



STRUCTURE AND SURFACE IN THE
GAWLER RANGES, SOUTH AUSTRALIA.

by

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awarded 5.6.90

A thesis submitted for the degree of
Doctor of Philosophy in the
Department of Geography and the
Department of Geology and Geophysics
University of Adelaide
South Australia.
February, 1990.

Frontispiece Landsat imagery of a part of the central Gawler Ranges showing the Moonaree Upland in the north (top), the Yardea Upland in the south, Lake Acraman in the central west and portions of Lake Gairdner to the east. Approximate scale 1:500,000

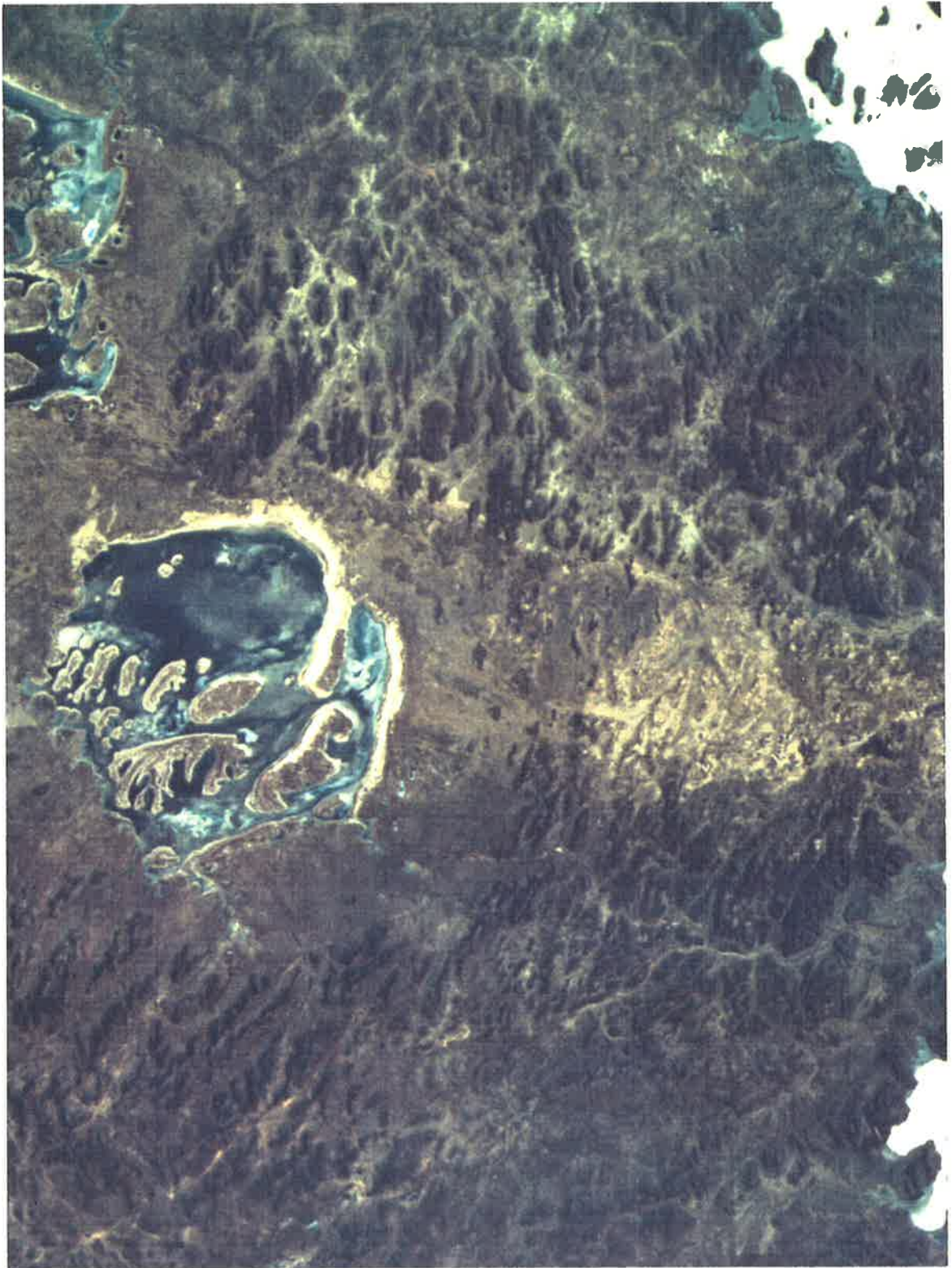


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ABSTRACT

The Gawler Ranges is an upland of some 25,000km² located in the arid-semiarid interior of South Australia. The upland is essentially coincident with the outcrop of Gawler Range Volcanics, a layered pile of silicic (or acid) rocks deposited during the Middle Proterozoic, about 1592 million years ago. The Volcanics occur beyond the confines of the Ranges, e.g. in the Tarcoola, Ceduna and Streaky Bay areas, and at depth east of the upland. Exposures of Hiltaba Granite (age circa 1585 million years) intrusive into the Volcanics occupy several areas in the western Gawler Ranges. But overall the Gawler Ranges is synonymous with a major exposure of Middle Proterozoic silicic volcanic rocks.

In the south the Ranges rise to heights of more than 460 m above sealevel and stand some 180 m above the adjacent plains and valleys. To the north both absolute altitude and relief diminish, but even there the hills stand abruptly from the plains and form distinct and distinctive landforms. Throughout the Gawler Ranges domes or bornhardts dominate the landscape. Many are bevelled, for overall a summit surface of etch type is prominent, and second only to the domical form of the hills in geomorphological importance. The domes eroded in silicic volcanics share many characteristics with their counterparts in other lithological environments. For instance, both in plan and in profile, fracture systems control the morphology in gross and in detail. The plan shape and size of the hills are determined by regional orthogonal fracture systems (Frontispiece), and local orthogonal fractures are responsible for the location and orientation of valleys within the domical masses. Sheet structure and banks of columns, both defined by fractures, determine the profiles of the hills.

