
IIN SECTION MINERAL								
.trix Quartz	55	30	35	35	40	40	40	30
.trix felspar	35	40	40	35	50	35	40	50
ılorite	5	15	10	5	2	5	5	5
.agioclase Pheno-cryst.	5	4	5	5	?	5	5	5
ıscovite-Sericite	Trace-1	T	3	5	5	10	5	3
›atite	T		T	T	T	1		
.rcon	T	T	T	T	T			T
›urmaline	T						T	
.otite		10		15		1	5	T
ılcite								1
›idote								T
›aques	1	1	5	1	3	3	1	1
)LISHED SECTION								
ırtite			50	T				
IGNETITE	T		45			20	T	65
EMATITE								5
itanium-mineral	T	T	3			20		25
rrite			1			40		3
ıalcopyrite			1			20		2
rrrhotite						T		
›ethite	T	T						
›ecific Gravity	2.72	2.74	2.73	2.73	2.71	2.79	2.77	2.73
ıagnetic Susceptibility (x10^{-6} cgs units)	50	50	2564	77	110	1134	1474	2215

.B. T = Trace of mineral present in specimen distinctly different, except unit X has a slightly higher chlorite content, between 5 and 15% compared with units Y and Z.

Table 5.17 shows principal components based on optical estimates for comparison between the units in DDH E1. The samples with higher susceptibility values range between 1134 and 2564 (x 10^{-6}cgs units), at depths shown in Table 5.17, and contain 0.6 to 2.5% magnetite, traces of titanium minerals, pyrite (0.03 to 1.20%) and chalcopyrite (0.02 to 0.06%).

Unit Z shows the greatest variation of opaque minerals the highest percentage of sulphides, including minor pyrrhotite at 74.37 m (P457/76). This sample has the highest percentage of sericite, the highest density (2.79 gm/cm^3), and lowest susceptibility (1134 x 10^{-6}cgs units) of the group. This petrophysical relationship may be significant for the sericite-pyrrhotite-magnetite association.

5.4.1.2 Moonta DDH E2

Comparison of lithological and petrophysical logs (Figure 5.8), shows two zones with a significant increase in susceptibility values. The major susceptibility response occurs between 88 and 110 m, has a value between 0.2 and 0.6 (x 10^{-3}cgs units), correlating with a zone of disseminated pyrite and chalcopyrite. The susceptibility response probably relates to disseminated bands of magnetite and/or pyrrhotite within this interval. The other major response is between 125.9 and 140.2 m, has susceptibilities between 0.05 and 0.15 (x 10^{-3}cgs units), and correlates with a brecciated and broken porphyry zone. This increase in susceptibility may be due to introduced magnetite, as no sulphides are present. Some chloritic layers and chloritic micaceous banded porphyry show a susceptibility increase to 0.2 x 10^{-3}cgs units. However, not all the chloritic layers show the same response.

The susceptibility histogram (Figure 5.7), shows three possible groups from 0.02 to 0.1; 0.12 to 0.34; and from 0.42 to 7.0 (x 10^{-3}cgs units) with median values of 0.04, 0.14 and 2.0 (x 10^{-3}cgs units) respectively. The corresponding S.G. histogram shows a median value of 2.67.

However, the log-linear cumulative frequency plot shows three possible populations with mean values of 2.59, 2.66 and 2.80 respectively. The ferromagnesium minerals in the ground mass probably correlate with this increase in density contrast (0.08 gm/cm^3), but there is no associated significant susceptibility response. This indicates the density variations are independent of the ferromagnetic component, as shown in drill holes E1 and E2.

This hole has three main rock types:

(i) Feldspar porphyry + chlorite and micaceous banding.

(ii) Feldspar porphyry - foliated.

(iii) Feldspar porphyry - massive, (increases in ferromagnesium minerals).

The susceptibility for all three lithologies is generally less than 0.01 x 10^{-3}cgs units, whereas the S.G. has average values of 2.80, 2.70 and 2.65 for lithologies (i) to (iii) respectively.

5.4.1.3 <u>Moonta DDH E3</u>

DDH E3 shows variations within the porphyry, with some chloritized sections, (chlorite-biotite schist), chalcopyrite and tourmaline. Martite-hematite and magnetite in that order, with some minor pyrite occur at 114.6 and 152.4 metres, (P480/76 and P483/76). Below 160 m the rocks contain up to a maximum 1.3% disseminated magnetite with no alteration products, and the empirical susceptibility, based on Grant and West (1965) for these rocks, would be 3 000 x 10^{-6} cgs units, which is a factor of 10 higher than that observed in this hole. This indicates the average magnetite content is approximately 0.13%.

The S.G. log (Figure 5.10) increases in value at 94.5 m, with a smaller increase between 33.5 to 48.8 m, correlating with 'porphyry with ferromagnesium banding', probably the biotite-chlorite schist variety of the meta-dacite. The susceptibility log does not show a distinct response at 94.5 m. However, the mean value changes above and below the density boundary at 94.5 m of 7.1 x 10^{-6}cgs units (Figure 5.10). The density increase is partly due to the increases in the magnetite and dolomite content, as indicated from P480/76 at 114.6 m. The dolomite is secondary, occurs as both vein fillings and within fractures, and represents 1% of the rock, (optical estimates, Table 5.18).

TABLE 5.18

OPTICAL ESTIMATES OF PETROLOGICAL SAMPLES IN MOONTA DDHE 3

ɛtrological Number	P478/76	P479/76	P480/76	P481/76	P482/76	P483/76	P484/76	P485/76
ɛpth (metres)	84.73	87.17	114.6	123.75	141.30	152.40	160.02	165.51
HIN SECTION MINERAL								
atrix Felspar	35	Ø65	Ø80	Ø85	Ø75	Ø80	Ø80	Ø80
atrix Quartz	45	*	*	T	*	*	*	*
hlorite	5	20	3	5	10	10	5	5
arbonate (Dolomite)	3		1	1			1	T/1
lagioclase Phenocrysts	5	10	10	5	10	10	10	10
uartz Phenocryst					T			
uscovite-Sericite	5	5	5	1	1	1	1	1
patite		T		T	T	T	T	T
ircon	T	T	T	T	T	T		T
ourmaline						T/1		
iotite								
pidote								
paques	3	T/1	1	2	3	2	2	2
utile			T	T/1	T		T	T
OLISHED SECTION								
artite	60⊛		90⊛	100⊛			100⊛	⊛
agnetite	35	✓	10			50	T	65
ematite	⊛		⊛	⊛	✓		⊛	30⊛
itanium Mineral	5	✓			✓			
yrite			T/1			20		
halcopyrite								
oethite								5
lmenite-Hematite						30		
PECIFIC GRAVITY	2.64	2.69	2.83	2.71	2.77	2.78	2.71	2.78
AGNETIC SUSCEPTIBILITY ($\times 10^{-6}$ cgs units)	55	55	216	250	75	75	210	2785

.B. Ø combined matrix - quartz and feldspar
⊛ combined with martite percentage

The S.G. histogram (Figure 5.9), shows two distinct groups having median and mean values of 2.63 and 2.65; and 2.72 and 2.75 respectively. The susceptibility histogram shows a slight range in the median and mean values. However, the groups of each depth interval show two similar distributions, having median values of 50 and 100 (x 10^{-6}cgs units). This correlates with the three levels of more susceptible material from 6.1 to 55 m; 107 to 126 m; and from 154 to 167 m; and with a slight increase in disseminated magnetite within the meta-dacite, and the magnetite associated with the chlorite-biotite foliations, (a retrogressive effect).

An optical estimate of the magnetite content, generally less than 1%, represents a susceptibility value of 2000 x 10^{-6}cgs units, which agrees with the susceptibility measurements. The origin of the highest value of 2785 x 10^{-6}cgs units (P485/76) at 165.5 m is explained by the 1.35% magnetite (total rock optical estimate), within this rock.

The petrophysical data of Moonta DDH E1 to 3 inclusive, confirms the three-fold subdivision of the porphyry based on the lithological logs (Figure 5.10). These rocks are meta-dacite, containing plagioclase phenocrysts which have suffered green schist facies - grade metamorphism, deformation and potash metasomatism, (Radke, 1977). No shards were observed. The ferromagnesium-rich bands within the porphyry (meta-dacite) in DDH E3 increase in S.G. to 2.80, with a corresponding slight increase in susceptibility contrast of 10 x 10^{-6}cgs units, compared with the general background level. The lithological units and physical responses compare with those in DDH E2 and E3, assuming a tabular sheet model, and indicate that these dip 52° NW within the porphyry mass.

5.4.2 DISCUSSION OF THE PETROPHYSICAL DATA FROM DRILL HOLES ASSOCIATED WITH THE MINERALISED ZONES

Previous drilling of the Bennets and Elders Lodes, (Moonta East DDH 2 and 4); Yelta Lode (Yelta DDH 2, 4 to 8) and Poona Lode (Poona DDH 1 to 4) were selected for petrophysical studies, to provide data on the mineralised Moonta Porphyry. The lode intersections are missing, but the wall rock alteration is available. At least 65 holes are associated with the lodes, drilled pre-1960, but some of these cores are unavailable. Seven of these holes, Moonta East DDH1 and 3; and five other Yelta holes (DDH1, 3, 5, 6 and 7) were petrophysically sampled (below the weathered zone) and their results compared with those selected above. The six holes drilled by W.M.C. and N.B.H. were not petrophysically sampled, as seven S.A.D.M. holes rejected, had comparable results.

5.4.2.1 Moonta East DDH2 and 4

The susceptibility and S.G. histograms (Figure 5.11) shows two distinct populations, correlating with the 'normal' porphyry and the 'combined' population (the porphyry plus mica), and the gneissic textured porphyry (Table 5.19).

TABLE 5.19

PETROPHYSICAL COMPARISON OF PORPHYRY IN MOONTA EAST DDH2 AND 4

	Specific Gravity Median Value	Magnetic Susceptibility ($\times 10^{-3}$cgs units) Median Value
Normal porphyry	between 2.65 to 2.67	less than 0.10
Porphyry (Gneiss & mica variety)	2.80	between 0.11 to 0.16

The second porphyry type is denser, has a contrast of 0.14 gm/cm^3 and has a slightly higher susceptibility.

The mineralised porphyry shows two groups of magnetic susceptibility values. The first is associated with chalcopyrite between 0.7 and 0.9 ($\times 10^{-3}$cgs units). The second has values from 2.4 to 5.6 ($\times 10^{-3}$cgs units), reflecting bands of disseminated magnetite and/or pyrrhotite.

5.4.2.2 Yelta DDH2 and 4 to 8 inclusive

The S.G. histogram (Figure 5.12) shows three groups, with median values of 2.60, 2.68 and 2.79. The lower density group correlates with weathered porphyry and some lower density material above and below the mineralised lode in DDH 7 and 4. DDH 6 and 8 also show a linear decrease of density with depth, from 2.70 to 2.60 gm/cm^3, whereas DDH5 increases with depth. The main mineralised zones correlate with specific gravities greater than 2.68 and some values in the higher group.

The susceptibility histogram shows the principal median value of the porphyry's distribution is less than 0.1 $\times 10^{-3}$cgs units, whereas the mineralised portions show two ranges from 0.2 to 0.8 ($\times 10^{-3}$cgs units) and 1.05 to 2.82 ($\times 10^{-3}$cgs units) respectively, which correlates with the variable pyrrhotite content. Magnetite may be present in the higher group, but the corresponding specific gravities show no significant response.

These holes in the Moonta Mines area and those at Moonta DDH E1 to 3 show similar distribution parameters and significant susceptibility differences, associated with the lodes. Ferromagnesium minerals in the lode sequence were not reported, but may be present. The major magnetic mineral in the porphyry is magnetite.

5.4.2.3 Poona Mines DDH 1 to 4 inclusive

The histograms (Figure 5.13) show similar distributions to those in the principal lode areas. The median value of the S.G. histogram of DDH 2 is slightly different from those in the other three holes, whereas the susceptibility values are comparable. This S.G. differrence may be just a function of sampling or relate to an increase in hematite content.

To summarise, a marked increase in susceptibility appears to be associated with the lodes and mineralised areas of the porphyry, and probably relates to pyrrhotite rather than magnetite. Hematite and martite are gangue minerals. The feldspar porphyry, meta-dacite and metasediments show distinct banding or layering within the Moonta Porphyry, and are present in the unmineralised and mineralised portions.

5.5 PETROPHYSICAL STUDY OF THE METASEDIMENTS WITHIN THE KADINA GRID

Susceptibility and S.G. measurements were recorded for Devon DDH 1 and 2 and Doora Mine DDH 1, associated with the Devon and Doora Lodes in the Jerricho and Doora Subprovinces. Susceptibility values of schists, metadacite and metarhyodacite are compared within the West Doora and Doora Subprovinces.

5.5.1 PETROPHYSICAL DATA FROM DEVON DDH 1 AND 2

These holes, which investigated the source rocks associated with the Devon magnetic anomaly, were sited on the possible western extension of the Devon Lode, outlined by a linear electromagnetic trend. They intersected low grade disseminated mineralisation, less than 0.2% copper, (pyrite, pyrrhotite and chalcopyrite). Thyer (1943) considered that the core of Devon DDH 2, between 107 and 174 m, which exhibited a high susceptibility and permanent moment, was the source rock for the Devon Anomaly. However, from their extrapolated location, the rocks intersected are not the major magnetic sources of this anomaly, but are associated with less magnetic metasediments, details are as follows:

5.5.1.1 Devon DDH 1

The susceptibility log is subdivided into four units A to D; whilst units B and C in the S.G. log are not clearly resolved.

Unit A from just below the weathered layer to 40.8 m, is a quartz-mica schist. It has a mean density of 2.67 $gm.cm^3$ and a susceptibility of 40 x 10^{-6}cgs units.

Unit B between 40.8 and 62.5 m, was originally described as a sequence of quartz-mica schist with feldspar phenocrysts and a quartz-feldspar rock. Some pyrite and chalcopyrite are present in both rock types, with a local concentration of 0.20% copper with minor gold between 59.6 and 62.3 m. The median specific gravity value of this unit is 2.71, and the susceptibility values range 1710 to 13640 (x 10^{-6}cgs units). The histogram (Figure 5.14) of the latter shows two groups having median values of 1500 and 5500 (x 10^{-6}cgs units) probably separated at a value of 3000 x 10^{-6}cgs units.

Two samples were selected from the higher susceptibility group at the 43.28 and 46.02 m depth. The first (P408/78) is a porphyritic metadacite, containing 2 to 3% magnetite, with traces of pyrite and chalcopyrite. The other (P409/78) is a fine grained metadacite, with some magnetite (Whitehead, 1978a).

Unit C between 62.48 and 106.68 m, contains the same rock types as unit B, but with some mica schist. Samples from this unit at depths of 67.97, 75.29 and 85.65 m are metadacites, with no quartz phenocrysts, but abundant plagioclase phenocrysts. They all contain migratory chalcopyrite and pyrite, but lack magnetite, consistent with low susceptibility values, which range 38 to 720 (x 10^{-6}cgs units), with a median value of 50 x 10^{-6}cgs units. At 99.4 m the unit has a high susceptibility value of 4656 x 10^{-6}cgs units within a mica schist, containing pyrite, chalcopyrite and possibly magnetite, deduced from the coincident density increase from 2.7 gm/cm^3 to 2.82 gm/cm^3, and the high susceptibility value.

This unit's S.G. ranges between 2.65 and 2.77, except the higher susceptibility band. The histogram parameters are given in Table 5.20. Samples P427/78 from 82.6 m within this high susceptibility band, is an hydrothermally altered metamorphic rock, probably a quartz-biotite schist, which contains chlorite and sericite, a moderate amount of potash feldspar associated with sericite, and 1 to 2% chalcopyrite, associated with some pyrite. The susceptibility is 109 x 10^{-6}cgs units which is higher than the values within the metadacite, and indicates some pyrrhotite and/or magnetite may be present.

Units B and C are metadacites. However, the petrophysical results show two different metadacite units, distinctly separated by their magnetite content. The major Cu ± Au concentration occurs near the boundary between these two units. The observable total field response produced by a 21 m thick magnetic metadacite at 95 m, with a susceptibility of 5 x 10^{-3} cgs units, would produce a 130 nT anomaly, which correlates with the observed linear magnetic zone type 8. If located at the surface, then the anomaly is 600 nT. This correlates with linear zone types ranging between 8 and 11. This shows the possible resolution of these metadacites from the other magnetic units. However, unit B with an intersected thickness of 20 m, would be resolved by a possible one point anomaly along a W.M.C. magnetic traverse profile with a sample interval of 100 ft.

Unit D from 106.68 m to total depth of 185.8 m, is a major sequence of mica schist with minor quartz-mica schist bands, with disseminated pyrite and chalcopyrite. Between 152.6 and 185.8 m it contains bands of 0.2 to 0.3% Cu, associated with pyrrhotite in a brecciated feldspathised mica schist. At 152.4 m D44/48 is a quartz-biotite-hornblende schist, containing magnetite, some pyrite and calcite in veins, interpreted to have originally been a quartz-rich metasediment. The susceptibility is 39620 x 10^{-6}cgs units and density is 3.14 gm/cm^3. At 170.3 m D45/48 is a quartz-biotite-hornblende gneiss. Biotite, magnetite and apatite are present in the foliation parallel to the schistosity, with scapolite developed near the biotite. Some disseminated pyrite also occurs. The nearest density and susceptibility at 178.6 m, is 3.12 gm/cm^3 and 41050 x 10^{-6}cgs units respectively. Therefore petrophysically these two rock types show no significant difference.

TABLE 5.20

PETROPHYSICAL PROPERTIES ON UNITS A TO D IN

DEVON DDH 1

Unit Number		SPECIFIC GRAVITY			
	Range	Number of Samples	Mode	Mean	Standard Deviation
A	2.66 to 2.67	7	2.67	2.67	0.01
B	2.65 to 2.76	10	2.71	2.70	0.03
C	2.65 to 2.82	26	2.71/2.74	2.62	0.53
D	2.74 to 3.63	51	2.93/3.10	3.01	0.16
		Magnetic Susceptibility ($x10^{-6}$cgs units)			
A	15 to 57	10	35 to 40	40	12
B	750 to 1110	21	1500/5500	5221	3616
C	30 to 720	28	50	88	68
	population less than 300	26	50	77	33
D	overall 1.7 to 95900	52	0/20000	18175	20210
	less than 1000	7	0	252	280
	up to 10 000	15	?	4966	2720
	greater than 10 000	30	20000	29163	20453

(measured by R.A. Gerdes, 1983)

This unit's S.G. ranges from 2.74 to 3.29, with a higher value of 3.63 at 106.98 m, and has a corresponding susceptibility of 20330 x 10^{-6}cgs units. Sample P413/78 is a layered metasediment containing biotite schists, hornblende schist and quartzite. The original sediment probably contained some calcareous layers, but these now contain anomalous concentrations of magnetite and minor apatite, (Whitehead, 1978a).

The major concentration of the magnetite, (5-10%) is intergrown within the hornblende, which occurs as dark coloured banding, 6-7 mm thick, and interbedded with 5 m thick bands of quartz (60%) - hornblende-biotite with minor apatite and magnetite. Large aggregates of magnetite are associated with chlorite, sericite and secondary feldspar, accompanied by sphene and zircon. Most of these mineral groups and aggregates are in layers, parallel to the layering.

The S.G. histogram (Figure 5.14), shows two possible populations with modes at 2.95 and 3.10. Alternatively the histogram may be a log normal distribution. The susceptibility histograms show a wide range of values with the largest (58%) being greater than 10 x 10^{-3}cgs units. The mode value ranges 20 to 25 (x 10^{-3}cgs units), which correlates with the higher density population. The remaining percentage forms two groups. The first group representing 12%, ranges 0.02 to 0.14 (x 10^{-3}cgs units) and the second ranges 7 to 90 (x 10^{-3}cgs units).

The petrology of these magnetic-rich rocks is summarised in Table 5.21. These schists and gneiss contain up to 2.5 and 3% magnetite respectively, and have an average susceptibility of 20 x 10^{-3}cgs units. Assuming a thickness of 106 metres, then the expected magnetic anomaly is 2150 nT, i.e. a linear magnetic zone type 13. However, the observed magnetic anomaly has an amplitude three times this value, and the interpreted source width is 85 m. The interpreted susceptibility contrast of these sources must be at least 60 x 10^{-3}cgs units. The empirical susceptibility for a 2.5 to 3% magnetite-rich rock ranges between 7 to 9 x 10^{-3} cgs units, indicating either this optical estimate is not representative or another magnetic source is present. The estimate source with a susceptibility contrast of 60 x 10^{-3} cgs. units should contain at least 20% magnetite by volume.

TABLE 5.21.

SUMMARY OF PETROLOGICAL AND PETROPHYSICAL DATA OF MAGNETIC-RICH ROCKS IN DEVON DDH1

›th Interval ı metres)	Petrological No.	LITHOLOGICAL DATA (Based on Petrology)	% Magnetite	Specific Gravity	Magnetic Susceptibility ($x10^{-6}$ cgs units
106.98	P413/78	Banded-biotite schist Hornblende schist quartzite (magnetite & apatite, mica pyrite)	5-10	3.63	203.3
107.90	P414/78	Biotite and hornblende schist. (+ calcareous layers)	10	3.15	877.0
112.78	P415/78	Quartz-biotite-magnetite-plagioclase schist	20-25	3.22	959.0
119.48	D43/48	Felspar-biotite gneiss. (Plagioclase ($\pm$orthoclase) -biotite $\pm$magnetite $\pm$quartz $\pm$apatite) very strong schistosity, with biotite in quartzo-felspathic bands.	?	Between 2.84 to 2.95	Between 31.2 to 173.‹
141.43	P428/78	Deformed and metasomatically altered basic gneiss. Contains abundant plagioclase associated with hornblende and biotite, minor apatite, pyrite and magnetite, traces of allanite and chalcopyrite. Pyrite and chalcopyrite replaces magnetite.	2-3	3.21	38.60

TABLE 5.22

PETROLOGICAL AND PETROPHYSICAL PROPERTIES OF DEFORMED ROCKS IN DEVON DDH2

pth n metres)	Petrological No.	Lithology	Specific Gravity	Magnetic Susceptibility ($x10^{-6}$cgs unit
104.85	P424/78	Deformed and chloritized schist or gneiss containing high proportion of 2^{o} chlorite with biotite, plagioclase, magnetite, and quartz. (Magnetite 5-10%).	3.04	39940
114.6	P425/78	Deformed plagioclase-biotite-magnetite gneiss? (Magnetite 10-15%).	2.94	54290
115.5	P426/78	Plagioclase-amphibole gneiss? Some of the amphibole is cummingtonite and actinolite. (Trace of magnetite).	2.34	780

5.5.1.2 Devon DDH 2

The susceptibility log shows four petrophysical units, W, X, Y and Z, with units W and Y being significantly magnetic. Only unit Y is clearly resolved in the S.G. log. Histograms and the physical parameters are given in Figure 5.15 and Table 5.23, and details are as follows:

Unit W between 28.65 and 70.1 m was originally described as a sequence of mica schist, and feldspar porphyry replacing mica schist. Six samples were selected on relatively high susceptibility values: Sample P416/78 at 38.56 m represents a 4 m thick band, having a susceptibility and density range between 19700 and 29370 (x 10^{-6}cgs units) and 2.99 to 3.11 gm/cm^3 respectively. These susceptibility values are 10 times greater than the surrounding rocks and the density contrast is 0.33 gm/cm^3. This rock is a metasomatically altered basic hornfels (?) or gneiss, which contains hornblende, biotite, plagioclase, 5-10% magnetite and quartz. The biotite and hornblende are extensively replaced by potash feldspar and chlorite with minor sericite.