Bornhardts are well and widely developed in other lithological environments, and especially in granite and granitic gneiss. The Gawler Range bornhardts are, however, unusual in the context in which they occur. Most indurated deposits of silicic volcanics, like those of North Island, New Zealand, and the west and southwest of the United States, give rise to plains and plateaux. The ash and other pyroclastic materials blanketed the pre-existing landscape as would a sheet of water. Only in the Ozarks of Missouri, in the central United States, are there landform assemblages comparable to those of the Gawler Ranges; and these deposits, like those of the South Australian locality, are Proterozoic, in contrast to the Cainozoic age of the other occurrences cited.

How and why, then, have bornhardts developed in the Gawler Ranges, and when did they evolve?

Most of the several hypotheses advanced in explanation of bornhardts from other parts of the world are readily discounted in face of the field evidence from the Gawler Ranges. Sound arguments can be adduced to suggest that the granitic hills, or nubbins of the western Ranges are intrinsically exposed stocks or protruberances developed at the margins of the plutons intruded into the already cooled and consolidated Gawler Range Volcanics. In this they are similar to granitic and gneissic forms described from southern Africa by such workers as Holmes and du Toit. The bornhardts developed in volcanic rock in the Gawler Ranges, however, are, on balance, best explained as two-stage developments or etch forms as outlined by such workers as Falconer, Linton and Budel. Such etch development involved first, differential fracture-controlled subsurface weathering of the rock mass, mainly by shallow groundwaters. Second, the weathered mantle or regolith was stripped to expose the irregular weathering front as bedrock hills that were domical in form due in part to the development of sheet structure, partly to the rounding brought about by preferential weathering of the corners and edges of fracture-defined blocks. Evidence supporting this interpretation includes the fact that each bornhardt is confined within a fracture-defined block; the presence of remnants of a summit surface which implies a period of standstill during which deep (differential) weathering could have taken place; the preservation of remnants of an old regolith, with corestones on hillsides in the central Ranges.