This unit was subdivided, as the standard deviation of all susceptibility values was large, and the cumulative percentage frequency plot separated the unit into two groups at 4000 x 10^{-6} cgs unit. Lithologically these groups correlate with the mica schist (W_2) and the feldspar porphyry + mica schist (W_1). The mean susceptibility value of group W_1 is 1060 x 10^{-6}cgs units and the mean density is 2.74 gm/cm^3. The higher susceptibility group W_2 have mean susceptibility of 1813 x 10^{-6}cgs units and density of 2.88 gm/cm^3. Two samples in group W_1 are metamorphosed porphyry (or dacite) showing banding and traces of magnetite, whereas, group W_2 contains 10 to 15% magnetite (P421/78). This sample has a susceptibility of 12.65 x 10^{-3} cgs units. The magnetite associated with biotite (P419/78), represents up to 50% of the band, and has a susceptibility of 23.27 x 10^{-3} cgs units. These bands are parallel to the schistosity of the rock. Therefore, the higher group W_2 contains more magnetite and has a more basic component than group W_1.

Unit X between 73.5 and 83.3 m, called "quartzite", is non-magnetic, having a mean susceptibility of 53 x 10^{-6}cgs units, and density of 2.72 gm/cm^3. It is a

TABLE 5.23

PETROPHYSICAL PROPERTIES OF UNITS W-Z IN DEVON DDH2

Unit Number	SPECIFIC GRAVITY Range	Number of Samples	Mode	Mean	Standard Deviation	MAGNETIC SUSCEPTIBILITY ($x10^{-6}$ cgs units) Range	Number of Samples	Mode	Mean	Standard Deviation
W	overall range 2.65-3.28	32	2.70-2.72	2.80	0.14	39-65910	31		8170	1323
W_1	2.66-2.96	19	2.70-2.72	2.74	0.79	39-400	19		1057	850
W_2	2.70-3.28	13	2.70	2.88	0.18	greater than 400	12		1813	1677
X	2.67-2.80	11	2.70-2.72	2.72	0.04	12-130	11	35-50	53	35
Y	2.67-3.14	30	2.80-2.90	2.86	0.15	overall	32	5000-20000	18970	22594
	2.34-2.98	6	-	2.70	0.21	up to 5000 (Quartzite rich horizons)	5		1366	1036
	2.76-3.11	10	2.82-2.85	2.85	0.11	5100-10000	11	5000-7500	728	170
	2.82-3.13	13	2.85-2.92	2.935	0.11	greater than 10000 (with 99999 values excluded)	15	17500-20000	28000	18805
Z	2.59-3.09	56	2.75-2.80	2.77	0.10	15-130	55	55	61	43

(measurements by R.A. Gerdes, 1983)

plagioclase-biotite-quartz schist, with some sulphides (pyrite, chalcopyrite), and a trace of galena occurring within fractures and/or deformed zones.

Unit Y between 85.7 and 118.9 m correlates with a mica and quartz-mica schist sequence, which has a mean susceptibility of 18970 x 10^{-6}cgs units and density of 2.86 gm/cm^3. The assumption that the susceptibility and S.G. data of this petrophysical unit represent one lithological unit may not be valid, as both parameters show large ranges and standard deviations. It is possible this unit has either a log normal distribution, or, is composed of two or more rock types (varieties of schist and/or gneisses). The latter agrees with the original drill log. Therefore, this unit was subdivided into 3 ranges, based on a detailed expanded histogram, a cumulative frequency plot and the model ranges of both the susceptibility and S.G. data. These subunits correlate with the percentage of quartz and magnetite within the original rocks, superimposed on the development of migratory quartz and feldspar, associated with some pyrite and pyrrhotite. A thin lode is present within a brecciated zone, associated with some chloritisation, which relates to a retrograde zone, and has a reduced susceptibility value. This lode is minor compared to the main chalcopyrite - pyrrohotite - pyrite lode within unit Z.

Table 5.23 shows a distinct increase in both parameters, consistent with a progressive increase in magnetite from a trace, (P426/78 to 10 to 15% in P425/78. Petrological evidence shows the magnetite occurs in two sizes, one randomly distributed or concentrated into broad zones, suggesting possible but weak magnetite zonations, but not sedimentary layers. The other occurs as isolated, grouped or aggregates intergrown with the biotite and plagioclase within a possible schistosity, or elongated in the foliation direction. In other cores the magnetite shows evidence of redistribution, or is associated with later quartz veins. Three samples (Table 5.22) at 104.85, 114.6 and 115.5 m depths, show these rocks have a complex history differing from those units above (Whitehead, 1978a).

Unit Z from 119 m to the total depth of the hole (185.9 m), is composed of interbedded laminated quartzite and mica schist. The schist (D 51/48) at 123.2 m is a porphyroblastic-feldspar-biotite-quartz schist. Its susceptibility and density are 40 x 10^{-6}cgs units and 2.77 gm/cm^3.

Microtonalite is present in this sequence at 157.12 m, consisting of hornblende-feldspar (andesine) with minor biotite. Disseminated accessories are magnetite and apatite. Its susceptibility is 74 x 10^{-6}cgs units and density is 2.85 gm/cm^3. It is 6.25 m beneath a thin lode horizon which contains pyrite, chalcopyrite with secondary quartz, feldspar, chlorite and has a pyrrhotite-pyrite association. Pyrrhotite and chlorite also occur in fractures beneath this microtonalite, and therefore the mineralisation probably relates to this intrusion.

Two magnetic units W and Y representing different rock types, are 41.5 and 33.2 m thick respectively. The expected magnetic responses, using their mean susceptibility values of 8.17 and 18.97 (x 10^{-3}cgs units) respectively, would produce anomalies with amplitudes of 1150 and 1040 nT, based on their respective source depths of 29 and 86 m. Their combined response, a 2000 nT anomaly, would correlate with zone type 12 or 13, which compares with the observed amplitude of the magnetic anomaly investigated by DDH 2.

5.5.2 PETROPHYSICAL DATA FROM DRILL HOLES IN THE WEST DOORA AREA

Before company drilling of West Doora Prospect, the S.A.D.M. in 1951-1952 sited numerous holes to evaluate copper anomalies resolved by Sokoloff (1948). Holes MG1, MG3, MG3A, MG4, MG5 and H49 were used for the following petrological and petrophysical studies.

5.5.2.1 Drillhole MG1

The dominant lithology is hornblende schist, (unit B) with a relatively uniform susceptibility (Figures 5.16 and 5.17). The median and mean values for this schist are 80 and 85 ± 28 (x 10^{-6}cgs units) respectively. Unit A, a hornblende schist, has a lower susceptibility range, with a mean value of 79 ± 26 (x 10^{-6}cgs units), and is slightly higher than the mica schist, (Table 5.24). This suggests that this unit is either a variety of hornblende schist, or represents unaltered schist.

The 4.57 m thick mineralised zone (unit C) within the hornblende schists at 73.2 m, contains mainly pyrite and quartz, and is slightly gneissic at its base. The mean susceptibility value is 148 ± 66 (x 10^{-6}cgs units), and is approximately double the mean susceptibility value of the hornblende schist. This value probably

TABLE 5.24

MAGNETIC SUSCEPTIBILITY DATA FROM ROCKS IN DDH MG1 and MG5

LITHOLOGY	DRILL HOLE	No. of Samples	MAGNETIC SUSCEPTIBILITY ($\times 10^{-6}$ cgs units) Range	Mean	Standard Deviation
HORNBLENDE SCHIST (UNIT B)	MG1	73	30 to 180	85	28
MINERALISED HORNBLENDE SCHIST (Gneissic)	MG1	7	43 to 284	148	66
HORNBLENDE SCHIST (UNIT A')	MG1	22	46 to 142	79	26
MICA SCHIST (overall)	MG1	23	34 to 102	66	18
(i) weathered	MG1	10	52 to 102	73	19
(ii) unweathered (UNIT A)	MG1	13	34 to 79	60	15
Metadacite	MG5 (overall)	37	0 to 1726	231	319
Metadacite (i)	MG5	28	0 to 201	101	55
Banded Metadacite (ii)	MG5	10	286 to 1726	600	440

(measurements by R.A. Gerdes, 1983)

relates to pyrrhotite and/or magnetite associated with pyrite. Another slightly mineralised zone contains some pyrite, associated with a porphyry and a scapolite zone. No significant susceptibility change is associated with this zone compared with the country rock.

5.5.2.2 Drill Holes MG3/3A

These holes, both inclined at 35^{o}S, are in a zone type 11, and an extrapolated portion of DDH MG3A passes into a non-magnetic zone.

DDH MG3 intersected weathered and oxidised rock to the total depth of 39 m. The main lithology is a quartz-feldspar-mica rock, possibly an acid volcanic rock. The mean of 8 susceptibility measurements is 108 ± 35 (x 10^{-6}cgs units).

DDH MG3A, near MG3, (total depth 56.4 m) has core weathered to 50 m, and between 27.7 and 47.1 m consists of a mica-feldpsar-quartz schist. The mean value of 12 susceptibility measurements is 123 ± 51 (x 10^{-6}cgs units), comparable to DDH MG3. The more quartzosic portion of this schist has susceptibilities between 700 and 2420 (x 10^{-6}cgs units).

Sample P670/78 at 45.9 m, has a susceptibility of 2420 x 10^{-6}cgs units. It is a quartz-microcline hornfels with minor chlorite and magnetite, some migratory pyrite, tourmaline and a trace of chalcopyrite, (Whitehead, 1978c). The presence of magnetite and martite explains the recorded susceptibility value.

Below 47.1 m the core consists of a quartz-feldspar schistose rock, having a susceptibility range of 265 and 3437 (x 10^{-6}cgs units) respectively. This interval consists of two petrophysical units, with mean susceptibility values of 265 ± 964 (x 10^{-6}cgs units) and 1443 ± 3437 (x 10^{-6} cgs units). The petrology is as follows:

Sample P671/78 at 47.91 m in the lower susceptibility range is a quartz-microcline hornfels, comparable with P670/78, but containing more alteration zones, represented by bands containing chlorite, turbid feldspar, secondary magnetite, apatite and tourmaline.

Samples P672/78 and P673/78, at 51.87 and 52.73 m respectively from the high susceptibility group, are hornfels, consisting of quartz-microcline-chlorite-plagioclase ± magnetite. The magnetite optical estimate compares with that in the low susceptibility group. The main differences are the secondary plagioclase, metasomatic alteration and traces of covellite. These rocks may be metasediments rather than volcanics, which have suffered hydrothermal and metasomatic alteration (Whitehead, 1978c).

5.5.2.3 Drillhole MG4

This hole at the contact between a linear zone type 10 and a zone type 1, (section 8.6.2.1.) was terminated at 122.94 m. The core is slightly weathered to 56.4 m. An additional oxidized band 2.4 m thick is associated with a porphyritic rock at 72.6 m. The susceptibility log shows four petrophysical units, which compare roughly with the lithology. Histograms are given in Figure 5.18.

The first unit occurs in the slightly weathered zone which extends to 38.10 m. The mean susceptibility value is 227±49 (x 10^{-6}cgs units) correlating with an augen mica gneiss.

The second unit between 38.1 and 68.6 m, has a mean susceptibility value of 4522 ± 10330 (x 10^{-6}cgs units). Lithologically this petrophysical unit contains two rock types, which explains the large standard deviation.

The upper portion of this unit is predominantly a mica schist with small feldspar porphyroblasts. Sample P674/78 from 53.47 m, is a plagioclase-quartz-microcline-magnetite (7-10%) - biotite hornfels containing traces of apatite, leucoxene, zircon, pyrite, chalcopyrite and goethite. Whitehead (1978c) considers the texture is characteristic of a porphyritic igneous rock. The susceptibility ranges from 600 to 2248 (x 10^{-6}cgs units), with a modal value of 200 x 10^{-6}cgs units. The mean susceptibility value of the 16.31 m thick upper unit, is 2224 ± 3190 (x 10^{-6}cgs units).

The lower portion is predominantly a biotite-feldspar-quartz-magnetite schist, which shows complex ptygmatic folding at the contact with the upper mica schist. The susceptibility values range from 265 to 50380 (x 10^{-6}cgs units). The mean value of 9 measurements is 2690 ± 2120 (x 10^{-6}cgs units), which does not include the two higher values of 27240 and 50380 (x 10^{-6}cgs units).

The <u>third unit</u> is 11 m thick, consisting of a quartz-mica schist with a local porphyritic texture. Some pyrite occurs relatively near the contact with the porphyritic zones. It has susceptibility values 30 to 905 (x 10^{-6}cgs units) and has a mean value of 284 ± 343 (x 10^{-6}cgs units). The higher susceptibility values are associated with quartz-rich bands.

The <u>fourth unit</u> consists of various mica schists with thin quartzite bands, and foliated gneiss. These quartzites have susceptibility values between 2 and 6 (x 10^{-6}cgs units). Gneiss from a thin unit at 87.78 m has a susceptibility greater than 27400 x 10^{-6}cgs units. This gneiss (P675/78) is a biotite-magnetite (20-25%) - plagioclase-quartz metasediment, and may contain a magnetite-rich vein. Local concentrations of apatite and remnants of hornblende are present (Whitehead, 1978c). Some of the magnetite is migratory, possibly associated with the veins.

The remaining schists with thin quartzite bands are at least 40.5 m thick and have a mean susceptibility of 4160 x 10^{-6}cgs units. Sample P678/78 at 119.48 m in a quartz-mica schist is a magnetite (45-50%) - biotite (40-45%) - hornblende-plagioclase-potash feldspar schist with secondary chlorite, and has a susceptibility greater than 99999 x 10^{-6}cgs units. The biotite has replaced some of the hornblende.

Two samples P676/78 and P677/78 at 91.44 and 94.18 m in a foliated schist and/or gneiss, have susceptibility values of 61 x 10^{-6}cgs units and 192 to 754 (x 10^{-6}cgs units) respectively. P676/78 is a quartz-microcline-actinolitic hornblende-biotite-plagioclase banded metasediment (hornfels), containing some calcareous layers and some thin layers of biotite schist. P677/78 is a hornblende-plagioclase (altered) - chlorite-potash feldspar rock, an amphibolite or hornblende schist, showing some evidence of metasomatic alteration. Its origin is unknown.

The mean susceptibility and corresponding width to depth ratios of these two magnetic units would produce a magnetic anomaly of 320 and 200 nT, corresponding to a zone type 9 to 10, which agrees with the observed magnetic response, (section 8.6.2.1).

5.5.2.4 Drillhole MG5

This hole, in a magnetic zone type 9, investigated a copper anomaly, but did not intersect any significant copper mineralisation. The basement was intersected at 5.1 m, and the depth of weathering is 17.04 m within a metadacite. The remaining core, to 44.42 m (true depth 31.41 m) consists of metadacite and/or metarhyodacite.

The petrophysical log shows the susceptibility increases with depth, and two possible petrophysical units correlate with the metadacite (plus feldspar) and the banded metadacite.

The susceptibility histogram (Figure 5.19), shows two main groups from 0 and 200 (x 10^{-6}cgs units) and from 280 to 650 (x 10^{-6}cgs units), with two higher values of 922 and 1726 (x 10^{-6}cgs units) respectively (not shown). The lithological susceptibility values (Table 5.24) show a marked difference for the metadacite and banded metadacite. The lower susceptibility group, metadacite is probably a metarhyodacite rather than a metadacite, based on its petrological composition, (Blissett, pers. comm.).

Three samples selected on the susceptibility data (Table 5.25) are quartz-microcline hornfels, with the significant susceptibility value (P786/78), containing minor biotite, magnetite (between 1 and 2%) with traces of pyrite, and copper sulphides (chalcocite, chalcopyrite and covellite), (Whitehead, 1978d). This indicates the significant change of susceptibility is associated with this magnetite-pyrite-chalcopyrite association, and demonstrates the possible use of susceptibility measurements for delineating mineralised zones.

In 1967, two core samples from MG5, which were assayed for tin, (in conjunction with samples from DDH CC1 and JJ1/2 and some granites in Eyre Peninsula), showed that one sample contains 200 ppm Sn, compared with a background of 25 ppm for the tourmaline granite, Cultana granophyre or less for all other samples. Repeated sampling with the sample detection limit of 10 ppm Sn showed all the Wallaroo-Moonta core samples were below this value.

TABLE 5.25

MAGNETIC SUSCEPTIBILITY VALUES OF PETROLOGICAL SAMPLES FROM DDH MG5

DEPTH INTERVAL (m)	PETROLOGICAL NUMBER	PETROLOGICAL NAME	MAGNETIC SUSCEPTIBILITY (x 10^{-6} cgs units)
34.90	P785/78	Quartz-microcline hornfels	121
36.02	P786/78	Quartz-microcline hornfels plus biotite & magnetite, & traces of sulphide	922
44.42	P787/78	Quartz-microcline hornfels	63

TABLE 5.26

PETROPHYSICAL PARAMETERS OF UNITS I TO V IN DDH H49

UNIT NUMBER (Depth Range)	NUMBER OF SAMPLES	MAGNETIC SUSCEPTIBILITY (x10^{-6} cgs units) Range	Mode	Mean	Standard Deviation
I (21.03-27.74m)	9	400-1300	500	624	281
II (27.74-33.53m)	9	800-3140	1600-2000	1807	596
III (33.53-54.86m)	31	4653-38890	10000-15000 and 30000	19463	9973
IV (54.86-70.1m)	23	46-417	50-200	129	84.7
(54.86-60.7m) (a)	11	116-417	200	184.8	92.1
(60.7-70.1m) (b)	12	46-139	70	78.5	27.1
V SUBUNITS V_{II}&V_{IV})	18	up to 2000		899	941
)	6	greater than 2000		14202	1166
SUBUNITS V_I, V_{III}&V_V	84			56926	33341

(measurements by R.A. Gerdes, 1983)

5.5.2.5 Drillhole H49

DDH H49 inclined at 45^{O}N and drilled to 131.4 m, is within a magnetic zone type 14. The first 65 m is a 'porphyry' containing disseminated pyrite with minor magnetite. The core is weathered to 21.03 m in mica schist and is oxidised to 32.6 m. The susceptibility log (Figure 5.20) shows five petrophysical units. The first two units show some oxidation and the third and fifth units are the major magnetic units (Figure 5.21). The latter unit is subdivided into subunits, and their susceptibility parameters are given in Table 5.26. The major units below the weathering are:

Unit I between 21.03 and 27.74 m, has a mean and modal value of 625 and 500 x 10^{-6}cgs units respectively. It was called a 'Moonta porphyry' by Bacon (1948) but is a mica-quartz-feldspar gneiss with some mica schist.

Unit II between 27.74 and 33.53 m, probably correlates with a less oxidised gneiss comparable with that in unit I. The mean susceptibility is 1800 x 10^{-6}cgs units and may represent a transitional change to the magnetic unit III. Units I and II are interpreted to be still within the weathered zone.

Unit III between 33.53 and 54.86 m, was called a 'porphyry' by Bacon. At 49.4 m P788/78 is a magnetite (3-5%) bearing, quartz-plagioclase-chlorite gneiss, in which chlorite has replaced biotite. The disseminated sulphide present is pyrite, with minor chalcopyrite and magnetite (hematite).

The susceptibility histogram (Figure 5.21) shows two groups with modal values between 10 and 15 (x 10^{-3}cgs units) and 30 (x 10^{-3}cgs units). The mean susceptibility is 19.5 x 10^{-3}cgs units. This unit is 21 m thick. Assuming the depth defined by the log, then the expected magnetic anomaly is 1200 nT for a width to depth ratio of 0.64.

Unit IV between 54.86 and 70.1 m, is non-magnetic. The mean value is 129 ± 85 (x 10^{-6}cgs units). This unit can be subdivided into two subunits, with mean susceptibilities of 185 and 78 (x 10^{-6}cgs units). The upper section of the core is more magnetic.

Samples P789-791/78 at 61, 62 and 63 metres are chloritized breccia, composed of potash feldspar, quartz and chlorite at 61 m, and a deformed, chloritized and sericitised gneiss, containing minor pyrite, with minor chalcopyrite and molybdenite. Some magnetite is present in P791/78. The susceptibilities are less than 100 x 10^{-6}cgs units.

Unit V below 70.1 m to the total depth of the hole, consists of a variety of quartz-feldspar ± biotite ± magnetite schist. Orthoclase increases at 118.9 m. The susceptibility values show a large range from 94 to 165600 (x 10^{-6}cgs units), with ten specimens greater than 99999 x 10^{-6}cgs units. The higher values were recorded on smaller fragments and corrected for volume variations. These rocks show a high degree of anisotropy (Figure 5.22), reflecting varying percentages of magnetite within the banding, and the concentration of magnetite in the nodes of microstructures.

This unit is composed of three magnetic units, separated by thin bands, with susceptibilities less than 2 x 10^{-3}cgs units. Sample P795/78 at 94.5 m from one of these thin bands is a hornblende-plagioclase schist and contains no magnetite. The remaining samples at 80.5, 81.7 and 109.1 m, are hornblende-plagioclase-magnetite schists and metasediments, derived from calcareous metasediments (Whitehead, 1978d).

The mean susceptibility is 56.93 x 10^{-3}cgs units, and the magnetic response, assuming a width to depth ratio of 0.63 estimated from the core intersections, would produce an anomaly with an amplitude of 3450 nT. As this value is below that observed in the area, these rocks are not the major source for the magnetic zone type 14. The magnetite/martite is estimated optically at 15-25% in two of these samples. At 109 m, the rock shows layering, which is almost isoclinally folded, and the schistosity (defined by hornblende) is almost parallel to the fold axis. The magnetite interbanded and concentrated into distinct layers parallel to the bedding, was interpreted to be primary, (Whitehead, 1978c).

5.5.3 PETROPHYSICAL DATA FROM DOORA MINE DDH1, CC1 AND JJ1/2 IN THE DOORA AREA

Devon DDH 1 near the Doora Mine is on a magnetic zone type 11, and DDH CC1 and JJ1/2 to the southeast on magnetic zone types 9 and 10. The porphyries from DDH1 differ petrophysically from those in DDH CC1 and JJ1/2, and are comparable with certain units defined in Moonta DDH E1 to 3 inclusive.

5.5.3.1 Doora Mine DDH1

The lithological and susceptibility logs (Figure 5.23) show four possible petrophysical units A to D, which compare generally with the lithological log, except units C and D are within the same lithological unit. The histograms and susceptibility parameters are given in Figure 5.24 and Table 5.27.

The main magnetic horizons are in unit C, and to 32.9 m in unit A. The expected responses for units A and C assumed the mean values for the intervals given below:

	Depth (m)	Thickness (m)	No. of samples	Magnetic Susceptibility ($\times 10^{-6}$cgs units) Range	Mean	S.D.
Unit A (upper part)	24.4	8.5	24	90-5408	1179	1403
Unit C	75	9.1	18	171-4127	1325	1341

These source parameters would produce magnetic anomalies with amplitudes of 40 and 20 nT. When the whole core is considered as one unit, assuming a mean susceptibility of 100 x 10^{-6}cgs units, then the expected response is 10 nT per metre of thickness. In this case, the response is a low frequency anomaly with an amplitude of 75 nT, correlating with either a zone type 1 or 7 depending on the source dimensions. As this hole is within a zone type 1 the results are as expected.

The higher susceptibility values in DDH 1 are from the feldspathised mica schist, (100 to 200 x 10^{-6}cgs units), quartz-biotite-magnetite schist in shear zones, (800 x 10^{-6}cgs units) and one thin vein of orthoclase-quartz±pyrite-magnetite at 59.1 m in unit B. Some porphyry shows thin bands of disseminated magnetite, with relatively sharp gradational contacts over approximately 0.03 m. Most susceptibility ranges reflect gradational changes of disseminated magnetite with minor pyrite, representative of compositional or layering within this porphyritic material.