Manifestly the various fracture systems and the summit surface are crucial elements in the development of the Gawler Range bornhardt assemblage. Some of the columnar joints are due to cooling and are presumably penecontemporaneous with the deposition of the pyroclastics in which they are formed. The orthogonal systems at various scales, including some of the columnar joints, are interpreted as conjugate shears developed in response to dislocation along megalineaments such as the Torrens Hinge Zone. Certainly the geometry of the various systems, as well as evidence of dislocation, is suggestive of such an origin. The orthogonal fractures are demonstrably more than 1424 and less than 1590 million years old. The sheet structure is probably of similar antiquity, and probably predates the Jurassic (200 million years or so old).

The weathering responsible for shaping the bornhardts in the subsurface took place beneath the surface of low relief ancestral to the present summit surface. The latter is of etch type implying

that the regolith that originally covered the bedrock plain has been eroded. The planation of the surface and its stripping to produce the present etch plain can be dated by reference to the sediments of the Eromanga Basin to the north and northeast of the Gawler Ranges. The surface was reduced to low relief and deeply weathered during the Jurassic. The regolith was stripped essentially during the Early Cretaceous, so that the bornhardts date from that period. Exposure of the bornhardts and erosion of the present plains of the interior of the Ranges was completed by, or during, the Early Tertiary.

The contrast in morphology as between the Gawler Ranges and the Ozarks, on the one hand, and other regions of silicic volcanics on the other, is attributed first to the compaction and brittleness of the older rocks; second to the consequent fracture patterns, in particular regional orthogonal and sheet systems; and third to the time available for deep differential weathering of the massifs.

Thus the landscape of the Gawler Ranges is an ancient one. The bornhardts demonstrably have changed but little over the past 65 million years or so, and like many other Australian and Gondwana landscapes, they pose problems for all the conventional models of landscape evolution. They also illustrate the supreme significance of fractures in landform development. It is an overriding factor, and this is illustrated by reference to bornhardts in granite, gneiss and quartzite in the regions adjacent to the Gawler Ranges.

DECLARATION

I hereby declare that none of the material contained in this thesis has been accepted for the award of any other degree or diploma in any institution and that, to the best of my knowledge and belief, the thesis contains no material previously published or written by another person, except where due reference has been made in the text of the thesis. I consent to this thesis being made available for copying and loan if it is accepted for the award of the degree.

ACKNOWLEDGEMENTS

The research on which this thesis is based was carried out under the auspices of the Commonwealth Postgraduates Research Awards Scheme. Without the financial support of this fund, it would not have been possible for me to carry out and write up this investigation of some aspects of the geomorphology of the Gawler Ranges. I am particularly grateful to Mr Tim Gent of the Adelaide office of the Department of Employment, Education and Training (which administered the scheme), who was considerate and supportive at all times.

This investigation is substantially field oriented and field work is expensive. Some support was obtained from University Research Grants administered by the Department of Geography, University of Adelaide. A grant from the Endowment and Scientific Research Fund of the Royal Society of South Australia also helped in this regard, and I wish to express my thanks to the Society. An ad hoc grant from the Department of Geology and Geophysics, University of Adelaide (1988) also assisted, as much for its implied moral support as for the actual amount. It is essential, as well as desirable to have assistance in the field, and I should like to thank Jacqueline Campbell, Robyn Campbell, Anne Stott and Lance Beck for their companionship and help at various times.

Many people have assisted in the preparation of materials for examination and in their analysis, and also in the physical production of the thesis. In this respect I am grateful to Wayne Mussared, Geoff Trevelyan, John Stanley, Christine Badcock, Sascha Illhardt, Phil McDuie, Sally Phillips, Hugh Rosser, Dr A. R. Milnes, Sherry Proferes, Max Foale, Richard Barrett, Sophie Tsemitsidis, June Wheeler, Simon Turner and John Willoughby.

The thesis has also benefited greatly from informal discussions on various topics. In particular, I thank Mrs J. A. Bourne; Professor D. M. Boyd, Dr J. Foden, Dr J. Francis, Dr N. M. Lemon, Miss E. M. McBriar, Dr R. L. Oliver, Ms K. Stewart and Dr G. E. Williams (Department of Geology and Geophysics); Mr R. Hinrichs (Hollingsworth Consultants, Spring Hill, Queensland); Mr G. Harvey (South Australia, Highways Department); Dr A. J. Parker, Mr A. H. Blissett, Ms S. J. Daly, Mr A. Pain, Mr A. R. Gerdes, Ms P. MacDonald (South Australia, Department of Mines and Energy); Dr E. S. T. O'Driscoll (Western Mining Corporation); and Dr H. Wopfner (University of Cologne).