TABLE 5.27

MAGNETIC SUSCEPTIBILITIES OF UNITS A TO D IN DOORA MINE DDH 1

Unit	Depth Range (m)	Range	No.	Median	Mean	S.D.
		Magnetic Susceptibility ($\times 10^{-6}$ cgs units)				
A	to 45.72	less than 1000	40	100to149	233	223
		greater than 1000	10	-	2962	1240
		80% are less than 1000				
B	45.72to75.0	less than 1000	66	70to79	118	137
		" " 400	64	"	95	44
		greater than 1000	2*	1074&6606	-	-
		94% are less than 500				
C	75.0to84.1	less than 1000	12	450to549	477	201
		greater than 1000	6	-	3020	922
		67% are less than 1000				
D	84.1to97.8	less than 200	34	100to109	102	27
		greater than 200	0	-	-	-

*Orthoclase vein with magnetite and pyrite. Two values above were 858 and 845 x 10^{-6} cgs units respectively.

(measurements by R.A. Gerdes, 1983)

5.5.3.2 Drill Hole CC1

Radioactivity decreases approximately 100 cps between 45.7 and 55 m associated with a pyrite-chalcopyrite zone within feldspar porphyry, and this has no distinct change in susceptibility.

These feldspar porphyroblastic rocks have a susceptibility less than 5000 x 10^{-6}cgs units. Petrophysically they are subdivided into four units, and their corresponding histograms and distribution parameters are shown in Figure 5.25 and Table 5.28 respectively. The distribution shows three median values, ranging from 250 to 500, 2500 to 2750 and 3500 to 3750 (x 10^{-6}cgs units).

The petrophysical units A, B and C correlate with a feldspar porphyry (metadacite), and unit D correlates with porphyritic gneiss, which has a slightly higher susceptibility than the other units. The lower values in the histogram within this unit are associated with disseminated pyrite.

5.5.3.3 Drillhole JJ1/2

This hole is 0.2 km northeast of DDH CC1. Both holes were sited on a radiometric anomaly, (Knapman, 1955). The logs show five petrophysical units A to E. The histograms and distribution parameters are given in Figure 5.26 and Table 5.29 respectively.

Unit A has a higher susceptibility than unit B, and both units were named 'feldspar porphyry', although Whittle suggested a rock from within unit A is a stressed porphyritic soda microgranite. The petrology shows a peculiar composition: dominant albite and quartz, minor anorthoclase (?) and orthoclase, with little poorly oriented chloritised biotite and an opaque mineral.

'The texture is definitely porphyritic with composite albite phenocrysts up to 0.5 cm diameter, while the groundmass is even grained xenomorphic granular to very fine. The stressed characteristics are shown by weakly oriented micas and composite phenocrysts'.

This description is included as C. Branch (pers. comm.) considers sodic rocks may be important in this Province, and the source of this 1951 data is difficult to locate.

The increase in susceptibility in unit A probably correlates with the slightly higher percentage of pyrite associated with magnetite. Unit C occurs at the bottom of this porphyritic sequence and has a mean susceptibility of 2500 x 10^{-6}cgs units,

TABLE 5.28

MAGNETIC SUSCEPTIBILITY DATA OF FOUR PETROPHYSICAL UNITS IN DDH CC1

trophysical Unit	Depth Range (m)	Number of Samples	Magnetic Susceptibility ($\times 10^{-6}$ cgs units) Range	Median	Mean	S.D.
A1		11	0-750	250-500	318	142
A2		15	1000-4250	1500/2500	2216	872
A(overall)	30.78-44.2	26	0-4250	-	1415	1159
B	44.3 -66.5	40	1315-4748	-	2959	917
C	66.5 -79.25	20	19-4000		1742	1336
C1		10	less than 1250	500-750	580	254
C2		10	1750-4000	-	2905	835
D	79.25-105.2	49	1508-4860	2750/3750	3357	762

TABLE 5.29

MAGNETIC SUSCEPTIBILITY DATA OF FIVE PETROPHYSICAL UNITS IN DDH JJ1/2

trophysical Unit	Depth Range	Number of Samples	Magnetic Susceptibility ($\times 10^{-6}$ cgs units) Range	Median	Mean	S.D.
A	28.96-33.53	4	140-1302	-	508	540
B	33.53-65.84	32	30-122	70	84	31
C	65.84-75.59	20	250-6500	-	2542	1650
D	75.59-82.3	10	40-75	-	44	10
E	82.3-110.64	13	less than 1000	500-1000	530	227
		45	greater than 1000	4000-5000	4607	2357

(measurements by R.A. Gerdes, 1983)

which is 30 times the mean value of unit B. Unit C is petrophysically different from units A and B. However, some thin bands of higher susceptibility material within unit B correspond to secondary disseminated magnetite.

Unit D has a low susceptibility, mean value of 44 x 10^{-6} cgs units and represents a pegmatized zone, 6.71 m thick between units C and E.

The histogram of unit E (Figure 5.26) shows two groups. The major one has a median value between 4000 and 5000 (x 10^{-6}cgs units), with a mean value of 4600 x 10^{-6}cgs units. This 'feldspar porphyry' is schistosic, and in places, gneissic, with biotite-chlorite ± magnetite bands. The lower susceptibility group with a mean value of 530 x 10^{-6}cgs units, correlates with feldspathised portions. This unit has a different lithology from B and is approximately twice the susceptibility value of unit C. The expected anomalies from units C and E are 38 and 170 nT respectively, assuming unit E has the thickness intersected in this hole.

5.6 PETROPHYSICAL DATA OF METASEDIMENTS WITHIN THE NORTH KADINA AREAS

North Kadina DDH KD1 to 6 inclusive investigated numerous high amplitude magnetic anomalies. As the lithological logs are based on field terminology, they were not relogged. Petrological data, some copper and iron analyses, and low sensitivity total count gamma logs are correlated with the petrophysical results.

5.6.1 NORTH KADINA DDH KD1

This hole investigated a 4500 nT anomaly (North Kadina Area I). The lithological and petrophysical units (Figure 5.27) show seven density and susceptibility units, but the exact boundaries between these petrophysical parameters are not coincident.

Miles (1954) described these rocks

'as migmatite gneisses, of mixed origins consisting of siliceous banded sediments, shaley siltstones and sandstones, which have been metamorphosed to granulite grade, and later impregnated by igneous material, quartz-felspar veins and pegmatites'.

The S.G. and susceptibility histograms (Figure 5.28), show that the migmatite gneiss and dark quartzite granulite, (susceptibility units III and VI), have the highest mean values from 65.6 to 77.1 and from 42.7 to 48.7 (x 10^{-3}cgs units) respectively, (Table 5.30).

PETROPHYSICAL DATA OF LITHOLOGICAL UNITS IN NORTH KADINA DDH KD1

LITHOLOGY	DEPTH RANGE (in metres)	THICKNESS (in metres)	SPECIFIC GRAVITY				MAGNETIC SUSCEPTIBILITY (x 10^{-3} cgs units)			
			No. of Samples	Range	Mean	S.D.	No. of Samples	Range	Mean	S.D.
Banded gneiss	12.19-79.25	67.06	44	2.44-3.32	2.73	0.14	44	0.056-13.4	4.65	3.43
Dark streaky migmatite gneiss	79.25-88.39	9.14	7	2.92-3.43	3.24	0.22	7	38.2-104.0	77.1	24.7
Cherty quartzite	88.39-94.79	6.40	4	2.61-3.71	2.93	0.52	4	1.07-36.4	13.84	16.53
Gneissic metasediments (sed. gneiss)	94.79-125.88	31.09	20	2.75-3.23	2.96	0.13	20	2.79-65.4	33.64	20.15
Migmatite gneiss	125.88-134.11	8.23	6	2.70-3.32	3.01	0.21	6	29.1-90.2	65.65	20.96
Feldspar-hornblende-epidote granulite gneiss with minor magnetite	134.11-136.55	2.44	1	-	2.87	-	8	1.11-94.7	42.76	40.46
	(*low susceptibility value not included in mean)						7*	10.3-94.7	48.71	39.75
Dark quartzite granulite	136.55-147.22	10.67	7	2.91-3.42	3.16	0.26	30	4.36-189	43.18	36.86
Chloritized gneiss	147.22-153.62	6.40+	5	2.69-3.02	2.86	0.13	4	1.71-10.3	3.84	4.40

(measurements by R.A. Gerdes, 1983)

These units (III and VI) from 80.8, 86.3, 126.2, 128.0 and 134.1 m are fractured or brecciated oligoclase-pyroxene-amphibole gneisses, with disseminated magnetite granules arranged along the bedding planes of the highly feldspathised quartzite. This magnetite is regarded as a constituent of the original sediments, probably not as magnetite, but as iron-rich minerals, (viz. siderite, limonite, etc.), the magnetite developed during metamorphism. Fragments of this feldspathised magnetite are distributed through these rocks as porphyroclasts of a breccia with a random orientation. Secondary magnetite is associated with pyrite and minor chalcopyrite and occurs interstitially among the brecciated rock fragments. According to Whittle (1954a) the magnetite is both sedimentary and introduced.

Copper and iron assays of samples between 134.1 and 147.2 m, within the dark quartzite granulite, averaged 0.01% Cu and 35% magnetite by weight, (total iron assays were between 11.9 and 25.1%). Both sets of assays show a percentage increase with depth, and within this interval the magnetite is finely disseminated throughout the siliceous matrix. The highest concentration of magnetite is associated with broken or brecciated sections and in veins.

The bedding dips 10^{o}-20^{o} to the core axis, subparallel to the hole. The histogram of dips in KD1, and the reconstructed dips of these units, shows the dip is either 45^{o}E or 55^{o}E above 72 m, and either 25^{o} or 75^{o}E below this depth. The dips 55°E and 75°E above and below this depth are realistic, and show an increase with depth.

5.6.2 NORTH KADINA DDH KD2

This hole, on an E-W anomaly with an amplitude of 9000 to 10000 nT, was inclined 40^{o}N, drilled to 106.83 m. It penetrated a gneiss and quartzite sequence, separated by a leached zone (3 m thick) of soft, decomposed and broken zone from 76.20 to 79.25 m. No mineralisation was observed and this leached zone was interpreted as a steeply dipping east-west shear.

The lithological and petrophysical units I and II are separated by the leached zone, (Figure 5.29). The parameters of the histograms (Table 5.31) shows unit II has both a higher mean S.G. and susceptibility.

TABLE 5.31

PARAMETERS OF PETROPHYSICAL UNITS IN NORTH KADINA
DDH'S KD 2,3 and 4

UNIT	SPECIFIC GRAVITY				MAGNETIC SUSCEPTIBILITY (x 10^{-3} cgs units)			
	No. of Samples	Range	Mean	S.D.	No. of Samples	Range	Mean	S.D.
DDH KD2								
I (above 76.2m)	22	2.27-3.08	2.78	0.20	22	0-46.5	8.06	13.7
	20+	2.63-3.08	2.83	0.15	-	-	-	-
	+ neglecting values less than 2.46							
II (below 76.2m)	28	2.77-3.24	2.96	0.12	28	0.04-86.8	22.53	18.2
DDH KD3								
I	2	3.26-3.35	3.31	0.06	3	10.2-44.7	32.4	19.3
II	22	2.60-3.51	2.86	0.23	20	0-9.60	2.54	3.0
III	19	2.72-3.25	2.91	0.17	21	0.78-88.8	35.40	32.5
IV	13	2.72-3.25	2.88	0.17	13	4.68-16.6	10.82	4.
DDH KD4								
A	24	2.63-3.34	2.91	0.18	23	6.64-95.4	28.2	24.4
B	17	2.67-3.48	2.91	0.23	18	3.15-129	52.6	36.3
Overall A+B	41	2.63-3.48	2.91	0.20	41	3.15-129	38.9	32.2

(measurements by R.A. Gerdes, 1983)

Unit I correlates with hornblende ± mica banded gneiss and a quartzite sequence, which contains magnetite and pyrite. The quartzite has a slightly higher susceptibility compared with that of the gneiss. The mean density is 2.83 gm/cm^3 and susceptibility is 8.06 x 10^{-3}cgs units.

Unit II correlates with the fine grained hornblende-biotite-feldspar gneiss and the banded pink and grey felsic gneiss sequence which has a mean density and susceptibility of 2.96 gm/cm^3 and 22.5 x 10^{-3}cgs units. This unit contains a varying amount of magnetite, and the fine grained portions at 98.37 m contain narrow magnetite laminae. In these laminae, the magnetite is syngenetic.

The median value of the dips of KD2 is 40°-50° to the core axis, indicating a true dip of between vertical to 80°S. There is a local deviation associated with a shear zone, where the individual dips show an angle of 30°-40° above the shear zone, increase to 50° across this zone, and then the departure decreases with depth. The general dips show no difference above or below this zone, except for a local increase immediately beneath the shear zone.

5.6.3. NORTH KADINA DDH KD3

This hole, inclined at 50°N, drilled to 106.7 m, penetrated gneiss and metamorphosed sediments with pyrite, chalcopyrite, epidote and magnetite. Between 63.86 and 63.91 m, a pink banded siliceous gneiss, (finely banded feldspar-rich gneiss), has the foliation of 70° to the core axis, is a banded feldspar-hornblende (±epidote) amphibolite gneiss with disseminated magnetite and pyrite, with accessory fluorite, tourmaline and calcite (veinlets). This rock showed a moderate radiometric response, (Figure 5.30). Pitchblende occurs as minute colloform aggregates less than 0.5 mm in diameter, associated with magnetite clusters in the host rock, or, occurring alone at intervals in the thin calcite veins. Whittle (1954b) considered the pitchblende was not associated with the sulphides.

The petrophysical logs were divided into four petrophysical units, which are compared with the percentage Cu and total Fe data, (Figure 5.30). Unit I correlates with magnetite-rich siliceous gneiss. The histogram parameters (Table 5.31) show a mean density of 3.31 gm/cm^3 and susceptibility of 32.4 x 10^{-3}cgs units. The remaining units II, III and IV correlate with pink-grey banded quartzite or gneiss and grey banded gneiss; pink and grey banded gneiss; and the last unit correlates with additional amphiboles within the banded gneiss sequence.

Unit II between 25 and 56.4 m. contains a higher percentage of disseminated pyrite plus chalcopyrite. The copper data shows a maximum value of 0.53% Cu, with a mean value from 19 analyses of 0.10 ± 0.11% Cu. No direct correlation exists between the copper and iron content of the rocks.

Three samples, P836/72-P838/72 within the pink grey banded quartzite (or gneiss) sequence, show hornfels composed of plagioclase, with minor actinolite, potash feldspar, quartz and sphene. The coarse grained zones contain pyrite, minor magnetite and chalcopyrite. Traces of allanite are interpreted as zones of hydrothermal alteration probably along fractures. Density and susceptibility values from P836/72 are 2.79 gm/cm^3 and 9.6 x 10^{-3}cgs units. The other two samples are metasediments composed of potash feldspar, biotite, actinolite, quartz, and sphene, with some coarse grained zones containing scapolite, actinolite, tourmaline and pyrite associated with chalcocite. The petrological data suggests a close pyrite-magnetite ± chalcopyrite association, and the amounts of pyrite and magnetite are between 1 to 2% and 2 to 3% respectively.

Unit III, between 56.4 and 87.2 m, was originally called a banded pink and grey gneiss sequence, but has no petrological data. Sample P839/72 at 87.48m, just below this unit, is a metasediment containing quartz, feldspar, actinolite, magnetite and sphene, with some layers containing garnet. It compares with the petrological data in unit II and its appearance suggests evidence of hydrothermal activity, (Whitehead, 1973a). This unit contains a higher percentage of total iron, between 15 to 38%. The magnetite ranges between 4.9 to 33.1%, and the mean magnetite value is 14.7 ± 11%. The mean density and susceptibility values of this unit are 2.91 ± 0.71 gm/cm^3 and 35.4 ± 32.5 x 10^{-3} cgs units respectively.

Unit IV is a metasediment, composed of actinolite-garnet-quartz-feldspar schist (P839/72) containing 3-5% magnetite. One layer contains 1-2% pyrite, associated with chalcopyrite and pyrrhotite, and a magnetite-actinolite-feldspar schist has 5-

7% magnetite (P840/73). The density and susceptibility values near these two samples are 3.08 and 2.81 gm/cm^3, and 7.03 and 12.2 x 10^{-3}cgs units respectively. The magnetite is derived from an iron compound deposited with the original sediment, as the magnetite occurs in fine grained zones containing more abundant magnetite and some evidence of layering due to variations in the magnetite concentration, (Whitehead, 1973a). In P841/72, a feldspar-actinolite schist or gneiss contains a band of allanite (3-5%) and 5-10% magnetite. A magnetite-bearing metasediment (P842/72) with 10-15% magnetite, shows evidence of hydrothermal alteration, due to the development of epidote. In these rocks, the magnetite and pyrite occur in bands as elongate crystals parallel the schistosity, in addition to the diagenetic magnetite within the coarse metasedimentary layers. The magnetite content ranges from 5 to 10% in P841/72 and from 10 to 15% in P842/72. The density and susceptibility values close to these samples are 2.78 and 3.25 gm/cm^3 and 16.6 and 15.3 (x 10^{-3}cgs units). The density reflects the increase in magnetite. However, the susceptibility values appear lower and require verification.

This possible two-fold origin of the magnetite is reflected by the two density populations in each unit, shown by a distinct grouping less than 2.94 gm/cm^3 correlating with diagenetic magnetite. The other is greater than 3.0 gm/cm^3, and correlates with introduced or remobilized magnetite. The latter group shows a density range from 3.01 to 3.51 gm/cm^3. The susceptibility histograms (Figure 5.31) do not show such a clear separation, and probably reflect the fine-grained nature of the magnetite. Only traces of hematite were reported (Whitehead, 1973a).

5.6.4 NORTH KADINA DDH KD4

This hole, inclined at 50°N to 106.7 m investigated a linear 12000 nT anomaly. It penetrated a pink to grey gneiss and metasedimentary sequence, containing abundant magnetite associated with pyrite.

The logs show the metasedimentary gneiss sequence is subdivided into two petrophysical units, A and B separated at 79.25 m, (Figure 5.32). The mean density values are similar, but the mean susceptibility value of unit B is approximately twice that of unit A, (Table 5.31). Their S.G. histograms show two distributions

(Figure 5.33) similar to that in DDH KD3. This suggests that the same two petrophysical units (or sequence) were penetrated in both holes.

Unit A is predominantly a pink gneiss sequence, (orthoclase-quartz ± hornblende ± mica rock plus disseminated magnetite and pyrite), grading downwards into a grey gneiss sequence, being a (plagioclase-hornblende-magnetite quartz rock) plus pyrite, with some possibility of amphibolite-rich rocks. The mean value of 53 assays from 1 m intervals is 0.03 ± 0.02% Cu. Unit A shows a distinctly higher copper response than unit B, between half to one standard deviation above the mean, and correlates with the dominant bands of orthoclase-rich gneisses, which is comparable with the observed copper responses elsewhere from the volcanic metadacite units. The major geochemical spikes are within a leached zone and is associated with a distinct radiometric response, i.e. 25 to 30 cpm between 45.72 and 46.63 m, which probably correlates with either allanite or pitchblende as in DDH KD3 and the Penang Mine.

The other geochemical response, 0.1% Cu between 68.9 and 70.4 m, is associated with an epidote-tourmaline zone at the contact between two dark grey gneiss units, possibly an igneous contact.

Unit B is predominantly a pink streaky banded gneiss sequence with a minor grey gneiss. The boundaries between these gneisses are either both sharp and gradational, especially between 87.2 and 87.5 m, or, are locally brecciated, and have relatively high susceptibility values. The mean value for the whole of unit B is 52.6 x 10^{-3}cgs units, reflecting the magnetite content, whereas pyrite is low. The copper values are generally less than 0.03% Cu.

Four samples, P843/72 to P846/72 at 89.0, 92.2, 97.23 and 106.2 m, are all feldspathised magnetite-bearing metasediments, which have the composition: plagioclase (albite) - potash feldspar-magnetite-actinolite ± clinopyroxene. The 3-15% magnetite is associated with pyrite and minor chalcopyrite. A magnetite-pyroxene-feldspar (microcline) hornfels shows evidence of feldspathisation or metasomatic alteration, (P845/72). In some specimens, cloudy and possibly orange-stained feldspars containing traces of radioactive inclusions, some chalcopyrite and opaques, indicate a uranium-iron-copper association.

5.6.5 NORTH KADINA DDH KD5

This hole, inclined at 50^{o}N to 106.83 m, investigated a 13000 nT anomaly, and penetrated a pink and grey banded gneiss sequence containing abundant magnetite.

The lithological, radiometric, copper assay and petrophysical logs, (Figure 5.34) show this gneissic sequence is subdivided into four petrophysical units I to IV inclusive, and their parameters are given in Table 5.32. Most S.G. values are greater than 3.50 and correlate with very rich magnetite bands. e.g. the interval between 92.96 and 97.54 m contains 90% magnetite. The density of this rock (unit III) ranges from 3.29 to 4.80 gm/cm^3 (mean value 3.82gm/cm^3) and the susceptibility values range from 24 to 183 (x 10^{-3}cgs units) with a mean value of 99 x 10^{-3}cgs units.

Sample P847/72 from 95.4 m is a magnetite-bearing hornfels metasediment and contains minor molybdenite. This hornfels contains plagioclase (oligoclase)-potash feldspar-magnetite-quartz, chlorite, with minor biotite, sphene, rutile or anatase, and minute traces of carbonate, apatite, tourmaline and zircon. The magnetite is contained within the darker layers, up to 50% and the molybdenite is associated with the magnetite and orthoclase. The latter mineral contains fine pyrite and chalcopyrite grains.

Sample P848/72 from 106.4 m within unit IV is a fine grained grey layered rock, plagioclase-quartz-potash feldspar-biotite-magnetite schist, with minor epidote, sericite and some disseminated allanite and tourmaline. The magnetite (3-5%) is fine grained and layered. The biotite is parallel to the layering and imparts a weak schistosity. Chalcopyrite and minor pyrite are associated with the epidote. The density and susceptibility values nearby are 2.79 gm/cm^3 and 4.43 x 10^{-3}cgs units.

The grey gneiss sequence has a mean susceptibility of 40.65 ± 53.76 (x10^{-3} cgs units), and provides the magnetic response. The pink gneisses have a susceptibility less than 1 x 10^{-3}cgs units.

The in situ radiometric total count gamma log shows a higher background level below 43 m and two distinct peaks greater than 1.0 lbs U_3O_8 per ton. Four radiometric assays show 0.7 to 1.3 lbs U_3O_8 per ton. The upper response between 48.5 and 52.4 m is just above the 0-5% copper zone, indicating a uranium-copper association which is verified by uranium, pyrite, chalcopyrite and fluorite in association with feldspar laths. This occurs near the boundary between units I and II, whereas, the lower radiometric response at 70.1 m, has a similar U_3O_8 assay value, but no associated copper. However a copper anomaly, a few metres below, is in a similar situation to the upper response. The lower anomaly is at the contact between the pink and grey banded gneiss sequence and the fine grained magnetite-rich gneiss, indicating either a lithological or stratigraphic/tectonic control, an unconformity. The in situ normal resistivity and S.P. logs gave no significant results to 30 m.

5.6.6 NORTH KADINA DDH KD6

This hole sited within a magnetic low between two linear magnetic anomalies, was inclined at 50^{o}W and drilled to 106.7 m. It penetrated relatively low density and susceptibility sequence. The petrophysical logs show this gneiss sequence is subdivided into 5 density units and 6 susceptibility zones, (Figure 5.35). The extra magnetic zone has no significant density response. The petrophysical parameters (Table 5.32) show a direct relationship between density and susceptibility, indicating the magnetite variations. The major magnetic zone, (unit D) has a mean susceptibility and density of 34 x 10^{-3}cgs units and 2.98 gm/cm^3. The other units have densities from 2.61 to 2.76 gm/cm^3 and susceptibility values less than 2.5 x 10^{-3}cgs units.

Correlations between petrophysical units and the lithological log shows unit A is an altered ferruginous gneiss, containing magnetite and chlorite just below the weathered zone. The relatively low magnetic units A and B' correlate with fine to medium grained gneisses and granitic gneisses containing hornblende, some disseminated pyrite and traces of magnetite. Units B" and C correlate with a gneissic granite, with minor interlayered gneiss and a thick aplite unit, which contains magnetite and disseminated pyrite, and shows a distinct negative S.P. and narrow radiometric responses.

TABLE 5.32

PARAMETERS OF PETROPHYSICAL UNITS IN NORTH KADINA
DDH'S KD 5 & 6

ETROPHYSICAL NIT	SPECIFIC GRAVITY				MAGNETIC SUSCEPTIBILITY ($x 10^{-3}$ cgs units)			
	No. of Samples	Range	Mean	S.D.	No. of Samples	Range	Mean	S.D.
:D5								
NIT I	13	2.67-3.81	3.076	0.395	14	1.24-161	39.71	54.9
NIT II	17	2.71-3.73	2.866	0.243	17	0.77-168	19.08	39.4
NIT III	6	3.29-4.80	3.823	0.608	6	23.9-183	99.05	52.1
NIT IV	3	2.79-2.91	2.837	0.064	3	4.43-16.9	10.68	6.2
)verall	40	2.71-4.80	3.079	0.479	40	0.77-183	37.66	52.7
:D6								
NIT A1	-	-	-	-	6	0.180-9.88	2.68	3.6
NIT A2	6	2.69-2.81	2.76	0.529	6	0.019-0.179	0.120	0.0
NIT B'	11	2.58-2.70	2.661	0.117	11	0-0.544	0.058	0.1
NIT B"	21	2.51-2.67	2.6105	0.037	21	0-4.84	0.937	1.2
NIT B'+B"	32	2.51-2.70	2.628	0.077	32	0-4.84	0.632	1.1
NIT C	10	2.59-2.92	2.680	0.101	10	0-3.06	0.714	0.9
NIT D	4	2.80-3.07	2.988	0.126	4	6.56-50.8	34.24	20.2

(measurements by R.A. Gerdes, 1983)

The major magnetic unit D, is a fine to medium grained streaky altered granite containing magnetite, which is possibly secondary, due to the alteration and the significant radiometric responses. The S.P. response over this unit shows a minor response, which is insignificant compared with the overlying section.

The discrete S.P. lows in this broad zone correlate with the local low amplitude radiometric responses, and may coincide with pyritised and chloritised zones within the aplite. The K_{40} in the potash feldspar may explain the radiometric response.

5.7 PETROPHYSICAL DATA FROM PENANG MINE DDH 1 AND 3

Magnetic susceptibility data was measured on the unoxidized core from Penang Mine DDH 1 and 3. DDH3 represents the unmineralised country rock, and DDH1 the mineralised zone. The susceptibility histogram for DDH3 (Figure 5.36), shows three possible groups having median values of 0.25, 2.0 and 4.25 (x 10^{-3}cgs units) respectively. Their means and standard deviations are tabulated below:

Group	Numbers of Samples	Magnetic Susceptibility x 10^{-3}cgs units	
		Mean	Standard Deviation
I	8	0.26	0.13
II	13	1.91	0.44
III	18	4.34	0.60

Group I correlates with a fine grained adamellite (P267/77) at 46.02 m, with a possible weathered granite above 37.2 m in DDH3. The other two groups correlate with granite, which has a variable composition of potash feldspar (orthoclase and/or microcline) - plagioclase-quartz-biotite(less than 7%)-hornblende(5%)-magnetite(2%) (Steveson, 1977a).

The susceptibility log of DDH3 (Figure 5.37), shows distinct gradational zones, which increases with depth. Units A and B are indicated by either biotite, hornblende and/or magnetite within the granite. Unit C correlates with adamellite, at 45.3 m and 48.2 m depths. Unit D correlates with a microcline-quartz-plagioclase-biotite granite, which increases in hornblende and potash feldspar with depth. Magnetite (approximately 1%) and pyrite are present, accompanied by the potash feldspar, (P269/77) from 49.7 m within this unit (Steveson, 1977a).

The total magnetic response of the higher susceptibility portions of units A, B and C, assuming a series of vertical thin sheets, would produce a 65 nT anomaly at the surface, showing that the observed response east of Penang Mine is not explained by these granites.

Penang Mine DDH1 drilled to 66.45 m penetrated granite and a very magnetic lode zone. A total count radiometric log shows an irregular response in the overburden and in the upper few metres of the broken core of the granite. Radiometric responses of similar amplitude, (450 cps compared with a background of 225 cps), are on each side of the mineralised zone, (Figure 5.38). The response is zero over the sulphide-rich (pyrite and chalcopyrite) band at 54.86 m. Below this, the log shows a gradual increase of radioactivity with depth towards another radiometric response, at 61 m, associated with pegmatitic (?) material within the granite.

The susceptibility log shows high responses from the granite and mineralised zone, and low response over the dark grey to black, medium grained granular rock at 61.9 m. Sample P264/77, at 62.61 m composed of scapolite-chlorite-quartz with minor carbonate, was interpreted by Steveson (1977a) to be a scapolitised (?)granitic rock. The mean susceptibility is 86 x 10^{-6}cgs units. The susceptibility decrease on each side (units B' and B") of the mineralised zone correlates with the significant radiometric response.

The histogram of the orthoclase-quartz-biotite-hornblende ± magnetite granite, (Figure 5.36), shows three median values of 1.0, 2.0 and 3.5 x 10^{-3}cgs units for DDH1. The low median value of 0.2 x 10^{-3}cgs units, in DDH3, is not represented in DDH1. The mean susceptibility value, based on the overall histogram, is 2.62 x 10^{-3}cgs units. Table 5.33, gives details of other units in DDH1.

The high susceptibility band between 53.40 m and 59.74 m consists of a secondary mineralised rock containing quartz-biotite-serpentine-magnetite-biotite rock, and this contains 5 and 3% of pyrite and chalcopyrite respectively, with minor calcite and chlorite (P260/77), at 53.49 m. The mineralised biotite-rich rocks are composed of biotite-magnetite-altered scapolite-quartz with pyrite (plus minor chalcopyrite), tourmaline and sodic amphibole, (P261/77) at 53.64 m. The latter rock contains 15% magnetite. The mean susceptibility is 142 x 10^{-3}cgs units.

TABLE 5.33

MAGNETIC SUSCEPTIBILITY DATA OF ROCK TYPES

FROM PENANG MINE DDH's 1 and 3

	Number of Samples	Magnetic Susceptibility ($x10^{-3}$ cgs. units) Range	Mean	S.D.
Orthoclase-quartz biotite-hornblende $\pm$ magnetite granite				
DDH3	52	0.127 - 5.565	2.515	1.729
DDH1 (31.7-50.29m)	36	0.716 - 5.028	2.508	1.056
Overall DDH1 (including lower section)	45	0.072 - 8.776	2.744	1.563
OVERALL (TOTAL OF DDH1 &3)	97	0.072 - 8.776	2.621	1.649

REMAINDER BELOW ARE TAKEN FROM CORE OF PENANG MINE DDH1.

Scapolite-bearing rock (DDH1) *Petrological sample P257/77 between 50.60-51.21 m.	2	0.250 & 2.717	-	-
Magnetite-rich ore one (53.40-59.13m)	9	44.06 - 289.84	141.63	93.02
lower values due to granite gneiss (petrology)	3	3.292 - 8.776	5.476	2.907
Quartzite (at 61.59 in DDH1)	2	0.046	0.046	-
Scapolitized ?granite DDH1 (between 62.18-66.29) (Pet. P.264/77)	8	0.066 - 0.104	0.086	0.016

(measurements by R.A. Gerdes, 1983

The lower part of the mineralised zone which is impregnated with granite, (P262/77) at 57.84 m, is an extensively altered and scapolitized granitic rock (?) (Steveson, 1977a). The mean susceptibility is 5.5×10^{-3}cgs units. A thin vertical sheet with a width to depth ratio of 0.13, representing this mineralised zone encountered in DDH1 at 50 m, produces a 1750 nT anomaly; and if dipping at 45°, gives a 1240 nT anomaly.

The thick granite sequence between 31.7 m and 50.3 m is composed of microcline-plagioclase-quartz-biotite-hornblende and contains opaques, which are magnetite, rutile, pyrite and chalcopyrite. The mean susceptibility is 2.5×10^{-3}cgs units, and the magnetic responses at the surface of this material, (in DDH3), would produce a 170 nT anomaly, thereby enhancing that provided by the magnetite-rich zone.

These rocks in DDH1 are a metasedimentary sequence which may compare with the scapolitised portion of the Doora Schists in the Doora Area. However, this scapolitisation appears to relate to the mineralisation, (magnetite-pyrite-chalcopyrite assemblage with minor tourmaline). The radiometric response relates to secondary feldspar (as K_{40}) and minor uranium. The serpentine in P260/77 is associated with unstained carbonate (dolomite or siderite), which Steveson (1977a) considered to be derived from the complete alteration of a magnesium-rich silicate metasediment. A metal scan of these rocks (Rowley, 1977) shows 30 ppm Cu and comparable Co values with the adjacent rocks. P259/77, the secondary pyrite rock, shows high Co and Ni values, 1500 ppm and 500 ppm respectively. The remainder shows a significant Cu response, with associated Pb and Zn plus minor Sn, above the mineralised zone; with a minor W and Zn response beneath. Lynch (pers. comm.) when resampling some auger rock chips near this drill site found no significant W. A similar Cu, Pb and Zn association occurs within the Doora Schists in the Kadina Fold Belt.

5.8 PETROPHYSICAL DATA FROM WEETULTA DDH 1 AND 2

The S.G. and susceptibility logs of DDH1, and DDH2 show three petrophysical units. The most dense and highly magnetic unit is a magnetite-biotite-chlorite metasediment or the quartz-biotite-magnetite rock from 73.4 to 99.1 m in DDH1, and 73.2 to 109.7 m in DDH2.

The combined histograms (Figure 5.39), and their group parameters for each rock type (Table 5.34), show a large standard deviation of the susceptibility for the quartz-feldspar-biotite gneiss and the quartz-biotite-magnetite rock. This is due to magnetite-rich bands in the former, and the marked reduction in susceptibility of the latter due to pyrite, shown by both the susceptibility and S.G. logs of DDH1, between 73.4 and 91.4 m. The difference in S.G. is 0.45. The susceptibility parameters show the change is a factor of 5 between the two rock types in DDH1, as given below:

	Magnetic Susceptibility ($\times 10^{-3}$cgs units)		
	Numbers of Samples	Mean	Standard deviation
Quartz-biotite-pyrite-magnetite rock	15	22.6	1.21
Quartz-biotite-magnetite rock	14	100.2	0.42

However, this change in DDH2 is of the same order, but with lower susceptibility values 6.31 ± 3.64 ($\times 10^{-3}$cgs units) for the quartz-biotite-pyrite-magnetite rock, and 31.5 ± 3.70 ($\times 10^{-3}$cgs units) for the quartz-biotite-magnetite rock.

5.9 PETROPHYSICAL DATA FROM BALGOWAN DDH 1 AND 2

Both holes were relogged by Whitten in 1962, who identified three main rock types:

Rock type 1. Quartz-orthoclase rock (granite gneiss), with minor magnetite, biotite and chlorite.

Rock type 2. Biotite-magnetite-hornblende-feldspar rock identified as a metasediment between 132.6 and 153.9 m in Balgowan DDH1 only.

Rock type 3. Magnetite amphibolite which included magnetite-feldspar-hornblende ± pyroxene rock, a recrystallised basic rock-hornfels and a biotite-magnetite chlorite-feldspar schist.

Susceptibility and S.G. measurements at a 5 ft. interval below the weathered zone, at 19.81 m in DDH1 and 35.05 m in DDH2 show three distinct groups which broadly correlate with these rock types. The histograms (Figure 5.40) and their parameters are given in Table 5.35.

The susceptibility histogram contains three populations. Rock type 2 has two populations. The relatively non-magnetic population compares with rock type 1 and

TABLE 5.34

PETROPHYSICAL DATA OF LITHOLOGIES

FROM WEETULTA DDH's 1 and 2

LITHOLOGY	SPECIFIC GRAVITY				MAGNETIC SUSCEPTIBILITY ($x10^{-3}$ cgs units)			
	NUMBER OF SAMPLES	RANGE	MEAN	S.D.	NUMBER OF SAMPLES	RANGE	MEAN	S.D.
Quartz-biotite metasediments	29	2.44to3.09	2.73	0.11	21	0.041to1.350	0.525	0.467
Quartz-biotite-magnetite rock	38	2.59to4.07	3.16	0.34	42	0.137to193.0	47.49	47.82
Quartz-felspar-biotite gneiss	40	2.42to3.24	2.69	0.12	41	0.33to21.60	5.93	6.19
Overall of DDH 1 & 2	107	2.42to4.07	2.86	0.33	104	-	21.62	37.76

(measurements by R.A. Gerdes 1983)

TABLE 5.35

PETROPHYSICAL DATA OF ROCK TYPES FROM BALGOWAN DDH's 1 and 2

	MAGNETIC SUSCEPTIBILITY ($x10^{-3}$ cgs units)				SPECIFIC GRAVITY			
Rock Type	Number of Sample	Range	Mean	Standard Deviation	Number of Samples	Range	Mean	Standard Deviation
1	40	0 to 20.67	4.14	4.99	29	2.19 to 2.95	2.63	0.15
2	15	1.5 to 135	67.42	89.52	19	2.60 to 3.44	2.89	0.25
3	69	1.2 to 416.4	111.16	80.91	80	2.39 to 3.69	3.12	0.29

(measurements by R.A. Gerdes, 1983)

the other population correlates with rock type 3 which shows a large standard deviation. The cumulative percentage frequency log-linear and log-probability plots of the susceptibility data for rock type 3 shows three log-normal distributions, which are classified below:

Populations in Rock type 3	Range of Magnetic Susceptibility (in cgs units x 10^{-3})	Probable Rock Type
a	0 to 20	Probable granitized material
b	20 to 130	Amphibolite
c	130 to 420	Magnetite-rich amphibolite

The major source of the Balgowan Anomaly is the magnetite-rich amphibolite. Other sources correlate with the lower amplitude residual responses, and the regional response is provided by rock type 2.

The combined S.G. histograms from both holes show a three-fold subdivision, correlating with the three lithological rock types, (Table 5.35).

The S.G. histograms below 30.5 m shows three groups with nodes ranging from 2.6 to 2.7, 2.9 to 3.0 and 3.3 to 3.4 respectively. The accumulated percentage frequency log-linear plot shows two normal populations, with S.G. from 2.4 to 2.6 and 3.4 to 4.2 correlating with rock types 1 and 3 respectively. The data plot for the range from 2.6 to 3.4 shows on both the log-linear and log-probability plots, two possible populations which have S.G. values from 2.6 to 2.95 and 2.95 to 3.4. These may represent either rock type 2, a less dense rock type 3, or a gradual transition between the two.

5.10 MAGNETIC ANISOTROPY

Some preliminary estimates of possible anisotropy were recorded using a Bison susceptibility meter on uncut cores, which were not sliced into rectangular blocks, to avoid unnecessary wastage, as some core had already been halved or even quartered. No intensity measurements were made.

The results showed a marked difference in readings along and perpendicular to the bedding, generally greater than 2, as shown by Jahren (1963), and the scatter was of the same order as the Koenigsberger ratio reported by Gunn (1967) from the Middleback Subgroup. The greatest variation was shown by the magnetite biotite-rich bands within the Doora Schists. Considerable remobilized magnetite was identified in the nodes of microstuctures in DDH H49, unit V (Figure 5.22), and a possible change in anisotropy is associated with the mineralisation in MG1, (Figure 5.16) where the unit B varied between 6 to 30% in the upper part of the unit above a mineralised zone. Systematic anisotropy and intensity measurements are required to determine if the permanent magnetisation is greater than the induced, and if a distinct change is associated with the migratory magnetite and the mineralisation.

5.11 SUMMARY

The susceptibility data shows that there are magnetic horizons within the Tertiary, Cambrian and Adelaidean cover rocks, but from their confirmed properties and thin nature within the whole sedimentary sequences, their expected magnetic responses are small compared with the crystalline basement rocks. The petrophysical data of the basement rocks show the higher the metamorphic grade, the greater is the magnetite percentage and therefore the magnetic responses. This is seen when comparing the increase in the degree of metamorphism and anomalies associated with the Willamulka metasediments in the Pirie and Bute drillholes and the increase with depth in the East Kadina area, and within East Kadina metasediments.

The dominant ferromagnetic mineral within these basement rocks is detrital magnetite, present in layers within the bedding of the metasediments. Some magnetite has been remobilized during folding, as magnetite is concentrated in microfolds, or possibly recrystallized as magnetite rods (cf quartz rods) in the apex of folds. Some particular magnetite units show a high percentage of anisotropy, but evidence for a strong remanent component has not been evaluated.

A significant amount of magnetite is secondary, and is observed in either veins and fractures, or as grains aligned within a foliation, schistosity, and cleavage which may cross cut the sedimentary layering.

The petrophysical data shows two or more porphyritic units, metadacites, metarhyolites and 'feldspar porphyry' within the metasedimentary sequences. The true Moonta Porphyry as defined, is interpreted as a layered sequence of units with varying density and magnetic susceptibility with depth (Chapter 7). Superimposed on this sequence is a magnetite-hematite-pyrite-pyrrhotite associated with the mineralisation, in the Moonta Mines Area.

The introduced magnetite within the metamorphic rocks showing a close association with pyrite, chalcopyrite and copper sulphides, and in places with uranium, was resolved by petrological data, radiometric logs and multi-channel spectrometric core measurements. It has also been observed associated with some feldspathisation, potash metasomatism, amphibolisation and some granitic and pegmatitic intrusions.

Magnetite associated with biotite-rich zones which cross cut the metamorphic sequence, and within some retrograde zones, which are associated with chloritization and rare epidotization is classed as secondary based on the petrological data and core inspections. In metamorphic terrains, detrital magnetite reflects original heavy mineral banding, gradational changes with a sedimentary unit, numerous graded cycles within a unit, similar to graded bedding, and in the amphibolitic units, if originally basic igneous intrusions or exhalatives, magmatic differentiation within a layered intrusion. All these primary occurrences may be used for the structural interpretation. A major problem is the secondary magnetite not associated with mineralisation, which occurs within the foliation or schistosity, and thereby complicates the structural interpretation. It could if in great quantity be interpreted as pseudo-structures and/or lineaments which obliterate the true fold pattern. The linear anomalies within the Warburto Subprovince may be of this type.

Future research should be aimed at a petrophysical and petrological study of the WMC and NBH drillholes, and their relationship to the occurrence of secondary magnetite. In addition, measurements of the remanent magnetic vectors and anisotropic properties of these metamorphics will provide data for computer modelling of some magnetic features, and thereby help target evaluation.

CHAPTER 6

REGIONAL GEOPHYSICAL SETTING OF THE WALLAROO-MOONTA PROVINCE

This account of the regional setting of the Wallaroo-Moonta Province and its relationship to the Torrens Hinge Zone is based on numerous years of study. The major structures and tectonic setting are based on interpretation of regional aeromagnetic data and minor analysis of reconnaissance gravity data, regional geology, stratigraphic drillhole data and mineral occurrences. The B.M.R. interpretations of the regional aeromagnetic data were reported by Tipper and Finney (1966) in ORROROO, and Wells (1962) in BURRA; and for the regional gravity data, (Tucker, 1972; Tucker and Brown, 1973). A petrophysical study of the major Proterozoic units in the Gawler Craton was made to define their magnetic signature.

The regional folds are well mapped in the Adelaide Fold Belt, but not for Proterozoic rocks of Yorke and Eyre Peninsulas, except for local studies in eastern Eyre Peninsula, which were interpreted from mapping of Johns (1961); in the Middleback Ranges, (Miles, 1954b, and Lemon, 1978); the Cleve-Cowell area, (Parker, 1978); and Tumby Bay area, (Coin, 1976). These later structural studies redefined the stratigraphy of the "Cleve Metamorphics", and showed the complex tectonic history, involving four fold deformations in the Gawler Orogenic Domain, comparable to the Willyama Orogenic Domain, (Glen *et al.*, 1977). The Wallaroo-Moonta Province between these two domains, geophysically, shows more similarities to the western part of the Broken Hill Sub-Domain and the eastern Olary Sub-Domain, than to the Cleve Sub-Domain.

Many faults shown in Figure 6.1 were not observed geologically, but were interpreted from geophysical data.

6.1 THE PRELIMINARY ERTS-1 PHOTOLINEAMENTS

ERTS, LANDSAT and SKYLAB remote sensing photos were used to interpret geological structures, lineaments and relationship with known mineral fields by Smith (1977), to identify surficial indicators for possible loci of concealed mineralisation, and to define the controls of mineralisation patterns and their tectonic framework. This comparison of photolineaments is similiar to that carried out in South Africa by Richards and Walraven (1975), and Viljoen et al. (1975) in their studies of the relationship of geophysical data with photolineaments and multispectral imagery data.

Preliminary results from the ERTS-1 imagery over South Australia by Thomson (1973b) were combined with data on major fractures and mineral deposits (Figure 6.2). These photolineaments show numerous orientations, with two major sets between 030° to 050° and 340° to 350°, having no distinct concentration and randomly distributed. The remaining photolineaments were classified into five distinct directions and distributed into possible corridors. However, this classification is not as statistical as the method of Crousilles et al. (1978) which may give better results. The term "corridor" is used for a broad belt or envelope of a series of discontinuous linear features, showing an increased concentration within that belt.

The dominant photolineaments in Yorke Peninsula consist of two sets, oriented from 030° to 050° and 140° to 160°, presumably representing a conjugate fracture system. The former set differs by only 10° from a major belt of corridors, (065° to 070°). It includes the Darling Lineament, and forms part of a major group of subparallel lineaments, which form a corridor approximately 160 km wide, containing the major mineralisation of Broken Hill, the Pinnacles, and Mutooroo Mines. In the Wallaroo-Moonta Province, two additional photolineaments are present. The first is oriented at 080°, subparallel to the Uno Fault, and to faults controlling the Elliston - Polda graben. Similar photolineaments were resolved north of Broken Hill, over the Kapunda Mine, and in a corridor 100 km. wide passing through the Olympic Dam Deposit. The second photolineament orientation is 100° to 110° between Wallaroo and Moonta, continuing southeast to the Kapunda Mine. This same lineament direction is dominant in Eyre Peninsula (Figure 6.2), where a corridor is approximately 60 km wide. Major copper deposits are at its southern boundary. One lineament coincides with the termination of the major set of gravity highs in northern Eyre and Yorke Peninsulas, and truncates the N-S Bouguer gravity high along the eastern boundary of ADELAIDE. The Olympic Dam Deposit is on the southern side of a similar corridor trending between 080 to 090^{o}.

The region between the Wallaroo - Moonta and Broken Hill Provinces contains other sets of ERTS photolineaments. These have a long strike length, up to 400 km, arranged en echelon, oriented between 330 to 350^{o}. They show a distinct grouping just east of the Wallaroo - Moonta Province, forming a fundamental N-S corridor, coinciding with the boundary between the Gawler Craton and the Adelaide Fold Belt, i.e. the Torrens Hinge Zone. This corridor is 50 km wide, has a strike length of 760 km, incorporating the Wallaroo - Moonta and Mt. Gunson Mines. The Olympic Dam deposit is 20 km west of this corridor. Similar corridors pass through Broken Hill, and another belt 100 km wide is on the western side of the Gawler Craton. These N-S corridors are between 360 and 440 km apart, and probably correlate with major crustal fractures.

Based on limited heat flow measurements in South Australia, (Lilley et al, 1977), increased heat flow, between 0.09 to 0.13 Wm^{-2} may be coincident with the N-S corridor, the Torrens Hinge Zone, with a local increase over the Wallaroo-Moonta Province, which may be a function of the present sampling interval. The heat flow also increases slightly in the Broken Hill area, where a similar N-S corridor exists.