In addition, various overseas visitors were taken through the study area- Dr R. Hay (University of Illinois, Champaign-Urbana), Dr J. E. Mueller (New Mexico State University, Las Cruces), Dr P. Patton

(Wesleyan University, Middleton, Connecticut), Dr J. D. Centeno (Universidad Complutense, Madrid)- and I gained much from their broader experience.

Finally, a particular debt of gratitude is due to my thesis committee, Dr V. A. Gostin, Dr P. R. James and Dr C. R. Twidale, and especially the last-named who was my principal supervisor throughout. I appreciate his encouragement, advice, assistance and patience.



CHAPTER 1 INTRODUCTION

1.1 INSELBERGS AND BEVELLED DOMES

On 19 September 1839, the explorer Edward John Eyre was travelling eastward on northern Eyre Peninsula in the arid to semiarid interior of South Australia (Fig. 1.1A). He observed '...many peaks of a range with a high broken outline...' which he named '...the Gawler Range, after His Excellency Colonel Gawler, the Governor of South Australia' (Eyre 1845, I, p. 199). The upland, now known as the Gawler Ranges, is essentially coincident with the outcrop of a mass of ancient silicic volcanic rocks (Fig. 1.1B), the landforms developed on which are the subject of the investigation discussed in this thesis. A few days later Eyre described the range as '...a vast mountain mass rising abruptly out of the low scrubby country around...' (Eyre 1845, I, p. 200), and as comprising '...a succession of detached ridges, high and rocky, and entirely of a porphoritic granite lying in huge bare masses upon the surface. The hills were...very barren, with their front slopes exceedingly steep, and covered by small loose stones...' (Eyre 1845, I, p. 201).

Eyre went on to describe the isolated hills of the southern piedmont of the Ranges as '...resembling so many islands in the level waste around them' (Eyre 1845, I, p. 203). As far as is known, Eyre was the first to liken such hills to rocky islands standing abruptly from the surface of the sea. The term 'island mount' was used by several other writers in English (e.g. Giles 1889; Holmes 1918), but it is the German equivalent, inselberg that has become established in the international technical literature (see e.g. Passarge 1895, 1904; Bornhardt 1900).

Inselbergs of domical shape are known as bornhardts after the German explorer of that name (Willis 1934). But not all inselbergs are bornhardts. The bornhardt is the basic form from which are developed both nubbins (known in the United States as knolls), which are block- and boulder-strewn, and castle koppies, which are angular (Fig. 1.2; Twidale 1981a, 1982a, p. 124 & 158). On the other hand, not all bornhardts are inselbergs. The isolated domes of the southern piedmont of the Gawler Ranges, such uplands as Waulkinna Hill and Mt Allalone, are inselbergs for they stand in isolation (Pl. 1.1). The same is true of many other residuals at the fringes of the uplands and in lowlands within the Ranges (Pl. 1.2). But most of the bornhardts of the Gawler Ranges stand in close juxtaposition and in ordered rows (Pl. 1.3A, 1.3B). Nevertheless, whether isolated or constituents of larger complexes,

domical hills or bornhardts, many of them bevelled (Pl. 1.4), dominate the landscape of the Gawler Ranges.

1.2 GEOLOGICAL BASE

Eyre was not a geologist and his identification of the bedrock of the Ranges as a 'porphoritic' (porphyritic) granite was in error. Possibly he examined Waulkinna Hill (Fig. 1.1B), which is granitic, and extrapolated to the entire upland. More likely, to him and to many laymen of the time, all igneous rocks were 'granitic'. Although granitic rocks are extensively exposed in the western Gawler Ranges, most of the upland is underlain by acid (or silicic) volcanic rocks. Known as the Gawler Range Volcanics, they consist of a subhorizontally layered sequence of ash flow tuffs or ignimbrites, with minor lava flows (Blissett 1975, 1986; Blissett & Radke 1980 - see Fig.1.3). The tuffs are thought to have been welded, though no welding features such as have been described from other areas (see e.g. Marshall 1935; Gilbert 1938; Ross & Smith 1961) have been observed in the study area.