6.2 PREVIOUS REGIONAL GEOPHYSICAL INTERPRETATIONS

Reconnaissance geophysical coverage consists of aeromagnetic, aero-radiometric, and gravity data, with detailed ground surveys. The airborne data has variable survey specifications, (Figure 1.2 and Table 1.3). Surveys which provide some qualitative interpretations of major faults and magnetic basement depth estimates are as follows: in the Adelaide Fold Belt: ORROROO (Tipper and Finney, 1966); and offshore: St. Vincent Gulf, (Hartman, 1965);

Investigator Strait (Stackler and Schoenharting, 1971); southern Spencer Gulf, (Hammons, 1966) and northern Spencer Gulf on WHYALLA, (Burton, 1968). Interpretations were also made on numerous detailed aeromagnetic surveys, flown over basement areas in eastern Eyre and Yorke Peninsulas, in the search for iron ore, uranium and base metals.

The aeromagnetic contoured data covering basement areas were qualitatively interpreted for background information to determine the expected magnetic signatures of particular Proterozoic rocks. These areas are 10, 15, 18 and 19 in eastern Eyre Peninsula, (Figure 1.2) and area 17 in the Adelaide Fold Belt. The Charleston area 19, was interpreted by Roberts (1978).

Gravity surveys interpreted around the Wallaroo-Moonta Province, are located on ORROROO, (Tucker and Brown, 1973); in the Curramulka area, MAITLAND for iron ore (Seedsman, 1957); in the Blyth and Wakefield areas for lignite (Kerr Grant, 1949); and in St. Vincent Gulf, (Sprigg and Stackler, 1965; Hoogenrad, 1969). The latter was combined with off-and on-shore seismic surveys for oil. These interpretations were directed towards detailed and restricted areas and did not consider the region as a whole.

6.3 THE WALLAROO-MOONTA AND ASSOCIATED GEOPHYSICAL PROVINCES

In terms of metallogenic provinces, Wallaroo-Moonta was grouped by Hills (1965) within the Stable Shelves Province, in which Yorke Peninsula was a sub-province, adjacent to the Adelaidean Province. Other subprovinces of this classification were the Eyrian subprovince and the Stuart Stable Shelf, but Hills considered that Broken Hill and Tarcoola were separate provinces. In this thesis, Wallaroo-Moonta is redefined as a separate province from the above, based on tectonic, metallogenic and geophysical data.

The American Geological Institute, Glossary of Geology, (2nd Edition, Bates R.L. and Jackson J.A. Editors) defines the term province as

"any large area or region considered as a whole, all parts of which are characterized by similar features or history differing significantly from those of adjacent areas; specif. a geological province or physiographic provinces".

A geophysical province, is here defined as a region characterised by any number of geophysical features, e.g. magnetic zones or trends having a similar characteristic, representing the magnetic fabric or density distribution of a region, and being significantly different from adjacent areas. The provinces and subprovinces referred to in this text are geophysical and not geological, as two superimposed deformations which do not interfere on the macroscale, or are present in the microscale may not be resolved in the geophysical fabric.

The geophysical provinces were resolved in terms of the magnetic fabric, as represented by the 1:10^6 aeromagnetic contour compilation of the southeastern quadrant of South Australia, and controlled by a qualitative interpretation of the BMR 1975 data. The Wallaroo-Moonta Province (A), (Figure 6.3) is triangular in shape and characterised by a complex area of high amplitude isolated randomly distributed anomalies, with some linear sources. It is surrounded in the north and southwest by the related Tickera and Hardwicke Subprovinces. The Tickera Subprovince (B') is characterised by a set of linear trends, oriented at 040^o, within a relatively low magnetic background area, characteristic of either a gneissic sequence or a batholithic mass. The Hardwicke Subprovince (B) contains both linear and randomly oriented high amplitude magnetic sources, in a relatively low magnetic background area, characteristic of granite gneisses and schistosic basement rocks.

Immediately west of the Hardwicke Subprovince and separated by the Soutter lineament (Figure 6.4) is the Joseph Banks Province, characterised by large non-magnetic areas, coinciding with granitic intrusions (Zones P and R), sedimentary basins (S) and an arcuate magnetic Zones (N and Q), interpreted as metamorphic contact zones associated with these intrusions. Further west from the Joseph Banks Province is the Tumby Province (Zones M and O), characterised by linear high amplitude anomalies striking N-S, the Sleaford and Carnot Provinces, which are characteristic of gneisses and schists of the Sleaford Complex.

North and northwest of the Wallaroo-Moonta Province and Tickera Subprovince is the Middleback Province, (the Gawler Orogenic Domain of Glen *et al.,* 1977), characterised by long linear high amplitude magnetic anomalies, associated with iron formations of the Middleback Sub-group, basic intrusions, and large non-magnetic interpreted granitic areas Zones (L), e.g. Charleston Granite. The western boundary of this province is delineated by a strong magnetic gradient associated with the Kalinjala Mylonite Zone (Parker, 1980a) which separates relatively high grade metamorphic rocks of the Middleback Province from lower grade metasediments of the Hutchison Group in Eyre Province. Zones U, T, V and perhaps W have a general trend pattern, similar in structural style to the western side of the Middleback Province. Both are considered by Glen *et al.* (1977) to relate to the Gawler Orogenic Domain. Zone W surrounds the Warramboo Province, characterised by E-W magnetic zones, correlating with (?) Archaean magnetite-rich rocks.

Immediately east of the Wallaroo-Moonta Province is a complex series of subprovinces, trending northeastwards, as follows:

(1) The Arthurton-Bute Subprovince, characterised by low amplitude linear N-S anomalies with some linear and lower amplitude anomalies characteristic of low grade metasediments and granites. A portion of this subprovince is overlain by both Shelf Adelaidean and Cambrian sediments.

(2) The Stansbury-Ninnes Subprovince, characterised by a linear zone of relatively non-magnetic metasediments, confined by linear fractures. These form a series of hinge zones at the edge of the Gawler Block. This subprovince is comparable with the Pirie Province and with portions of the Stuart Shelf, further north.

The Orontes Province is separated from the Stansbury-Ninnes Subprovince by the Orontes Lineament, and bounded on the east by the Wakefield and Troubridge Lineaments. It is characterised by a series of high amplitude linear anomalies trending 010^{o} to 020^{o}, with a strike length of 270 km. It is discordant with both highly magnetic and dense sources, and the regional

Bouguer gravity high is correlated with a belt of high grade granulite facies at depth, similar to the Broughton area, (Gerdes, 1978). This province confined between two subparallel lineaments, may be either a belt of basic intrusions, comparable with the basic wedges introduced at depth in the axial zone of rift systems, e.g. Red Sea Rift Valley, a possible mechanism for triple junctions; or, a graben containing thick basic volcanics, comparable with the Guyana Rift in South America. Geophysical modelling of a graben infilled with basic volcanics shows that this model gives a comparable profile.

The Investigator Province may be a continuation of the Wallaroo-Moonta Province at depth, and Zone E' may be a continuation of the Curramulka Subprovince, separated from the latter by the discordant Orontes Province. The Investigator Province is separated from the Kanmantoo Province on the southern side by the Cygnet Fault or Thrust, and is separated from the Vincent Province in the northeast by the Vincent Lineament.

The Vincent Province is a low intensity area of non-magnetic sediments within the St. Vincent Basin and is probably underlain by a non-magnetic basement. The eastern boundary of the Vincent Province is separated by the Burnside lineament from the Barossa Province, which is an uplifted or thrust block of Middle Proterozoic rocks within the Adelaide Fold Belt, and is controlled by the Burnside lineament and the Meadows-Kitchener fracture system.

The Riverton and Barabba Magnetic Anomalies are situated within a horst block, (see magnetic basement depths, Section 6.6), in the northern part of the Vincent Province, which is probably a continuation of the Barossa Complex, in a similar structural configuration, but at a greater depth.

North of the Wallaroo-Moonta Province and east of the Pirie Province is a narrow belt of magnetic anomalies, the Wandearah, Cultana East and Wilkatanna Anomalies, forming the Wandearah-Wilkatanna Province, which is coincident with the Torrens Hinge Zone. This province, the Barossa Province and the Riverton and Barabba anomalies form the east side of the Torrens Hinge Zone, separating the Adelaide Province from the multiple provinces of the Gawler Craton.

6.3.1 RELATIONSHIP OF THE WALLAROO-MOONTA PROVINCE TO THE BOUGUER GRAVITY CONTOURED DATA

The reconnaissance Bouguer gravity contours (Figure 6.5) reflect the average density distribution of the crust at a depth of 6.5 km. As no gravity data are available in Spencer Gulf, the relationship between the offshore portion of the Wallaroo-Moonta Province, as defined by the magnetic data, is unresolved, except that this Province is on a regional gradient on the western side of the Orontes Province and of a major gravity high, (Figure 6.6) trending at 010°, centred over the Curramulka, Arthurton-Bute and Stansbury-Ninnes subprovinces in eastern Yorke Peninsula. This gravity anomaly, which cannot be explained by the thickness of the Cambrian limestone sequence, is comparable in strike direction and magnitude to: (i) the Bouguer gravity high coincident with the Carnot and Sleaford Provinces in LINCOLN, (which consists of Archean-Early Proterozoic granulite-grade rocks); and (ii) the gravity high over the Barossa Province. Therefore, it probably relates to a belt of Early Proterozoic granulite-grade metamorphic rocks within the upper 6 km of the crust. Model studies of the Tickera gravity traverse show these rocks are probably shallower, (Gerdes, 1978).

The alignment of lower magnitude Bouguer gravity anomalies coinciding with ultrabasic rocks associated with the Kàlinjala Mylonite Zone in Eyre Peninsula is another possibility, as similar ultrabasics may be associated with the Orontes Lineament.

The gravity low over the Tickera Subprovince correlates with the Tickera Batholith, which may extend northwestwards at depth across the northern part of Spencer Gulf, to connect with the gravity low on the coast, east of the Charleston Granite, which coincides with an interpreted granite (L). Gravity data covering Spencer Gulf may verify this hypothesis.

In general the magnetic provinces relate to shallow magnetic sources or horizons above that reflected by the gravity data. More detailed gravity data in the Province is discussed in Chapter 16.

6.3.2 RELATIONSHIP OF THE WALLAROO-MOONTA PROVINCE TO THE METALLOGENIC DATA

Part of the initial research on the Torrens Hinge Zone involved a study of all mines and prospects in the crystalline basement and Adelaide Fold Belt, to determine the distribution of the mineralisation in each province, and to separate the stratabound deposits, using the principles of Nicolini (1964). Other types of deposits were assumed to relate to structural features, possibly reflected in the basement. The strike directions of the lodes, secondary fractures and their relationship to major folds, diapirism, major fractures, igneous activity and metamorphism were researched from various sources, and classified into seven categories, based on criteria used by Warren (1970) and Stevens (1972).

The known copper mineralisation (Figure 6.7) shows a marked concentration of the fissure + pegmatite-type in the Wallaroo-Moonta Province and stratiform and/or stratabound grouping in the Cleve subprovince. A scattered distribution and a variety of classifications occur within the Adelaide Fold Belt, including a possible porphyry copper deposit near Bendigo prospect. A similar distribution was obtained for the lead, silver, gold, barite and uranium mineralisation, (Figure 6.8). Most of the known lead, silver and uranium in the Gawler Block occur in the Cleve area and a minor amount at Wallaroo-Moonta.

Figure 6.9 shows the distribution and possible limits of the major mineral occurrences in both the Early-Middle Proterozoic and the Adelaidean to Cambro-Ordovician basements. The copper mineralisation in the Adelaidean Province is well dispersed, whereas the lead-zinc-silver and gold mineralisation relates to the metamorphism and the Ordovician granites. These appear to be zoned and possibly relate to a large granitic batholith (Palmer

Batholith), (defined by the regional gravity low in ADELAIDE), and to a N-S fracture system.

Wallaroo-Moonta contains the major copper occurrences in the area, and the coincidence of copper with minor lead-zinc and silver may imply a significant polymetallogenic province. Although the metallogenic data is based on limited sampling, it is significant, and the uniqueness of the province geophysically justifies that Wallaroo-Moonta area be classed as a Province in its own right, and not included in a subprovince as suggested by Hills (1965). The following geophysical interpretation fully justifies this concept.

6.4 INTERPRETATION OF THE MAGNETIC FABRIC OF THE SOUTHEASTERN PART OF THE GAWLER BLOCK NEAR THE WALLAROO-MOONTA PROVINCE

In many metamorphic terrains, the most significant linear magnetic anomalies are produced by bands of ironstone. Examples are: the Biwabik Iron Formation in the Lake Superior region, Minnesota, U.S.A. (Bath, 1962; Leney, 1966); and in Scandinavia, (Espersen, 1970).

Intermediate to basic volcanics are commonly magnetic and produce prominent linear magnetic anomalies, when interbedded with non or weakly magnetic sediments. Common conformable magnetic horizons in metamorphic terrains, i.e. greenstones, amphibolitic/magnetite quartzites and some types of schists, form extensive broad magnetic zones. In the Spotsylvania area in Virginia, U.S.A., Neuschel (1970) reported a series of narrow parallel linear anomalies, extending for many kilometres, which coincided with hornblende gneiss and/or chlorite actinolite schist, both containing pyrite and magnetite, interbedded with quartz muscovite schist.

In Australia, considerable geophysical mapping of regional geological structures was based on the magnetic anomalies over banded iron formations and greenstone belts in Western Australia, (Young and Tipper, 1966; Tipper and Gerdes, 1971). In the Northern Territory, magnetite quartz rocks with associated gold mineralisation in the Tennant Creek area (Daly, 1957), were outlined by numerous B.M.R. aeromagnetic studies. Shelley (1969) interpreted some linear anomalies in the Daly River area as either basic sills (dolerite), or magnetite-rich metasediments interbedded with non-magnetic metasediments. Young (1965) reported linear anomalies coincident with volcanic sequences in the McArthur River area.

Acidic and basic extrusions within Ordovician metasediments in the Lachlan Geosyncline, New South Wales, were studied by Rees and Taylor (1973), where a long linear belt of anomalies with amplitudes between 100 and 200 nT was correlated with post-Ordovician volcanics.

The regional interpretation of the Gawler Craton is based on 1956 and 1962 aeromagnetic contoured data and some analog charts covering *Wakefield*, the northern portion of PORT AUGUSTA, BURRA and WHYALLA.

The qualitative interpretation of the Spencer Gulf contoured data involved the classification of the magnetic trends into orders 1 to 5 based on their magnitude and predominant anomaly. These orders correlate with rock types and different magnetic units within the basement. The distribution of these trends, fractures, faults, and non-magnetic areas characteristic of granite intrusions and/or sedimentary basins, are shown in Figure 6.10.

The 1st order trends along the Kalinjala Mylonite Zone correlate with magnetite-rich rocks associated with ultrabasics. Drilling of 1st order trends, e.g. the Bungalow and Minbrie Anomalies investigated by Seedsman (1958), revealed that the source of the Bungalow Anomaly is a quartz-magnetite rock. Roberts (1978) who interpreted these sources as thick dyke models, showed the susceptibility contrast has values from 15 to 57 (x 10^{-3} cgs. units). Magnetic susceptibility core measurements show similar values.

The 2nd order trends which are the dominant trend type in the region, are coincident with iron formations in the Middleback Subgroup, and the Winton Anomaly (Roberts, 1978) may coincide with iron formations and/or magnetite-rich gneisses. The 3rd order trends coincide with thin magnetite-rich bands in the Hutchison Group, east of the mylonite zone, and with lesser magnetic rocks, similar to those resolved by the 2nd order trends. The 4th and 5th order trends, west of the mylonite zone correspond to magnetic bands or susceptibility contrasts (lithological changes,) and amphibolites within relatively non-magnetic metasediments.

These trends show the magnetic fabric of the region. The correlation between every trend with rock type is impossible, since most of the area is concealed by post-Adelaidean sediments, or is beneath Spencer Gulf.

6.4.1 DISTRIBUTION OF MAJOR FOLD STRUCTURES

Selected simplified magnetic trends of orders 2 to 5 (Figure 6.10), were regrouped into new orders 1 to 3 (Figure 6.11), which were not grouped as before, on zone types. The observed magnitude changes of some zone types along strike may be due to: changes in magnetic properties of the unit, (ie. facies changes); increases or decreases in the depth of overburden, dislocations and deeper weathering profiles; or metamorphic changes within country rocks, (ie. metamorphic grade boundaries and/or granite intrusion metamorphic aureoles). For these implied trends, the above changes were assumed small, so that the distribution of that magnetic unit represented a geological unit. A series of discontinuous magnetic horizons, produced by the streaking out of a band and/or lens, and the thickening of the unit due to folding, were considered as one continuous unit.

These assumptions supplemented by geological correlations from detailed aeromagnetic survey data, suggest that most of the new 1st order trends (Figure 6.10) are either magnetite quartzites, amphibolite-magnetite quartzites, jaspilites or banded magnetite-rich gneisses and schists. The new order 2 is interpreted to be less magnetite-rich than those above, and may also include amphibolite-rich rocks of either basic or metasedimentary origin. The new order 3 correlates with magnetite present in lower concentrations or in thin bands within metasediments.

The fold closures were interpreted from a combination of parameters given in Appendix I. Their axial planes, plunge directions and their correlations between adjacent magnetic units (Figure 6.11), show changes in fold axial plane direction and style within each Province, and a distinct change in style on either side of the major lineaments.

The Eyre Province is characterised by long arcuate linear anomalies, small closed fold structures, e.g. domes, and open ended structures pitching southwards. The directional changes of the fold axis correlate with the F_3 folds as defined by Glen et al. (1977).

The Middleback Province and Broughton Subprovince are characterised by major N-S axial planes of two types. The first are short strike length closed folds, showing both domes and troughs, isoclinal in style e.g. Middleback Ranges, and are equivalent to the F_2 folds of Glen et al. (1977). The second fold type have elongate axial planes, long linear limbs, strike N-S and plunge northwards in the northern portion of the province. In the southern portion, the fold style is the same. However, the axial planes strike NE-SW and become asymptotic to the Spencer Lineament. This suggests a westerly lateral movement of the Middleback Province in relation to this lineament. These folds are comparable to the F_3 folds in the Eyre Province (Gawler Orogenic Domain). The Tumby Province (Zones O & N), is comparable in fold style to the Middleback Province. The Sleaford Province is dominated by N-S axial planes reflective of the F_2 system in the Gawler Orogenic Domain, or the F_1 system of the Willyama Domain. The Joseph Banks Province is dominated by a large granitic dome (batholith) which has its long axis trending 100° to 110°, and has distorted the earlier fold directions. However relic trends are still visible in the Tumby Province and on eastern side of the Joseph Banks Province.

The Wallaroo-Moonta Province was difficult to interpret using the B.M.R. 1975 aeromagnetic computer contours, as they are based on a preset computer contour programme, which is not ideal for complex basement areas. The interpreted trends shown, are controlled by previous aeromagnetic and ground magnetic interpreted data. Two styles of folding are shown: The first has long linear E-W striking axial planes, with fold closures towards the east and northeast. It is also present in the ground data, e.g. Bird Island structure, which changes in direction from E-W to NE-SW, comparable with the F_3 folds in the other provinces. The E-W axial direction which makes the Wallaroo-Moonta Province unique, is dominant e.g. Kadina Fold Belt, and may be affected by the Spencer Lineament. This axial direction compares with folds in the Warramboo Province, or with the F_4 deformation (A.J. Parker, pers. comm.). Alternatively it may be a higher level of the batholithic intrusion, e.g. Butte-Boulder Batholith Model, comparable with structures associated with the Joseph Banks batholith, of which the Spilsby granite is a part. The Tickera and Arthurton Granitic complexes, with a similar radiometric age to the Spilsby granite, provide additional evidence for the above model for Wallaroo-Moonta. The second fold system in the central and southern Yorke Peninsula has a N-S axial plane direction, and is presumably comparable with the F_2 or perhaps F_3 folds in the Eyre and Middleback Provinces.

6.4.2 DISTRIBUTION OF GRANITES IN PRE-ADELAIDEAN BASEMENT

A belt of concordant and discordant non-magnetic areas over Spencer Gulf and PORT AUGUSTA is interpreted to be granite (Figure 6.12). Basement depths are shallow being less than 250 m in WHYALLA and less than 500 m in the LINCOLN-MAITLAND areas of Spencer Gulf, except for the 1.5 km deep basin, resolved by marine seismic surveys, 35 km southeast of Tumby Bay, and a narrow half graben west of Wallaroo, (Burton, 1968). This granite belt widens from 94 km east of Wallaroo to 150 km in the south.

These granites form two major types. The first consists of irregular-shaped homogeneous discordant areas showing no distinct contact zone, produced by granitisation or anatexis. The second group have regular outlines, generally defined by a distinct contact zone which has both affected the magnetic fabric of the basement rocks and shows an increase in ferromagnetic component, reflected by a marked increase in magnetic response. These two types are economically different, as the group 1 type includes uranium-bearing granites, e.g. Hiltaba and Burkitt Granites and perhaps the Carpa Granite, whilst the second type relates to granites containing molybdenite and tungsten, e.g. Spilsby granite.

The granites appear to be at different levels, on either side of the Spencer Lineament, which is the boundary between the Middleback and Joseph Banks Provinces, although both provinces contain both types of granites. Those to the north are 0.2 to 1.2 x 10^3 km^2, in area, whereas those to the south are 1.2 to 3.1 x 10^3 km^2 in area, with a number of smaller ones having areas less than 0.13 x 10^3 km^2. The areal extent may reflect different levels of an intrusion and suggests a tentative downthrow of the Spencers Lineament to the north. Further details of granites in Yorke Peninsula are not shown but are present in the 1:100 000 compilation, (Chapter 16).

6.4.3 DISTRIBUTION OF BASIC INTRUSIONS

Ultrabasic and/or basic intrusions are interpreted from either isolated magnetic positive anomalies, (zone types 3 and 4), or, isolated positive-negative doublets (dipolar anomalies), characteristic of remanently polarized prism models, (Andreasen and Zietz, 1969). These intrusions and known basic volcanics, including the Roopena Volcanics, are shown in Figure 6.13. Those resting unconformably on the crystalline basement in PORT AUGUSTA, may be remnants of Roopena Volcanics or basalts equivalent to the basic members within the Gawler Range Volcanics. The distribution of isolated positive anomalies over the crystalline basement shows a random scatter. Some may coincide with either surface volcanics or interpreted basic dykes.

The larger bodies resolved in the Joseph Banks Province, are both within and outside the large granitic areas. Their distribution may be a function of the relative uniformity of the granitic basement, whereas those within the metasediments are not so clearly resolved due to the interference produced by other magnetic units. East of the Charleston Granite, in the Middleback Province, is an isolated negative anomaly, resolved by the Charleston aeromagnetic survey contours, and interpreted by Roberts (1978) to be either a large folded basic intrusion, or, a folded remanently polarized iron formation. This structure has a negative remanent polarization dipping 60^{o}N, oriented along the plunge. No geological data are available, as this body is concealed at 100 m. b.g.l. Two other interpreted basic intrusions occur just west of Corny Point in southern Yorke Peninsula, and to the north of the Sir Joseph Banks Group of islands.

The positive-negative doublets are of two types. One has the negative either due south or southeast of the positive. The other is northwest of the positive, and has a strong remanent component, but is different from the positive-negative arrangement over the Cambro-Ordovician Black Hill Norite in ADELAIDE.

The distribution of the doublets appears to relate to the Kalinjala Mylonite Zone, and to a possible lineament trending at 125^{o} and 150^{o}. The Point Neill magnetic anomaly is at the intersection of this mylonite zone with the lineament striking at 125^{o}. The other group of doublets are dispersed along a belt or corridor trending between 070^{o} to 080^{o}, coincident with the Spencers Lineament.

6.4.3.1 Basic Dykes

Series of sub-parallel isolated or continuous linear magnetic anomalies extending for hundreds of kilometres in many parts of the world, have been interpreted as either a basic dyke swarm or a fracture system infilled with basic material. In Africa, Behrendt and Wotorson (1971) reported a series of long linear anomalies which were known to correlate with a diabase dyke swarm, and extended for 430 km from Sierra Leone into Liberia. These dykes showed two groups having different remanent components. Boyd (1970) also reported abnormal remanent magnetised dykes in Tanzania and Uganda. Strangway (1961) reported similar dyke swarms which were multiple with a variable strike orientation extending 480 km in the Precambrian shield of Canada. Strangway found that the remanent component of the magnetisations had different inclinations within the plane of the dyke, and classified them accordingly.

The Gairdner Dyke Swarm, is represented in the Gawler Craton as a series of long linear magnetic anomalies which were first observed in GAIRDNER, (Quilty, 1962) and ANDAMOOKA and TORRENS (Young, 1964). The prominent trend direction is 140^{o} extending discontinuously (en echelon) for 100 km.

Ground magnetic profiles over one of these anomalies trending at 150^{o} in PORT AUGUSTA (Tucker, 1969), show a composite intrusion. He interpreted these assuming a tabular body model, to have a source depth of 150 m, a width less than 180 m, susceptibility contrast from 0.83 to 1.30 (x 10^{-3} cgs units), and the mean is 0.83 ± 0.41 (x 10^{-3} cgs. units). This dyke was reinterpreted as three parallel doleritic dykes 460 m apart, (Tucker, 1972).

Another interpretation for the source of these dykes is a multiple dyke intrusion composed of material having different directions of remanent polarization. Hays and Scharan (1963), investigating a rhyolite intrusion in Missouri, U.S.A., found that the magnetic susceptibilities ranged between 0.76 and 2.03 (x 10^{-3} cgs units), which compare with Tucker's results. This implies that if some of these sources are rhyolite, they are younger than both the Gawler Range Volcanics and the Pandurra Formation on the Stuart Shelf. Non-magnetic rhyolite dykes intrude the volcanics, but have not been intersected in the Pandurra Formation. Some diorite dykes intersected in company drilling in the Pernatty area in TORRENS have a mean magnetic susceptibility of 4.5 x 10^{-3} cgs units, and 3.52 x 10^{-3} cgs units in GAIRDNER.

These dykes in the Stuart Shelf are of post-Pandurra age and are assumed feeders to the Beda Volcanics, which have an Rb/Sr isochron age of 1076 ± 34 Ma, (Webb, 1978a; Webb and Coats, 1980). The susceptibility values, based on Beda Arm DDH2, fall into two groups, one between 1.0 and 3.2 (x 10^{-3} cgs units) (basal portion of sequence), and the other between 5.3 and 7.5 (x 10^{-3} cgs units) (upper half of sequence). These values are slightly higher than Tucker's (1969) estimates.

An interpretation of the detailed aeromagnetic survey of S.M.L. 204 and 205, (Taylor, 1970) revealed many linear magnetic sources trending at 0^{0}, 45^{o}

and 135^{o}, indicating three orientations and ages for these dykes, within the crystalline basement rocks in *Roopena*. One of these linear magnetic features, trending at 120° to 130°, with an amplitude of 1600nT, drilled by BHP, (drill holes P.H. 21,32 and 34), revealed the depth of weathering over the source is 82 m. A multiple dolerite with 8 to 10% magnetite was intersected, (Jones, 1970). Drill holes P.H. 32,33 & 34 indicate the intrusion is wider than 135 m, and that this dolerite dyke is associated with a fault. Dykes of this trend in the Iron Monarch Quarry, also have a possible dyke-fault association (Taylor, 1970). Geological details of basic dykes in the Middleback Ranges were reported by Miles (1954b), Jack (1922), Edwards (1936) and Van Wees and Jones (1970). A smaller amplitude linear anomaly, characteristic of a dyke was identified as a micropyroxene diorite body. The susceptibilities of these rocks are unavailable.

Figure 6.14 shows the basic dykes in the Gawler Platform and Stuart Shelf have a dominant 150^{o} direction, whilst those in the Gawler Block strike at 120^{o} to 130^{o}, and are interpreted to be the older of the two. These dykes appear to be dominant in the Middleback Province, and are terminated by the Spencer Lineament, which contains some dykes trending at 050^{o}.

None of these older linear features (dykes) were clearly resolved in the Charleston aeromagnetic survey, although some may be present in *Cowell* and southern Yorke Peninsula. A few speculative dykes oriented at 120^{o}, were resolved in northern Yorke Peninsula. However, these are isolated features with a short strike length. Other dykes are given in Chapter 16.

These linear features and dykes are resolvable in other aeromagnetic data and show a possible grouping into three belts called the Middeback Dyke Swarm, separated by regions having a lower dyke percentage. They are older than the Gairdner Dyke Swarm which both intersected and offset these earlier dykes. Some dykes with a similar orientation, were observed in Yorke Peninsula, (Giddings and Embleton, 1974), but their magnetic response is unresolved.

Only a few fractures, without associated magnetic expressions, characteristic of dykes were resolved.

The dykes in the Adelaide Fold belt are scattered, with variable orientations, whilst those in the Kanmantoo Trough, within the Palmer Granite, trend at 150°, form a corridor approximately 150 km long, 20 to 30 km wide, and are part of the Melrose-Kapunda-Palmer Lineament, which is a major fracture affecting both the crystalline basement and Adelaide Fold Belt.

6.4.4 DISTRIBUTION OF LINEAMENTS, FRACTURES AND FAULTS

O'Leary et al. (1976), defined

'a lineament is a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon.'

The term "magnetic lineament" or "lineament" used in this study is based on O'Leary et al's definition, and is interpreted to represent a macro-fracture and/or structure within the basement with a strike length of many kilometres. The term "magnetic fracture" is similar to the above, but has a strike length less than 2 km, considered as microfractures correlating with either a fault or joint. Linear zones or a group of magnetic fractures showing some or little lateral displacement are termed a "fracture corridor" or "lineament".

As with photolineaments, often the genetic relationship of the linear feature to the tectonic framework is unknown. They may correlate with faults, fractures and/or joints; and with dykes, unconformities, mylonite zones, lithological horizons and/or rock boundaries, and lastly may reflect a line between two different grades of metamorphism. On the microscale, they may also relate to ferromagnetic minerals located and aligned within bands relating directly to secondary features, such as the structural fabric of basement rocks, eg. introduced ferromagnetic minerals infilling a particular cleavage and/or joint set of a fold, or, a particular lineation within the rocks. The latter types are discussed in the Kadina area, (Chapter 8).

6.4.4.1 Criteria for the recognition of Magnetic Lineaments

Two main types of lineaments are recognised in magnetic data:

(i) Longitudinal lineaments are generally nearly subparallel to the axis or trend of the magnetic anomaly, and are indicated by the extension of sharp gradients in the magnetic contours. They generally extend beyond the strike of the magnetic trend or contours. This type of lineament is difficult to resolve, and is only resolvable if a good strike length is present and if the magnetic anomalies or other trends diverge from this gradient.

(ii) Transverse lineaments are oriented at an angle to the anomaly axis or trend, and are recognised by shifts in the alignment of the anomaly maxima or minima. These features are generally of unknown origin, but sometimes may correlate with known faults and ERTS lineaments. The throw or lateral displacement may be estimated by the displacement between two correlatable magnetic units or a sequence of magnetic units, and from quantitative interpretation (source depths) obtained from these and neighbouring areas.

Major basement lineaments and/or faults are defined by a distinct group of magnetic basement depths of similar magnitude on either side of a linear structure. These structures generally have a long strike length, extend and cross-cut structures and may correlate with alignments of earthquake epicentres, axes of gravity maxima or minima, and coincide with or be slightly displaced from major surface faults, e.g. the major basement lineament along the margin of the Valley and Ridge Province within the Cumberland Plateau in Tennessee and Kentucky, (Watkins, 1964). This lineament is considered a transition zone separating the tectonically active Appalachian crustal block from the stable cratonic block, comparable to the Torrens Hinge Zone.

On the minor scale, steep basement gradients, (longitudinal lineaments) can be either classified as a fault or a monocline and/or hinge. These structures require geological control, eg. the East Bute hinge, but may really correlate with a series of small scale, parallel basement faults, all down thrown east. In the magnetic basement interpretation, some of the steep basement gradients are assumed to represent faults.

The transverse lineaments interpreted from the basement depths are resolved by sudden changes in magnetic depths, based on a cluster of estimates, which appear to be discrete. They must also correlate with structures interpreted from other magnetic data. Another type of transverse lineament is a linear feature that progressively terminates a series of magnetic basement depths, eg. North-West Fault, (Young and Gerdes, 1966).

Both types of lineaments have been recorded e.g. in Canada (Steenland and Brod, 1960); and in Australia, a fault within MOUNT RENNIE in the Amadeus Basin was defined in this way, (Young and Shelley, 1966).

The aeromagnetic data, (Figure 6.15), show different concentrations of fractures in the Gawler Craton (where they are greater and have more variable orientations), than in the Adelaide Fold Belt, which shows a distinct set of orthogonal fractures oriented NW in BURRA and NE in ORROROO. Both areas have some additional NNW and NNE sets, and a minor N-S set. Geological mapping in ADELAIDE shows the N-S fractures are dominant, and related to the minor mineralisation in Kanmantoo Province (Thomson, 1965).

6.4.4.2 The north-north-west fractures

These fractures oriented between 320° and 345°, resolved in PORT AUGUSTA, are outlined by the linear magnetic anomalies, interpreted as dolerite and/or diorite dykes in a 90 km wide belt, representing the Gairdner Dyke Swarm, which appears to be terminated by the Spencer Lineament in the south, and is generally confined to Middle Proterozoic and Shelf Adelaidean rocks. They are not known (age wise) in the Adelaide Fold Belt but later fractures infilled with igneous rocks are within the Melrose-Kapunda-Palmer Lineament (corridor).

Similar trending linear magnetic anomalies occur in southern Yorke Peninsula, and a few tentative features are present in central and northern Yorke Peninsula. They represent a 30 km wide belt of fractures, which may extend from Cleve southwards to Warooka. This belt 180 km long, is coincident and subparallel to the Souttar Lineament, which it includes (Figure 6.16). No resolved linear anomalies are associated with the Souttar Lineament.

The region between these two belts contains few fractures having this orientation, suggesting a zone or corridor having a different stress field (under compression), at the time these dykes, the feeders of the Beda Volcanics, were intruded.

6.4.4.3 The northwest fractures

Positive linear magnetic anomalies, oriented 300° to 310°, resolved in the detailed aeromagnetic data of *Roopena*, have amplitudes from 100 to 1600 nT, depending on the susceptibility contrasts between the magnetic sources and country rocks. The Middleback Dyke Swarm is associated with these fractures, and forms a distinctive fracture corridor, which has dislocated the Middleback Ranges.

Numerous major lineaments having these orientations are reflected in the magnetic basement depth (Figure 6.26) data in the Gawler Platform, the Orontes Province and in the Adelaide Fold Belt. They are the Whyalla, Burra and Dublin Lineaments or lineament corridors (Figure 6.16). The relationship between the Whyalla and Burra Lineaments is unknown, but may represent one, en echelon fracture system or a lineament corridor, with the western portion of the Burra Lineament being a secondary feature.

The Dublin Lineament Zone when extended, passes between the Wallaroo and Moonta Mines. It contains the Kapunda Mines, and the possible alignment of the reversely magnetized ultrabasic bodies, of which the Black Hill Norite is just one of three similar magnetic bodies. The Dublin Lineament was active in both Adelaidean, Cambrian and Tertiary times, as it influenced the distribution of certain lithologies within each of these systems.

6.4.4.4. The northeast fractures

Numerous NE fractures are evident in the aeromagnetic data, and are interpreted from steep magnetic gradients, terminations and displacements of magnetic anomalies, particularly the NW and NNE basic dykes. Features with this orientation are the Cowell, Uno, Spencer, Bute and Curramulka lineaments and in the Middleback Province, mapped faults and quartz reefs. The westward continuation of the Bute Lineament is uncertain, and its relationship to the Redan-Anabama Lineaments is suggested on geophysical grounds, as the linear magnetic anomalies in *Oakvale* have a distinct similarity and may be tentatively correlated with the Bute Dyke Swarm fractures, shown by the East Kadina aeromagnetic survey, (Chapter 15).

6.4.4.5. The east-west fractures

Geological data indicate E-W fractures, eg. the Uno Fault, in PORT AUGUSTA, and some quartz reefs in the Cowell area. Roberts (1978) proposed an E-W fracture, terminating the southern end of the Charleston Granite, 'the Charleston Fault,' which extends eastwards and has an overall, but discontinuous, strike length of 40 km.

In the Wallaroo-Moonta Province, numerous fractures are present. The western extension of the Spencer Lineament is oriented E-W, and shows a distinct curvature. The Wallaroo Lineament, east and just south of the Spencer Lineament, has a strike length of 50 km, resolved by the linear termination of magnetic anomalies, and is coincident with a distinct magnetic gradient. Additional discontinuous E-W features south of the Wallaroo-Moonta Province are discussed in Chapter 16. Fracture or lineaments with this orientation were difficult to resolve in the 1975 B.M.R. data as they are subparallel to the flight lines.

6.4.4.6. The north-south fractures

Many N-S discontinuous and possibly en echelon magnetic discontinuities or fractures resolved, decrease in spacing, or increase in concentration within the eastern Gawler Block, presumably relating to major fracturing and the formation of the thick Adelaidean sedimentary pile. Similar concentrations are seen in the eastern side of the Dore Lake Complex, associated with the boundary of the Grenville Province, (Allard, 1970).

The N-S faults resolved in detailed aeromagnetic data covering *Roopena*, correspond to either the axes of negative magnetic anomalies, with the positive anomalies on either side, or to steep magnetic gradients. The Roopena Fault corresponds to a continuous zone of magnetic lows, and extends further north than geologically mapped. It is traceable, west of Wallaroo and Moonta, extending southwards (Figure 6.15). Its strike length is 260 km. The Ash Reef Fault correlates with a series of four separate N-S magnetic low anomalies with another set further east. The Randell Fault defined geologically in a regional magnetic low, is not clearly defined.

The important major N-S lineaments are, the West Cultana Lineament, formerly called the Torrens Lineament, (Dalgarno et al., 1968), the East Cultana Lineament and East Bute Hinge, which forms a major hinge zone at the edge of the Gawler Block. These two lineaments enclose a major discontinuous horst structure which contains the Wilkatanna, Arden, Stirling North magnetic anomalies in PORT AUGUSTA; the Cultana Granite Complex and interpreted uplifted Roopena or Beda Volcanics to the east (East Cultana anomaly); and the Wandearah magnetic anomaly, which was verified by company drilling as an uplifted horst block. The Wilkatanna and Wandearah anomalies are discussed in section 6.5.

6.4.4.7. The north-north-east fractures

These fractures are restricted to the Stansbury-Ninnes, Orontes and the northern part of the Vincent Provinces. They are distinctly different from those in the Gawler Block, and relate to major faults, Eden Burnside - Spalding Lineaments, Meadows and Kitchener fault system. This area of the crust appears to have behaved differently from either the Gawler Block or the Adelaide Fold Belt.

The fractures within the Stansbury-Ninnes Province are interpreted to be a series of fault-controlled hinge lines, which downthrow east, influencing the thickness of Adelaidean sediments, eg the East Bute, Ninnes, Clinton and Broughton hinge zones.

The Orontes Province contains numerous fractures and lineaments trending between 010° and 020°, and is confined by the major lineaments, eg. the Orontes and Wakefield - Troubridge lineaments. The Orontes anomalies are discussed in section 6.5.1. A similar, but shallower belt of magnetic anomalies forms the Barossa Province, which is confined by the Burnside-Spalding Lineament and the Meadows-Kitchener fault system (lineament), and contains a series of pre-Adelaidean inliers. The Orontes Province may be similar to the Barossa Province. Note the term 'Orontes Platform' proposed by Beach Petroleum Ltd., refers to a depositional environment interpreted for the Cambrian sediments and is not used in a tectonic or structural sense.

6.4.4.8. The Melrose-Kapunda-Palmer Lineament

In ADELAIDE, this lineament is resolved as a major fracture zone (corridor) 140 km long, and 30 km wide in the south, 20 km in the north. It is infilled with some NNW dykes and breccia zones, interpreted as faults, eg. the N-S Bremer Fault Zone, the Rathjen Fault, and other NW fracture zones in the north.

The lineament truncates the northern ends of the Orontes and Barossa Provinces, aligns along the eastern edge of the Riverton and Barabba Magnetic Anomalies, and then extends northwestwards through the northern part of the Cultana Anomaly. The magnetic basement depths show this lineament is coincident with the uplifted horst structure, (Figure 6.26). It affects both the deeper magnetic basement contours, (assumed crystalline basement), and an higher intermediate Middle Proterozoic or Adelaidean horizon, (Section 6.6).

It is coincident with the steep gravity gradient, along the western side of the Bluff gravity low in BURRA and PORT AUGUSTA, and is illdefined in ADELAIDE, where it is obscured by a series of N-S gradients. Figure 6.6 shows the distribution of the major axes of the gravity anomalies and the steep gravity gradients.

6.5. INTERPRETED RESULTS OF IMPORTANT AEROMAGNETIC ANOMALIES IN THE REGION

Numerous deep seated sources are represented by high amplitude broad aeromagnetic anomalies associated with the boundary of the Gawler Craton. Both quantitative and qualitative interpretations were made to define the possible source parameters for these anomalies in different provinces, and to provide susceptibility contrasts for the source rocks as a first approximation of the source dimensions of the deep seated bodies.

6.5.1. THE ORONTES AND ASSOCIATED MAGNETIC ANOMALIES

The Orontes Anomalies in the northern part of the Orontes Province form a series of deep seated magnetic sources trending at 010^{o} and extending for 170 km in *Wakefield* and *Blyth*. This belt is along the eastern flank of a major N-S Bouguer gravity high, over east-central Yorke Peninsula. These regional gravity contours show a deflection or residual anomaly coincident with these magnetic sources, indicating that they are relatively dense and contain ferromagnetic material, suggestive of either magnetite-rich metasediment, a basic and/or ultrabasic intrusion, or, an extrusion. The interpretation using the analog data, revealed a composite anomaly, composed of distinct magnetic zone types, displaced by major NW and NE fractures, which are associated with discordant trends, eg. the Price Magnetic Anomaly.

Immediately east of the Orontes Anomalies, in *Wakefield*, is a series of subparallel zone types 7 and 8, and further east is another subparallel set of linear zone types 6 and 7, 60 to 70 km long with near vertical to steep westerly dips, and susceptibility contrasts of less than 0.5 x 10^{-3} cgs units. The mean of over 50 estimates is 0.39 ± 0.16 (x 10^{-3} cgs units). They are within the Vincent Province and correlate with major fractures interpreted to have affected the Adelaidean sediments and presumably the basement. The interpreted dips agree with the observed dips of near surface faults affecting the Adelaidean sediments. However, the magnetic sources are unknown. If the source is within the Adelaidean sedimentary pile, they must correlate with basic rocks, either Roopena or Beda Volcanics. The alternatives are either basic rocks intruded within the basement associated with faults, or uplifted inclined horsts of basement within the Vincent Province.

6.5.1.1. The Orontes Anomalies

The Orontes Anomalies on the western side of *Wakefield* form a belt of zone types 10 to 12, associated with linear zone types 7 to 9. Figures 6.17 shows these lower order zones are on the eastern side of this feature. The major magnetic trends strike between 010° and 015° and form two or three subparallel sources, only one of which is resolved in the Blyth Anomaly, north of the Orontes Anomalies in *Blyth*.

The magnetic basement depths, (Figure 6.26) show that these magnetic sources along the Orontes trend are 1.2 km deep south of the Dublin Fracture Zone (Figure 6.18) and 1.6 km deep immediately north of the same zone, indicating a possible vertical movement of 0.4 km northwards along the Dublin Fracture Zone. Still further north along strike, the Orontes trend is again fractured before the Blyth Anomaly is located, which has a source depth of 1.8 km. The Orontes trend is dislocated and block-faulted by NW fractures, which progressively down-throw northwards, giving a total northerly vertical displacement of 0.6 km. The overall northerly dip of this block-faulted surface along the whole strike length of the Orontes trend is less than 0.5°, a flat platform surface. The Orontes trends both north and south of the Dublin Fracture Zone are similar, indicating that this fracture zone is a normal fault down-throwing north.

The magnetic anomalies north of the Dublin Fracture Zone form two subparallel zone types: a zone type 12 in the west, and a subparallel zone, type 10, immediately east. Each zone is 2 km wide. Zone type 12 has a continuous strike length of 60 km, a mean dip of 73°E, and a susceptibility contrast, 7.2 to 56.6 (x 10^{-3} cgs units), the mean value being 9.46 x 10^{-3} cgs units. This estimate ignores the extreme value of 56.6 x 10^{-3} cgs units, which is characteristic of magnetite-rich metasediments. The subparallel zone type 10 is resolved into two trends, arranged en echelon, and their interpreted dips range from 62 to 80°W and 80 to 86°W respectively. The corresponding mean susceptibility contrasts are 4.19 and 5.49 (x 10^{-3} cgs) units. These two zone types have different, opposing dips, interpreted as either a possible graben or syncline. The latter is questionable as these two trends have distinctly different zone types and susceptibility contrasts.

The main anomalies south of the Dublin Fracture Zone show a similar difference in dip estimates, but at least three major trends are on the western side, within the possible graben, (Figure 6.18) with a steeper westerly dip on the eastern side. The difference in susceptibility contrasts between the two main trends is not as pronounced as those in the north. Also, these trends are complicated by a discordant shallower basement anomaly, the Price Anomaly, which is associated with a NE fracture, west of the main structure.

6.5.1.2 The Price Anomaly

The discordant trends within the Orontes Anomalies were resolved as discrete zone types 11 and 12, associated with a northern zone type 8. They strike at 20^{o} in the west and then change orientation eastwards, subparallel to the Orontes trend. These zone types and trends are comparable with those in the Bute Anomaly to the north, as both anomalies are truncated on the eastern side by a major N-S lineament and are associated with NE fractures.

The Price Anomaly is composed of two subparallel magnetic sources 610 m bgl in the west and 910 m bgl in the east, indicating an easterly dip of less than a degree for the upper surface of this source. The major southern source (zone types 11 and 12) dips at 70^{o} NW, the northern source is vertical, and both have a mean susceptibility contast of 7.7 x 10^{-3} cgs units. The northwestern and northern sources (zone type 8) have contrasts of 1.6 and 0.6 (x 10^{-3} cgs units) respectively. These susceptibilities suggest that the main source of the Price Anomaly is a magnetite-rich metasediment, comparable with the Doora Schist. The other subparallel sources may correlate with lesser magnetic metasedimentary units, within the above sequence.

6.5.1.3 The Blyth Anomaly

The Blyth Anomaly, the northern extension of the Orontes structure, is a broad magnetic zone type 12, 135 km long and 45 km wide. The only difference between this anomaly and the Orontes is the apparent absence of the two subparallel trends. The unresolved nature of these trends may be explained by a combination of increased source depth and a decrease in the separation between the two magnetic units. A possible, but tentative convergence of these magnetic sources may be present.

The individual magnetic trends are discontinuous in the south, being subparallel and 30 km long, whilst the northern trend has a continuous strike length of 90 km. These trends are probably the same unit, but arranged <u>en echelon</u> by a lateral displacement along NW fractures.

The southern magnetic anomalies, which dip 60^o to 80^oE, increase in dip northwards. The northern trend dips 68 to 84^oE, and the mean value is $80^o \pm 7^oE$. On one flight line the anomaly was resolved into two sources, the interpreted dips of which are both 84^oE. The susceptibility contasts show a mean value for these northern two trends of 14.4×10^{-3} cgs units.