The Gawler Range Volcanics are differentiated on the basis of silica content (Blissett 1985); basalt < 53, andesite 53-63, dacite 63-69, rhyodacite 69-73 and rhyolite > 73 % by weight of silica (Table 1.1). Basalt and andesite are minor constituents and rocks ranging in composition from dacite through rhyodacite to rhyolite form extensive outcrops (see Martin 1989). The acid rocks, as Eyre noted, are markedly porphyritic, and tend to grade into one another though they can usually be distinguished in hand specimen. The rhyolites contain phenocrysts of quartz and pink potash feldspar in a finely granular, yellowish brown matrix. The dacites consist essentially of cream-coloured plagioclase phenocrysts (which have been partly altered to ferromagnesian minerals, mainly chlorite and epidote) set in a purplish-brown matrix. The rhyodacites are intermediate in composition. Quartz phenocrysts are rare or absent, but both potash feldspar and plagioclase phenocrysts are present as are minor amounts of ferromagnesian minerals all set in a reddish-brown matrix. The groundmass consists of felsic minerals, principally quartz and feldspar (Blissett 1975, 1985, 1986).

The Gawler Range Volcanics are indurated, compact and impermeable. By both Los Angeles Abrasion tests (Table 1.2) and Schmidt Hammer tests (Table 1.3) the fresh rock is hard to very hard. It is, with the exception of a metaquartzite which underlies the Darke Range to the south, consistently harder than other rocks in adjacent areas (e.g. Hiltaba Granite, sandstone, gneiss), and also harder than many rocks considered suitable for use as road aggregate (e.g. granite, dolerite, basalt, gneiss).

Table 1.1 Chemical composition of selected samples of Gawler Range Volcanics (from South Australia Department of Mines and Energy -SADME- Rock Sample Analyses. Rock names from Blissett 1985; Blissett *et al.* 1988).

Sample number	Rock name	Classification	SADME
1	Pac1	basalt	5935/410
2	Pac2	andesite	5935/118
3	Yardea Dacite	dacite	6033/1
4	Eucarro Dacite	rhyodacite	5932/14
5	Paney Rhyolite	rhyolite	6032/23

	1	2	3	4	5
SiO ₂	52.25	54.31	65.92	71.00	73.76
TiO ₂	0.76	2.26	0.79	0.44	0.31
Al ₂ O ₃	13.96	14.22	13.92	12.70	12.53
Fe ₂ O ₃	2.82	3.83	1.50	3.90	1.11
FeO	6.20	6.95	3.90	0.46	1.85
MnO	0.15	0.18	0.12	0.08	0.06
MgO	8.89	3.11	1.03	0.26	0.15
CaO	7.44	6.36	2.55	1.50	0.33
Na ₂ O	2.77	3.04	3.36	3.40	2.61
K ₂ O	1.45	2.71	4.47	6.23	5.76
P ₂ O ₅	0.21	1.15	0.24	0.30	0.04
H ₂ O ⁺	1.32	1.34	1.52	0.92	1.07
H ₂ O	0.14	0.06	0.14	-	0.13
Ignition loss	-	-	-	1.15	-
Total%	98.36	99.52	99.46	99.65	99.71

Table 1.2

LOS ANGELES LOSS

SAMPLE NUMBER	LOCATION	ROCK TYPE	L. A. LOSS %
GAWLER RANGE VOLCANICS			
1	Mt Cooper	rhyodacite	16-21
2	Paney	Eucarro Dacite	16-22
3	Paney	Eucarro Dacite	15-16
4	Kingoonya	rhyolite	18
5	Mt Sturt	dacite	31
OTHER ROCK TYPES			
6	Coober Pedy	granite	29
7	Musgrave Ranges	dolerite	13-21
8	Tailem Bend	calcrete	24-30
9	Mt Schank	basalt	18-29
10	Yaranyacka	granitic & mafic gneiss	17-24
11	Koppio	granitic & amphibolitic gneiss	21-28

TABLE 1.3

SCHMIDT HAMMER TESTS

NO.	LOCATION	ROCK TYPE		RANGE	MODE
GAWLER RANGE VOLCANICS					
Field assessment					
1	Mt Cooper	rhyolite	from quarry	56-66	58.1
2	"	"	weathered	14-29	22.5
3	"	"	smooth surface	52-70	62.5
4	"	"	"	55-64	60.2
5	Peterby	Eucarro Dacite	surface	60-67	64.5
6	"	"	"	50-66	57.6
7	"	"	smooth surface	42-62	54.2
8	"	"	"	64-71	67.3
9	Yandinga	"	surface	56-63	58.4
10	"	"	"	46-62	56.1
11	"	"	"	55-65	55.4
12	"	"	weathering rind	36-48	43.1
13	"	"	weathered	34-56	47.1
14	"	"	"	37-51	43.2
15	"	"	"	49-59	53.3
16	"	"	blister	32-44	37.0
17	Hiltaba	"	surface	56-64	58.0
18	Yardea	Yardea Dacite	"	21-50	33.1
19	"	"	iron incrustation	50-61	56.9
Samples held in vice					
20	Mt Cooper	rhyolite	from quarry	59-65	62.5
21	Paney	Yardea Dacite	corestone-centre	48-56	52.7
22	"	"	" outer zone	35-50	43.8
23	"	"	corestone-centre	46-62	54.6
24	"	"	" outer zone	28-42	37.4
25	"	"	corestone-centre	33-48	40.8
26	"	"	" outer zone	18-34	26.5

TABLE 1.3 continued

SCHMIDT HAMMER TESTS

NO.	LOCATION	ROCK TYPE		RANGE	MODE
OTHER ROCK TYPES					
Field assessment					
27	Darke Range	Warrow Quartzite	from quarry	60-68	64.4
28	Waddikee	gneiss	"	40-52	45.8
29	"	"	surface	50-60	54.4
30	Tcharkuldu	granite	"	50-61	54.9
31	Hiltaba	"	"	42-62	50.9
32	Yarwondutta	"	quarry	37-53	44.0
33	"	"	surface	30-50	38.0
34	Talia	sandstone	"	31-41	36.1
35	"	grit	"	19-30	24.3
36	"	calcrete	"	22-38	29.1
37	Calca	granite	from quarry	28-56	39.4
38	"	"	surface	22-41	29.7
39	Murphy	"	"	35-60	47.1
40	Haystacks	calcrete	"	34-53	42.1
Samples held in vice					
41	Port Lincoln	augen gneiss	quarry	26-50	36.4
42	Port Elliot	granite	"	31-50	41.2
43	Adelaide	quartzite	"	24-44	35.5
44	Hills	dolomite	"	10-20	14.2
45	Black Hill	norite	"	11-41	29.1

In many areas, the intrinsic hardness of the Gawler Range Volcanics is augmented by a thin ferruginous or siliceous veneer (Table 1.3, Samples 3, 4, 8, 19).

Deposited on a basement of Archaean and Early Proterozoic rocks, the Gawler Range Volcanics are 1592 ± 2 My (million years) old (Fanning *et al.* 1986), i.e. of Middle Proterozoic age (Table 1.4). The main volcanic exposure covers an area of some 25,000 km², but similar rocks crop out over a wider area and have also been intersected in drill cores east of the Ranges (Fig. 1.3), suggesting that originally the extrusive mass occupied an area conservatively estimated to be of the order of 60,000 km². The volcanic sequence was at least 1500 m thick (Blissett 1975), and this estimate, taken together with the possible former extent of the deposits, suggests that the volume of material extruded was of the order of 60-90,000 km³. By comparison, the volume of material ejected during the May 18th, 1980 eruption of Mt St Helens was 1.1 km³ (Sarna-Wojcicki *et al.* 1981).