The northern magnetic anomalies have a susceptibility contrast of 3.5 to 6.72 ($\times 10^{-3}$ cgs units), with a mean value of 7.56 ± 4.72 ($\times 10^{-3}$ cgs units). These results indicate a decrease in susceptibility contrast northwards, reflecting either a facies change within the unit, if it is the same; or a change in contrast produced by different adjacent country rocks, or an increase in source depth. These susceptibility contrasts are comparable with different trends in the Orontes structure.

6.5.2 THE BARABBA ANOMALY

The Barabba Anomaly, on longitude 138.50^o between <u>Dublin</u> and <u>Kapunda</u> is outlined by a magnetic zone type 10, in a N-S belt of zone types 6 to 8, (Figure 6.16), and north of the Dublin Fracture Zone. The displacement of this belt of anomalies from a similar belt of zone type 7 situated west, suggests the Dublin Fracture Zone is a transverse dextral fault zone with a displacement of 2.5 km. However, the displacement in the Orontes structure is not clearly defined. The continuity of the Orontes trend across the Dublin

Fracture Zone suggests that the Orontes structure has only undergone later, relatively recent, normal rejuvenated movements along the Dublin Fracture Zone, as discussed previously.

The aeromagnetic contours of the Barabba and Riverton Anomalies, (Figure 6.19) show the Barabba Anomaly trends approximately N-S, 6.4 km long and 4.8 km wide. If a smaller partially resolved anomaly, 4 km north is an extension of these anomalies, the strike length is 12.87 km.

The contour data suggests the source of the Barabba Anomaly is a prismatic model, 408 and 520 m b.g.l., and 1.83 km wide. However, profiles across it show the source is not a simple single body, but is composed of thick tabular bodies. The magnetic E-W profile, for flight line 22, (Figure 6.20) was interpreted as a series of three dipping thick tabular bodies. The interpreted parameters, (Table 6.1) shows the sources dip 20^{o}W. The western source has a mean depth of 1.48 km b.g.l., a mean width of 3.68 km and a susceptibility contrast of 4.20×10^{-3} c.g.s. units. The sources (B and C) further east, form two dipping sheets, which have similar susceptibility contrasts (1.41×10^{-3}, cgs units). They are possibly the same rock type, and have a common depth of 538 m. The differences in depth between the western and eastern sources, if both correlate with the same magnetic basement, indicate a possible fault, downthrowing 940 m west. This agrees with the graben model accepted for the formation of the St. Vincent Basin. The source models and their theoretical curves are shown in Figure 6.20. The source rocks of these anomalies are interpreted to be either magnetite-rich metasediments of pre-Adelaidean age, or basic rocks.

6.5.3 THE RIVERTON ANOMALY

The Riverton Anomaly on the western side of Riverton is north of the Barabba Anomaly. The source trends at 350^{o}, is 16.1 km long and 12.87 km wide (Figure 6.18).

The magnetic profiles of flight lines 8 to 11 inclusive, across this anomaly, show it is composed of three major sources, labelled A,B and C in the

TABLE 6.1

INTERPRETED PARAMETERS OF THE BARABBA ANOMALY

Line 22	Amplitude (in nT)	Depth (m)	Dip	Magnetic Susceptibility Contrast (in c.g.s. unit x 10^{-3})
Anomaly A	800	1 426	20°W	4.260
Anomaly B	375	538	20°W	1.409
Anomaly C	375	538	20°W	1.409
Line 23				
Anomaly A	820	1 525	20°W	4.176

TABLE 6.2

INTERPRETED PARAMETERS OF THE RIVERTON ANOMALIES A & B

	Amplitude (in nT)	Depth (m)	Width (m)	Dip	Magnetic Susceptibility Contrast (in x 10^{-3} cgs unit
Anomaly A	770	1 378	1 530	70°W	6.868+
Anomaly B (residual)	200	286	875 approx.	-	0.891

TABLE 6.3

INTERPRETED PARAMETERS FOR THE RIVERTON ANOMALY C

Line No.	Amplitude (in nT)	Depth (m)	Assumed Width (m)	Magnetic Susceptibilit Contrast (in x 10^{-3} c units
8	520	2 096	3 947	2.488
9	470	1 930	3 947	2.084
10	455	1 777	3 947	1.868
11	480	1 820	4 935	1.494
* 9 (Anomaly C)	470	1 673	7 300	0.987

* Interpreted for a thick dyke model.

profile of line 10, (Figure 6.21). Anomalies A and B are two parallel striking tabular bodies 11.26 km long, which is large compared to the width of the source. The interpreted parameters of these anomalies, (Table 6.2) show that anomaly A is 1.4 km deep, has a susceptibility contrast of 6.87×10^{-3} cgs units, for a vertical body, and if dipping at 70°W, is 7.31×10^{-3} cgs units. Anomaly B is considerably shallower, ie 300 m, and has a susceptibility contrast of 0.9×10^{-3} cgs units.

The straight slope depth estimated from the overall anomaly, assuming a prismatic body with dimensions of 1 x 1, gives depths between 580 and 634, which is shallower than the above results obtained for the tabular bodies.

Anomaly C, just east of the other two anomalies is either a tabular body or a fault model, as follows.

(i) Tabular Body Model

Table 6.3 shows the model characteristics for interpretations of lines 8 to 11 inclusive. The source has a mean depth of 1906 m, a width of 3.95 km and a susceptibility contrast of 1.984×10^{-3} cgs units, but is shallower, having a lower susceptibility contrast, and dips 40°W, if interpreted as a thick dipping dyke model.

(ii) Fault Model

If the fault model is assumed to be equivalent to a thin buried horizontal step, as advocated by Grant and West (1965), and assuming a susceptibility contrast of 1.5×10^{-3} cgs units, then the estimated depth and throw of the fault for the following lines are:

Line No.	Depth (in m.b.g.l.)	Throw of Fault (m) (for $N=1.4 \times 10^{-3}$ cgs units)	Assumed Variable contrast as below (in $\times 10^{-3}$ cgs units) corresponding throw is	Throw (km)
8	588	2 156		2.13
9	785	2 470	1.5	2.25
10	1 558	4 360	2.0	3.27
11	1 984	5 746	2.5	3.44

Depth appears to increase southwards over a distance of 6.44 km, ie. a possible dip of 26°S for the upper surface of the block, with a corresponding southerly increase in the throw of this fault, assuming a constant susceptibility contrast. If a linear increase of susceptibility contrast is assumed, then the corresponding throw is given in the last two columns above.

These results indicate the pre-Adelaidean basement surface dips southwards from 0.73 to 2.13 km, b.g.l. over a distance of 6.4 km, a dip of 74°S. The possible major fault shows an increase in throw to the south, suggesting a hinge fault with the pivot to the north of line 8. The basement depths to the west of this major fault line range from 0.73 to 2.13 km bgl, and to the east from 2.74 to 7.71 km, suggesting this fault and/or hinge controls the sedimentation of the Adelaide Fold Belt.

Further south is a series of Pre-Adelaidean inliers and/or thrust wedges, at the surface. By comparing the Barabba and Riverton Anomalies and those over the Barossa Complex, or, by downward continuation techniques, the Riverton and Baratta sources may possibly be buried basement thrust wedges within the Adelaide Fold Belt. The proposed cross section based on the present interpretation for line 10 is shown in Figure 6.21.

Basic rafts (andesite) and greenstone breccia from Spalding DDH D1, 2 and 3A in the Willouran Inlier represent either basement or Adelaidean volcanic fragments. Gibson (1966) logged these holes and subdivided the andesites and greenstone breccia into two types. The magnetic susceptibilities of the andesite (Type I) and the greenstone breccia (Type I) show mean values of 7.76 and 5.06 (x 10^{-3} cgs units) respectively. The median values from histograms are around 0 and 11 (x 10^{-3} cgs units) for the andesite, but are ill-defined for the greenstone breccia core. The other greenstone breccia, (Type II) which was leached and dolomitised, has a mean susceptibility value of 1.07 ± 2.22 (x10^{-3} cgs units).

These andesites, the vesicular andesite in DDH SD2 and the brecciated greenstones are assumed to be widely distributed within the Adelaidean sedimentary pile, but their thicknesses are unknown. Therefore they could be the sources of the N-S magnetic anomalies in the Vincent Province, if thick enough. Some sources within the Riverton, Barabba and Kybonga anomalies may relate to the less altered andesite and/or greenstone at depth. The thin basalt in the River Broughton Beds, (Preiss, 1974) is another possible magnetic source. The relationship of the andesites and greenstone breccias to these basalts is unknown. Deep stratigraphic drilling within these lower Adelaidean units is required before the significance and sources of these magnetic anomalies are resolved. Pre-Adelaidean magnetic sources are also present.

6.5.4. THE WANDEARAH ANOMALY

This anomaly is divided into two zone types 11 in the north, truncated from a zone type 12 in the south, by a NW fracture (Figure 6.18), and controlled on its eastern side by a fault which down-throws 5.8 km east. The magnetic depths over this fault indicate that it hinges southwards, and increases in displacement northwards, (a total change of 3.7 km). The magnetic source depths of zone type 12 is 490 m. Zone type 11 is deeper, as the NW fault probably has a vertical displacement of 3.7 km. Drilling intersected a banded finely laminated and dolomitic metasiltstone sequence, containing banded hematite and magnetite (martite), with some disseminated magnetite between 300 and 400 m. b.g.l., and have a moderate susceptibility, but less than that interpreted. These rocks contain detrital material, and differ from the banded-iron formation of the Middleback Ranges, which is a chemical precipitate, (Whitehead, 1979).

The magnetic trends of the northernmost zone type 11 converge and change slightly in anomaly character, characteristic of a variable dip in a folded limb, whilst one trend within zone type 12 consists of two en echelon trends, which also change slightly in anomaly character. A smaller discontinuous zone type 12 to the southwest is also part of the same folded unit. Zone types 8 and 11, northeast and west of the major anomaly, may correlate with a second magnetic horizon folded around the larger zone type 11.

The west and east limbs dip at 70°E, and 46°W respectively, whilst other parts of the same unit show a steep easterly dip of 70° to 74°. These suggest that the magnetic units form a synform outlined by a magnetite-rich rock, and that the dominant easterly dips (Figure 6.22) relate to a major fracture system. The interpreted data from other zone types further west, indicate tight folding, with the fold axes sub-parallel to the Wandearah Anomaly. The susceptibility contrasts range from 5.26 to 5.55 (x 10^{-3} cgs units), and for zone type 12 to the southwest is 4.15 x 10^{-3} cgs units, considerably less than for the Port Broughton Anomaly, which ranges 11.2 to 24.0 (x 10^{-3} cgs unit). The source rocks of the latter anomaly are interpreted as either iron formations of the Middleback Subgroup/or Devon Group.

Figure 6.22 shows the depth to Middle Proterozoic basement and the thickness of the Beda Volcanics overlying this horst. Minor Cu-U mineralisation is just below these volcanics in a structural trap against the faults, within the Adelaidean rocks. Deep drilling into the Wandearah Metasiltstone is warranted for possible stratabound Cu-Pb-Zn mineralisation, if these rocks are equivalent to the Smithams or Pridhams sequences; and to test the contact relationships between the Wandearah Metasiltstone and the underlying magnetic basement.

6.5.5 THE WILKATANNA ANOMALY

The BMR 1975 aeromagnetic contours over the Wilkatanna Anomaly were overlain by the reconnaissance Bouguer gravity contours. Figure 6.23 shows the Arden and Stirling North Magnetic anomalies associated with the Wilkatanna East Anomaly. The gravity and magnetic maxima are displaced by 12.5 km SW, representing either a concentration of mass (density) of a westerly dipping source for the Wilkatanna body, or, a secondary source independent of the above body. The possible Cambrian basin in Wilkatanna Bore No. 1 is not sufficient to produce this gravity anomaly.

Figure 6.24 shows the 1st order trends associated with the Wilkatanna and Wilkatanna East Anomalies. The discordant zone of N-S, 2nd order trends is interpreted as a fault zone, displaced by 1km, based on magnetic basement depths. This fault zone separates the Wilkatanna Anomalies in the east from the Stuart Shelf in the west. The Shelf is characterised by multiple zone types 2 and 7, trending at 150°, which are cross cut by linear trends, striking at 120°, interpreted as basic dykes (Gairdner Dyke Swarm) in a relatively low magnetic background area, (zone type 1).

The Wilkatanna Anomaly is composed of two major sources. The main anomaly is resolved into some trends which strike at 020° and then change to 350° in the north, suggesting a deeply buried banded and/or folded magnetite-rich source. One of these sources has a mean depth of 7.3 km bgl, width of 15.5 km, and dips at 56°E. It has a mean susceptibility contrast of 2.78 x 10^{-3} cgs units, for an assumed thick dyke model, with a depth to width ratio of two (Figure 6.25). The Wilkatanna East Anomaly further east, is a N-S linear feature, interpreted as a thick dipping tabular body. The source increases in depth northwards from 2.6 to 3.5 km, is 0.66 to 15.8 km wide, dips at 80°W, and has a mean susceptibility contrast of 1.60 x 10^{-3} cgs units, which is considerably more than the recorded susceptibility value of the Roopena Volcanics, but is comparable with the Beda Volcanics and the other source. Modelling of the magnetic and gravity data shows a horst but more data are required to test this hypothesis. Detailed gravity data recorded by P. Faulkner, and the drilling of Depot Creek DDH1 by the S.A.D.M.E. may help to solve this problem. Susceptibilities and modelling of the Arden and Stirling North Anomalies show comparable results.

The residual third anomaly east of the Wilkatanna Anomaly, was interpreted from both flight lines 27 and 28 to have a source depth between 3.5 and 7.0 km bgl, and a susceptibility contrast of 0.8 x 10^{-3} cgs units, assuming an infinite vertical side prism. This magnetic source is coincident with the regional gravity anomaly, which indicates that magnetite-rich rocks are beneath the Cambrian limestones and the source of this anomaly.

6.5.6 COMPARISONS BETWEEN THESE ANOMALIES

All these magnetic anomalies are deep seated, with unknown sources except for the Bute and Wandearah Anomalies, and they are east of the main hinge lines, which define the shallow basement cover relationships along the edge of the Gawler Block. A comparison has already been made between the Bute (Chapter 15) and Price Anomalies, just west of these hinges.

The Orontes and Blyth Anomalies have similar trend directions, dips and susceptibility contrasts, and correlate with a belt of faults defining a graben, infilled with basic material. These anomalies and the East Cultana magnetic anomalies, beneath Spencer Gulf, may be tentatively compared with a belt of basic volcanics uplifted within the Cultana horst.

This belt, (the Wandearah-Wilkatanna Province) north of Cultana has a discontinuous strike length of 130 km and includes the Stirling North, Arden and East Wilkatanna Anomalies. The main differences between these and the Orontes Anomalies are their discontinuous nature, the low susceptibility contrasts, the anomaly character and the similar residual gravity response, compared to the Orontes-Blyth Anomalies. Source material is comparable between the Wandearah and Wilkatanna Anomalies based on the anomaly style, possible internal fold structures, and on convergent magnetic trends and susceptibility estimates.

The Barabba, Riverton and the smaller Kybonga Anomalies to the northwest, have a comparable source type within a horst, (Section 6.6). Any relationship between this horst and the Cultana-Wilkatanna horst is unresolved. However, the major fracture zone comparable with the Dublin Fracture Zone, further north, may have displaced the horst into a series of en echelon horst units.

6.6 MAGNETIC BASEMENT DEPTHS

The magnetic basement depths are based on a study of analog aeromagnetic survey charts. Methods are discussed in Appendix I.

6.6.1. RESULTS - DIFFERENT MAGNETIC HORIZONS

Depth estimates reflect four magnetic horizons. The shallower depths are correlated with heavy mineral sands and/or Tertiary glauconitic sands e.g. Blanche Point Marls; Cambrian glauconite beds (Section 2.2); and near surface magnetic horizons and basic plugs in Adelaidean sediments, some of which are quite magnetic, (Tucker, 1972; Gerdes, 1973b). Petrophysical data were used to confirm these sources.

An intermediate basement horizon resolved in BURRA and ADELAIDE, within the Adelaide Fold Belt (Figure 6.27), may correlate with either basal Adelaidean units, e.g. Beda Volcanics, or with an unknown magnetic source.

The only known Middle Proterozoic metasediments (Corunna Conglomerate and Moonabie Formation), are weakly magnetic. The Gawler Range Volcanics, except for the lower thin basic volcanics, and the Roopena Volcanics are the only magnetic units present. Therefore, the magnetic basement contours (Figure 6.26) represent pre-Late Middle Proterozoic basement, and was verified by a study of the Myall Creek, DDH RC1 volcanic sequence in PORT AUGUSTA.

The pre-Middle Proterozoic magnetic basement surface is slightly shallower, compared with those in St. Vincent Gulf (Hartman, 1965) and considerably shallower than those in Spencer Gulf, (Burton, 1968). A reinterpretation of marine seismic refraction data in this Gulf, after correction for water depth (Figure 6.28), shows that the high velocity layer, interpreted as crystalline basement, correlates with magnetic basement depths determined from the 1960 aeromagnetic data.

The basement depth estimates in BURRA in the Adelaide Fold Belt, are shallower than in ORROROO (Tipper and Finney, 1965). However, comparable depths were found in Wilkatanna in the Torrens Hinge Zone. These results are not included, but were made during this research. These depths within the Adelaide Province, reflect a considerable thickening of the Adelaidean sequence northwards from BURRA into ORROROO, differing by 3 km. Depth of crystalline basement beneath the Adelaide Fold Belt is 6 to 7 km b.s.l., with local uplifted blocks at 1.2 km b.g.l.

6.6.2 DISCUSSION OF RESULTS

The magnetic basement contours (Figure 6.26) show the continuation of shallow basement across Spencer Gulf and the basement around Wallaroo-Moonta Province is just above sea level, with local shallow basins of 150 m b.g.l. infilled with Cambrian sediments. The basement in Spencer Gulf is shallow, generally not exceeding 150 m. b.s.l., except for a narrow graben oriented at 040°, west of Wallaroo. The maximum depth within this structure is 600 m b.s.l., and probably correlates with a basin infilled with either Cambrian limestone or Adelaidean and/or Middle Proterozoic non-magnetic metasediments. Comparison of available seismic velocity data and a reinterpretation of the Western Geophysical marine refraction seismic survey (Figure 6.28), shows a fault-controlled structure, interpreted as similar to the Uno and Corunna synclines in PORT AUGUSTA, containing the Corunna Conglomerate. Unfortunately no velocity data are available for this unit.

The 150 m magnetic basement contour defines the limit of the shallow crystalline basement. The steep basement gradients between the contour intervals 150 to 300 m define the boundary faults or hinge lines and/or zones where the Adelaide metasediments greatly thicken. The inflections of the 50 m contours on to the shallow basement represent embayments of post-Middle Proterozoic rocks showing the basement-cover relationships. The major embayments are the Cambro-Permian Stansbury Basin in southern Yorke Peninsula and the north Spencer Gulf embayment. The minor or sub-embayments, possibly fault - controlled containing Cambrian limestones, are the Ardrossan, Clinton-Cunliffe and the Kadina - Bute sub-embayments. The latter embayment contains shelf Adelaidean rocks underlying the Cambrian limestones.

The magnetic contours on the western side of BURRA resolved the Pirie-Blyth Basin System or half graben, with a maximum depth of 2 km. This half graben is the northern extension of the St. Vincent half graben, 3 km deep, infilled with Adelaidean, Cambrian and possibly Permian sediments overlain by the Tertiary sediments, forming the St. Vincent Basin.

The major eastern fault of the Pirie - Blyth half graben is coincident with the Redbanks - Owen Fault in ADELAIDE and eastern boundary fault of the Adelaide Fold Belt in BURRA. This fault is the western fracture of a basement horst block which strikes 160° to 170°, southwards from Mt. Zion to Barabba. It is 10 to 15 km wide, 150 km long, and probably extends northwards into ORROROO. The eastern boundary fault of this horst has a throw of 500 m in the north and 600 m in the south. This fault is coincident with the Emu-Oakden fault in *Clare*, and the Alma fault in *Kapunda*. A N-S fault east of the Spalding Inlier has a vertical displacement of 1.8 km in the basement, and 1.67 km on the intermediate magnetic basement horizon. This fault is coincident with the near surface meridional fault between Spalding and Clare.

The Zion-Barabba Horst may be compared tectonically with the three uplifted blocks of basement, e.g. Barossa Complex. The geophysical model based on magnetic depths for these blocks shows a horst structure 12.5 km wide, and 125 km long, striking 020°. Assuming these two horst blocks have similar dimensions and rock types, a lateral displacement appears to be approximately 30 km along a sinistral fault, produced by fractures oriented either NE-SW or NW-SE, as both fracture orientations are represented within the magnetic basement contours. The latter direction is the most probable as shown by major fractures AA' and BB' in Figure 6.26.

CHAPTER 7

AN INTERPRETATION OF THE MOONTA PORPHYRY AND ASSOCIATED MINERALISATION

This is a reinterpretation of numerous geophysical surveys carried out by W.M.C. between 1962 and 1968. The purpose is:

(i) to define the outline of the Moonta Porphyry based on geophysical data,

(ii) to determine the geophysical responses of the Moonta Lodes.

These aims are important for this Province and provide a model for similar studies elsewhere in the Gawler Craton and Stuart Shelf.

The shallow distribution of the Moonta Porphyry based on geological data, (Figure 7.1) was compiled from Jack (1917) and from many drilling records. Numerous geologists, Jack (1917), Crawford (1965), and Wright and Lynch (1973) have attempted to outline the distribution of the Moonta Porphyry based on geological data only. The actual boundary, contact relations with the country rocks, its stratigraphic position and the internal structures of the Moonta Porphyry are unknown due to the concealment. The main information available is on the mineralised lodes.

This interpretation attempts to solve these complex geological problems, on both the regional and detailed scales, especially those that control, or, are associated with the mineralisation. This study is supplemented by petrophysical data and identification by Radke (1977) of opaque minerals in some drill core.

7.1. PREVIOUS GEOPHYSICAL DATA AND RESULTS

Geophysical coverage (Figure 7.2), consists of vertical magnetic traverses; induced polarization, frequency domain dipole-dipole array data having a 300 ft. dipole spacing, and Schlumberger vertical electrical soundings. The aeromagnetic and gravity coverage is not shown, as these are discussed for the whole province in Chapter 4.

The interpreted results of the W.M.C. probes (pre-1970) are questionable, because the AB/2 distance (half the current electrode distance) was usually no more than 200 feet, which indicates the limited penetration in this area. The results obtained give only at best the apparent resistivity changes within the weathered bedrock. They are based on:

(i) The interpretations of electrical soundings in the Tickera area (Gerdes, 1974);

(ii) The I.G.E.S. study, (Edge and Laby, 1931). During the I.G.E.S. survey, resistivity, shallow test pit and drilling data revealed that in situ weathered clay corresponding to decomposed porphyry, passed gradually into solid porphyry. The resistivities of the weathered clay, decomposed and fresh porphyry showed comparable values varying from 1.87 to 3.2 ohm m, the mean value being 2.71 ohm m. The rocks are conductive to 2.74 m in the test pit at Moonta, which show that the apparently fresh porphyry contains highly conductive solutions, and is still highly weathered, as the resistivity of porphyry is normally at least 100 times this value.

(iii) The theoretical computer resistivity depth probe based on the test pit data (Edge and Laby, 1931), was compared with some observed apparent resistivity depth probes recorded by W.M.C. This showed the W.M.C. results are unreliable after the resistivity low portion of the V.E.S. curve, due to the skin depth and coupling produced by the frequencies used.

The B.M.R. electromagnetic data (Thyer, 1943), over the Elders Lode system was not used, as these experimental studies showed similar responses over mineralised and unmineralised ground.

The total count radiometric data (Knapman, 1954) around the Moonta Mines (Figure 4.3), shows isolated radioactive responses, reflecting either dumps of porphyritic material, or weathered basement. Since this region has been subjected to a considerable feldspathization, (Chapter 2), the radiometric response, above four times background, may correlate with either gneiss, porphyry or feldspathized metasediments, assuming most of these responses are produced by the K_{40} in the feldpsars. Jack (1917) reported the radioactive minerals, thucholite, associated with the Moonta Lodes, but later radiometric data by Knapman did not find any uranium prospects in this area.

7.2. VERTICAL MAGNETIC TRAVERSE DATA AND INTERPRETATION

The aeromagnetic (BMR 1953 and 1975) contour data (Figs. 7.3 and 7.4), show no distinct magnetic signature over the Moonta Porphyry. The 1953 contours have an interval of 100 nT, from data flown N-S over the porphyry with a spacing of $^1/_2$ mile. The contour cuts were extracted from the analog charts at 100 gamma intervals. No further data is available as these charts are lost, but the traverse sample interval would have been at least 100 feet.

The 1975 computer contours were produced using a bicubic spline, based on E-W 1.5 km flight lines, which were computer sampled at a 60 ± 10 m interval for the 1:250 000 compilation. The magnetic profiles at this scale only, were produced with a similar interval and show two discrete lows south and southwest of Moonta, coincident with the Moonta granite and a major E-W trending magnetic anomaly east of the porphyry. This anomaly is probably 'artificial', produced by extrapolation in the computer processing. A linear E-W anomaly further north 'cross cuts' the porphyry. Details are given in Chapter 9.

This data and the ground reconnaissance WMC data (with a traverse station spacing of 300 feet) both having a contour interval of 250 nT, were inadequate to resolve the porphyry boundary or other structures. For better resolution, the author compiled the magnetic profiles based on the original W.M.C. data, (Figure 7.5). This data was interpreted, using methods given in Appendix 1 and using computer fault model curves, to estimate the dip and susceptibility contrast of selected anomalies, (Figure 7.6). Some problems were experienced in correlation between anomalies on adjacent lines, as some trends have a limited strike length, due to dislocations, oriented 110° to 130°. These probably represent faults, which correlated locally with lode dislocations found during mining. The lodes trend between 040° and 060°, with a directional change in the north. The magnetic trends within the main mines area are at 030°, approximately subparallel to the lodes.

7.2.1. SIGNIFICANCE OF MAGNETIC ZONE TYPES

Correlation of zone types with geological data is poor due to the sparse information. However, by comparing the interpreted susceptibility contrasts of these anomalies with the susceptibility core data, magnetic zones may be correlated with particular rock types.

Zone types 12, 13, and 14 and perhaps some zone type 11 in the east, correlate with iron-rich metasediments. The susceptibility contrasts are comparable with magnetite quartzite. Zone types, 9, 10 and 11 probably coincide with linear magnetite-rich bands within schists, hornblende schists or calc-silicate rocks. Susceptibility contrasts are shown in Figure 7.7. The discrete zone types 3 and 4 may coincide with either a possible basic intrusion, or, areas of complexly folded metasediments and volcanics, whereas the larger areas of this zone type coincide with schists and calc-silicate rocks.

Zone type 1 correlates with each of the following:

(i) granite gneiss which crops out along the coast,

(ii) quartzite in the north of the area,

(iii) areas within the Moonta Porphyry, as defined by this interpretation,

(iv) perhaps dolomite, if the zone type 1 is between two higher order zone types, parallel to the lineation.

Zone type 2 is due to rocks with a greater ferromagnetic content than those rocks discussed for zone type 1. Within the porphyry, this zone type coincides with either:

(i) foliated (banded) porphyry, (banded rhyolite), or

(ii) a change in the mafic composition of the porphyry, or

(iii) metasediments (granitized).

7.3. STRUCTURE OF THE MOONTA PORPHYRY AND SURROUNDING ROCKS

The geological structural information is very limited, except for the data on the lodes. The structural interpretation based on magnetic zones and trends, qualitative dip and susceptibility contrast estimates for both tabular bodies and fault models, (Figure 7.7) shows two northeasterly trending belts of folded metasediments having a considerable magnetic response on either side of the Moonta Porphyry, which has a similar trend orientation to the metasediments.

The zones of intense magnetic anomalies are interpreted as magnetite quartzites or Doora Schists within three synforms, labelled, A, B, & C, (Figure 7.7), in the southern portion of the area, based on comparable structures in the Kadina Grid, (Chapter 8). The axial planes of these structures trend between 050° and 070°. The structures A and B are terminated faults trending at 110° and 130°.

The northern extension of structure A is outlined by a series of sub-parallel magnetic features which are fairly symmetrical and, combined with the dip estimates, indicate a synform with a possible closure to the north. These local magnetic features correlate with iron-rich and/or mafic bands within mica schists and gneisses, confirmed by auger data (Lynch, pers. comm.). Amphibolites and/or hornblende schists may be present, as elsewhere these metasediments have a similar magnetic response to those observed in A.

In the east, the main magnetite unit defining the structure C is partially surrounded by two sub-parallel magnetic trends having susceptibilities and magnetic characteristics similar to the magnetite-rich metasediments, (Doora Schists). These trends are northeast and southeast of area C. The distribution of these anomalies suggests a synform which closes to the southwest. The discontinuous zone types 10 and 8 arranged and located just outside the major magnetite-rich metasedimentary unit reflect this, closure and have susceptibility contrasts of 1.5 to 2.5 (x 10^{-3} cgs units). These bands may coincide with either schists and/or amphibolites, or calc-silicates stratigraphically above the magnetite-rich metasediments, cf. Doora Schist within the Kadina Fold Belt.

7.3.1. FAULTS AND FRACTURE PATTERN

The major fracture system oriented 110° to 130°, was resolved from the abrupt dislocations and terminations of the magnetic anomalies, and disrupt the regional trend. These fractures locally have dextral movements of 1 km, shown by the displacement of the magnetic units north of Moonta.

The other fracture system oriented 20° to 30° developed in the porphyry area and locally, correlates directly with the Moonta Lodes. By comparison with normalised fault model curves, they dip 40° to 80°NE, which correlates with the overall dip envelope of the lodes in the old mining cross-sections. Due to the traverse and station spacing interval, not all known lodes were resolved. Some significant P.F.E. anomalies (Figure 7.8) correlate with linear magnetic features having a similar geophysical signature as the mineralised lodes, and require further evaluation.

7.4. THE MOONTA PORPHYRY

The northwestern and southeastern edges of the interpreted porphyry are defined by linear magnetic anomalies, which correlate with the mica schist-porphyry contact, based on drill hole data. The western edge appears to be parallel and concordant with the magnetic lineation of the country rocks (Figure 7.7). The eastern boundary is defined by a linear magnetic trend, which represents a fault and/or a possible metamorphic effect, (based on drillhole data), has susceptibility contrasts between 0.75 and 4.3 (x 10^{-3} cgs units), and dips 40° to 50°SE. It is discordant with the magnetic grain and structures within the country rocks to the southeast. Its discordant nature is also reflected by the changes in susceptibility contrast along strike, as different lithological units are terminated. The southwestern and northeastern ends are discordant and fracture controlled, (Figure 7.7).

The general area of the porphyry is represented by zone types 1 and 2. The zone types 2 may coincide with:-

(i) compositional changes within the porphyry, produced by banded or foliated rhyolite which contains slightly more mafic minerals, as banded rhyolite has been observed in the dumps and most shafts.

(ii) bands of metasediments (zone type 2) which, with linear zones 9 and 10, suggest a possible fold closure. Portions of zones 9 and 10 may be interpreted as a fault. Another linear fault trending at 030^{o} extending outside the porphyry, exists within the porphyry as a shear zone, confirmed from auger data, (Lynch, pers. comm.).

7.4.1. THE FORM OF THE PORPHYRY

The surface extent of the porphyry, resolved from the magnetic data, (Figure 7.7) is comparable with the apparent resistivity 'weather basement' contours (Figure 7.9) derived from V.E.S. This data represents the resistivity values of the in situ clays, different degrees of weathering within the porphyry and country rocks, and does not reflect the contours of the high resistive basement, as previously discussed.

This resistivity low probably correlates with weathered in situ clay (2.70 ohm m) which gradually passes into the solid feldspar porphyry as resolved from the I.G.E.S. test pit at Moonta. This revealed clay having resistivities of 3.0 ohm m with saline conductors within clays having values of 0.44 ohm m (based on standing water samples). A sheet of highly conductive clay covers the entire area to 3 m (Edge and Laby, 1931). The S.A.D.M. DDH E1-E4 sited on possible electromagnetic conductors, outlined by Thyer (1943), confirmed Edge and Laby's results.

W.M.C. frequency domain, I.P. dipole-dipole traverses, oriented NW-SE (at right angles to the lodes), 2000 feet apart, were too wide to resolve the individual lodes.

The original pseudo-sections based on the apparent resistivity and P.F.E. anomalies were interpreted to map structures within, and to define the porphyry boundary. The P.F.E. anomalies and the apparent resistivity contours

(Figure 7.8), based on dipole spacing values for n = 3 and 4, shows areas of notable saline surface clay and saline layers.

The apparent resistivity contours show a general NE-SW trend, with two distinct saline belts, west of Moonta township and east of the main mines area, probably representing Recent concealed channels. The porphyry is not clearly resolved, except that it is surrounded by a discontinuous series of resistive areas which tend to surround the main ore zone. The main lodes are represented by local narrow zones of apparently conductive and resistive material, and is contained within the general conductive zone of the porphyry.

The P.F.E. anomalies classified with respect to the magnetic responses and apparent resistivity data, (Figure 7.8), indicate areas for reinvestigation, especially I.P. types A and B, within the porphyry.

The porphyry boundary agrees with these results, but very little data is available on the vertical extent of this body. The magnetic source depths are within 150 m of the surface. The porphyry is known from mining operations to be over 585 m thick, e.g. Taylor's West Lode (Jack, 1917).

7.4.2. GEOPHYSICAL MODELS OF THE PORPHYRY

Magnetic interpretation suggests two porphyry models:

Model I

The interpreted NW-SE cross section passing through Moonta, (Figure 7.10), shows the Moonta Porphyry is confined to an antiform between two synforms. The distribution of zone type 2 correlates with either a banded rhyolite, or, metasediments, and may indicate a closure within the porphyry.

Model II

Many geologists interpreted the Moonta Porphyry as equivalent in age to the Gawler Range Volcanics, confined to a basin resting unconformably on basement. The following interpretation questions the speculative nature of this conceptual model. The overall interpreted dip estimates of the surrounding country rocks suggest a questionable regional west and east gradients towards the porphyry mass, (Figure 7.11) a possible basin model for the porphyry. The discordant dips estimated for the linear zones types 9, 10 and 11 at the eastern edge, could correlate with later granitic intrusions, known to exist within the porphyry.

7.5. THE MOONTA GRAVITY TRAVERSE

This traverse (Figure 7.10) combined with core density data, enabled the depth, extent, and form of the porphyry mass to be estimated, assuming that the Moonta Porphyry is a sheet of volcanics, resting unconformably on the metasedimentary basement. The petrophysical data (Chapter 5) provides the necessary parameters for this computer modelling.

The NW-SE road from Moonta Bay, through Moonta township over the Halls, Youngs, Bennetts and Elders Lodes (Figure 7.2) was selected for a gravity profile to model the porphyry mass. The Bouguer gravity and vertical magnetic profiles are shown in Figure 7.10. The magnetic response is a composite profile, compiled from lines 80NE, 100NE and 120NE (Figure 7.5) onto the same traverse lines as the gravity data. The gravity stations are recorded at an irregular spacing, between 250 to 400 m apart, and the corresponding elevations are barometric, (elevation error ± 1 foot). The regional gravity profile is assumed to be linear, having the equation $Y = 1.2307 \times 10^{-3} X - 10.8$. The residual profile composed of 15 data points, was digitised at an interval of 250 m for model studies as the computer programme required equidistant data points.

Residual gravity and magnetic profiles show a displacement between the gravity and magnetic maxima on the southern edge of the porphyry, since the magnetic sources have a general northwesterly dip component, (based on the previous data and other interpretations in the Province). This indicates the main magnetic source is concentrated down dip from the gravity response.

7.5.1. THE INTERPRETED SECTION BASED ON MAGNETIC DATA

The interpreted geological cross section shows two possible models. Model I shows tabular bodies which dip towards the centre of the porphyry. Model II shows two relatively tight synforms on either side of the porphyry.

The major difference is the interpretation of the boundary or contact zone of the porphyry. The southeastern boundary is defined by a tabular body dipping at 50°SE, which correlates with either a fault (Model I), a dipping contact zone, or, a conformable folded boundary (Model II), whereas the northwestern boundary dips at 65°NW and represents either a tectonic contact (Model I), or, the limb of a synform, (Model II).

Inside the porphyry, two types of linear features were resolved from the magnetic data. The first are distinct major faults trending at 030° and dipping 70° to 80°NW. The second type interpreted as either thin sheets or possible fractures, dipping 40° to 50°NW, are nearly coincident with, and subparallel to the mineralised lodes, (Figure 7.7). They are interpreted to be the magnetic anomaly coincident with the alteration zone associated with the lodes, e.g. Youngs, Bennetts and Elders Lodes. The thin sheet near the northwestern edge of the porphyry is subparallel to Halls Lode. Disseminated magnetite and pyrrhotite in the lodes are probably the source material for these low amplitude linear magnetic features. No deep magnetic sources beneath the Moonta Porphyry were resolved.

7.5.2. THE ANTICLINAL MODEL FOR THE MOONTA PORPHYRY

An anticlinal model (Model I) is proposed from the interpretation of the vertical magnetic data. The possible fold structure within the porphyry, (Figure 7.7) is based on an apparent increase in the ferromagnetic content of zone type 2, which may reflect either a lithological change and/or a magnetic unit within the porphyry. The repetition of this unit is assumed to reflect a fold. The magnetic anomalies character is distinctly different from that observed over the mineral lodes, which are linear discordant features cross cutting the eastern limb of this fold, defined by another zone type 2.

The assumptions for this model are as follows:

(i) The axial planes of the synforms on either side of the porphyry dip 70°W, subparallel to the lodes, along the axial plane cleavage of the macrofold. These folds are composite structures (macro dragfolds) in the limbs of an anticlinorium, which has a porphyry core.

(ii) The background density of the gneisses is 2.65 gm/cm^3 and the depth of the computer model is restricted to 2 km for the residual profile.

The variations of density with depth shown in Moonta DDH's E1 to E3, (Chapter 5) and the drill holes associated with lodes at Moonta East DDH 2 and 4 and Yelta DDH 2 to 8 inclusive, show that with depth, three cores increased, four decreased and four alternated (both high and low). The two deepest holes Moonta DDH E2 and Yelta DDH 4 (total depths of 222.5 and 222.8 m respectively), show a decrease and alternating density with depth.

Two models were computed, the first having a higher density upper slab, which is 500 m thick and has a contrast of 0.01gm/cm^3, followed by a lower density folded layer, represented by a zero contrast 250 to 500 m thick, (Figure 7.12, model A) with the high density core having a contrast of 0.02gm/cm^3 to 2 km. The difference between the observed curve shows departures around the 4 km mark, and over the maxima on each side of the porphyry.

The second model B has a surface slab having a zero contrast. The intermediate zone originally having a zero contrast in model A, has a contrast of 0.01gm/cm^3 with the deeper core remaining the same. This model gave a better curve match of the maxima and a slightly lower response over the porphyry, when compared with model A. However, a slight change in the slope of the upper layer, or, a gradual change in density of the same may produce a better fit. In these models, the effect of the lode horizons have been ignored as being too small in width compared to the original data.

7.5.3. THE MOONTA PORPHYRY-BASIN MODEL

The basin model assumes the bedrock metasediments have a uniform density, and that the region occupied by the Moonta Porphyry can be represented as a thick horizontal sheet confined between the two local gravity maxima. This model assumes that the Moonta Porphyry has a similar isoradiomeric age to the

Gawler Range Volcanics, and therefore may be represented by a thick sequence of porphyry infilling a depression on the older metasedimentary sequence.

Figure 7-13, shows thickness variations for different density contrasts, which may be equal to or less than 0.05 for the thickness of 670 metres. This case is comparable with the maximum known thickness of the porphyry. The thicknesses for density contrasts of 0.04 and 0.03gm/cm^3 are 835 and 1110 metres respectively.

7.5.3.1. Shape of the Porphyry based on the gravity profile

The shape and dimensions of a volcanic pile of dacites and rhyodacites, were based on the first and second derivative method (Bott, 1962). Profiles of these derivatives $\Delta g'$ and $\Delta g''$ and two dimensional cross sectional models are shown in Figure 7.14. This method requires additional detailed data points to be strictly valid, and these results should be considered as a first approximation. The interpreted boundaries of this basin have dips, 80° to 90° in the west and vertical in the east. This suggests a vertical prismatic model for the porphyry, with a depth extent greater than 600 m. If this model of a thick volcanic pile in a basin is correct, it would only be valid for either a graben or a cauldron subsidence.

7.5.4. THE SYNCLINAL - 'GRABEN' MODEL FOR THE MOONTA PORPHYRY

The computer model profile based on the cross section outlined from the derivative methods, represents a deep keeled synclinal model for steeply dipping blocks of magnetic quartz gneisses and metasediments dipping inwards to the porphyry. This model for the contrasts outlined in Table 7.1, gave an unsatisfactory curve match, with too high amplitudes over the magnetite-rich units and metasediments (density 2.75 gm/cm^3). The corresponding profiles (Figure 7.15) with reduced density contrasts and polygons gave a better curve match.

Two major discrepancies between the computed and observed profiles, were firstly, the location of the maxima and secondly, the distinct negative response over the porphyry produced by the negative density contrast.

However, when the polygon representing the porphyry had a zero contrast, the resulting curve match was considerably better, (Figure 7.16).

TABLE 7.1

DENSITY AND LITHOLOGICAL DATA USED FOR THE GRAVITY PROFILE ACROSS THE MOONTA PORPHYRY

Lithology	Density	Contrast
Gneisses (Basement)	2.69	zero
Mica schist	2.67	-0.02
Hornblende schist	2.75	0.06
Amphibolite (Basics)	2.74	0.05
Magnetite-rich gneisses, amphibolites and metasediments	2.79	0.
Porphyry	2.66	-0.03, put to zero (profile 3)

As major discrepancies were still present, (Figure 7.15) a revised model, based on the magnetic interpretation was developed with additional polygons of shallow depth extent. The porphyry was initially assumed to have a zero contrast. The profile produced (Figure 7.16a) shows a better correlation, comparable amplitudes and maxima positions, but the response over the porphyry shows a mass deficiency. This implies that the initial assumption for a negative and zero contrast of the porphyry is incorrect, and suggests that the porphyry has a higher density than the basement gneiss.

The petrophysical data shows the porphyritic material is not of uniform density, but may increase with depth. The porphyry was then assumed to be composed of two thick slabs having density contrasts of 0.01 and 0.02 gm/cm^3 respectively. The resulting gravity profile and model, (Figure 7.16b) shows good agreement with the original profile. The model represents a general synclinal structure with a graben filled with porphyritic material, 2 km thick, between two synclines.

The major problem with this model, a down fault block or graben, is the outward dipping sides of the porphyry. The vertical prism of lower density material may represent either a region of leached porphyry associated with a fault, or, a lower density granitic intrusion along the western boundary. The better geological models are either a plutonic granitic intrusion into a volcanic pile of rhyolites and rhyodacites, or, a cauldron subsidence, a volcanogenic model.

7.5.5 CAULDRON SUBSIDENCE PORPHYRY MODEL

Ash flow tuffs, rhyolite tuff breccias, intrusive micro-granites and later granites within the main porphyry mass; and air fall tuffs interbedded with schists to the east (Lemar, 1975), suggest a possible cauldron subsidence model for the porphyry, (C. Branch, pers. comm.).

This model is based on the development of porphyry copper and stratiform volcanogenic ore bodies. The size of the subsidence is assumed to be 3.2 - 4.8 km wide, with a vertical extent of approximately 1 km. Beneath the main subsidence areas is an overall cylindrical or prismatic body extending to a depth of 4 km. The density distribution of the prism is divided into two parts. The lower part is assumed to be andesite (2.71 gm/cm^3) and the upper part has a density contrast intermediate to those of the porphyry and andesite.

The model's computed and the observed residual profiles are shown in Figure 7.17. The changes in the polygons on the eastern side of the model's cross section is derived from the anticlinal core model for the porphyry, (Section 7.6.2). Minor adjustments in blocks A and B show departures from the observed profile.

The model of the country rocks shows a wedge of hornblende schist (2.70 gm/cm^3), represented by Block A and a closed synform of schists represented by Block B, which possibly contains amphibolites surrounding a core of magnetite-rich metasediments. The interpreted susceptibility contrasts of these anomalies are comparable with those reported for magnetite-rich metasediments.

The vertical sheet 250 m thick of density 2.61 gm/cm^3 represents a leached zone associated with a fault on the western side of the porphyry. This was introduced into the model to explain the shallow negative gravity anomaly in the observed residual profile.

7.6. SUMMARY OF MODELS

All models interpreted from the gravity traverse are only first approximations for the structure of the Moonta Porphyry. The widely spaced station interval of the gravity traverse limits the validity of the models, and requires verification. A regular grid, with a 250 m spacing, or better is required to cover this area for a 3D model study of the porphyry.

The basin and graben models, representing horizontal sheets of porphyry resting unconformably on basement, confined to a buried valley or fault-bound basin (graben) is an unsatisfactory solution.

The synclinal model for the metasediments, intruded by an outward dipping mass of porphyry, showing an increase of density with depth, gives a satisfactory model. Also satisfactory is the anticlinal model, which hinges on the hypothesis that zone type 2 forms a folded magnetic unit, but may equally represent a multiple or later intrusion within the porphyry. Petrophysical data and drill hole correlations suggest the porphyry is a layered complex.

The outward dipping contacts defined by the magnetic interpretation, the layered and possible compositional changes of these rhyodacite and dacites may be comparable with a rhyolite dome, (concept discussed later in thesis). The cauldron subsidence model, intruded into a folded metasedimentary sequence, with an andesite core or plug at depth, produces a satisfactory geophysical model, and agrees with the magnetic interpretation and geological data. Further data is required to verify whether the anticlinal, synclinal plus intrusion, rhyolite dome and cauldron subsidence models are correct for this volcanogenic-intrusive environment.

7.7. GEOPHYSICAL RESPONSE OF THE MINERALISATION

The main mineralised area, except for the Poona Lode is in a relative low magnetic area, (Figure 7.7). The eastern belt of lodes correlates with linear low amplitude magnetic anomalies (second order trends), which dip 40° and 55°NW, and has susceptibility contrast, between 0.64 and 1.29 (x 10^{-3} cgs units) respectively. The source of these linear features are magnetite-hematite associated with pyrite, sulphides and biotite zones within the porphyry. Other non-linear features, (zone type 2), have similar interpreted dips, in the western mineralised belt. A series of subparallel fractures interpreted as normal faults have a similar dip to the lodes, but have a higher susceptibility contrast, between 2.01 and 4.73 (x 10^{-3} cgs units). These presumably represent zones of magnetite without sulphide infilling these fractures, but some are coincident with some lodes, namely the Paramatta, Mid Moonta and Alice Lodes, and Bennetts and Elders lode system extended to the south. The higher grade mineralisation appears to be concentrated and mined in the areas between the secondary set of cross fractures.

The gravity data shows a low amplitude negative anomaly over the porphyry, and a distinct low (a one point anomaly) along the western side, coincident with the Alice-Halls Lode. This is interpreted as a possible leached zone within the porphyry. The resistivity data shows that the porphyry, as outlined by the magnetic data, is within the low resistivity zone, indicative of either deep weathering, or, a high degree of alteration within the porphyry, potash metasomatism and deformation.

I.P. pseudo-sections over the Bennetts and Elders Lodes show a low order P.F.E. associated with a low resistivity zone, and some degree of conductive coupling, relating to conductive overburden. Some significant P.F.E. over the porphyry, (Figure 7.8), and other P.F.E. trends worthy of further investigations are outlined.