Soon after the volcanic phase the region was intruded by the Hiltaba Granite Suite. These granites, which are well exposed in the Hiltaba-Kondoolka area, around Kokatha H.S. (Homestead) and at Waulkinna Hill are extensively exposed to the north, west and south of the Ranges. They are about 1585 ± 16 My old (Creaser 1989, cited in Blissett *et al.* 1989). Their younger age relative to the volcanics is confirmed by field relations of the two crystalline suites, for intrusive contacts are clearly exposed at several sites (Pl. 1.5).

1.3 GEOMORPHOLOGICAL REGIONS

Weathering and erosion of the Gawler Range Volcanics have resulted in the development of a landscape dominated by bornhardts. The area has been divided into various geomorphological regions (Fig. 1.5) based on the nature of the land surface (whether erosional or depositional), the rock type, the degree of dissection and the type of deposition (e.g. dunefield or lake plain). The major uplands are shown in Figure 1.6.

1.4 PREVIOUS INVESTIGATIONS

Purely descriptive and frequently incidental accounts of landforms in the Gawler Ranges have been recorded in the reports of such early explorers as Eyre (1845, I), Hack (1857) and Warburton (1858); in investigations of hydrological and mineral resources by such workers as Brown (1908), Dickinson (1942) and Shepherd (1968); in explanatory notes relating to geological maps prepared by

Table 1.4 Summary of geologic events in the Gawler Ranges until cratonization.

Age Ma	Orogenic event	Supracrustal rocks	Intrusive rocks	
Proterozoic	1400	↑ Cratonization ——— ↑ ↓ Pandurra Formation ↓		
	1500		↑ Hiltaba Suite ↓	
	1600	↑ ↓ Wartarkan Event ↓	↑ ↓ Gawler Range Volcanics Corunna Conglomerate ↓	↑ Lincoln Complex ↓
	1700	↑ Kimban Orogeny ↓		
	1800		↑ Hutchison Group ↓	
	1900			
	2000			
	2100		↑ ? ↓	
	2200			
	2300			
Archaean	2400		↑ Sleaford Complex ↓	
	2500	↑ Sleaford Orogeny ↓	and	
	2600		↑ Mulgathing Complex ↓	
2700				

the South Australian Geological Survey (e.g. Blissett 1985); in geological studies of specific areas within the Ranges (e.g. Branch 1975; Turner 1975; Giles 1977); and in purely descriptive accounts, e.g. reports of the Nature Conservation Society (1972) and by Laut *et al.* (1977). The area has also previously been mapped as part of small scale continental or state mapping of landforms, principally on the basis of relief and rock type (see e.g. Löffler & Ruxton 1969; Mabbutt 1973; Twidale *et al.* 1986) and more recently as part of the Regolith Terrain Map of Australia at 1:5,000,000 (Chan *et al.* 1986). However, no part of the Gawler Ranges was subjected to systematic geomorphic study until the mid 'seventies when Smith (1976) prepared an M.A. thesis concerned with a general physiographic account of the Yardea map sheet area (Fig. 1.1A). Despite its general nature, and the incomplete nature of geologic and topographic information available at the time, the thesis constitutes a valuable introduction to the geomorphology of the area.

A paper by Twidale *et al.* (1976) arose partly from the study by Smith and partly from similar work in adjoining areas. It summarized the state of knowledge at the time on the age and origin of the surfaces of erosion in the southern Gawler Ranges and adjoining areas.

1.5 PURPOSE OF STUDY: THE PARADOX AND THE PROBLEM

The weathering and erosion of indurated acid rocks in other areas have given rise to a variety of landforms, but mainly to plains and plateaux. The ignimbrites of the Lake Taupo area, New Zealand, for example, are of rhyolitic composition and less than one million years old. They apparently filled depressions, flowed around some obstacles and buried others. The ignimbrite sheets form plains and plateaux, little modified by later weathering and erosion, although columnar forms are well developed, at least at the sheet margins (Marshall 1935). Similarly the welded layers of the Quaternary Bishop Tuff of eastern central California, U.S.A. maintain their original planate form. Columnar joints are again well developed (Gilbert 1938). In southwestern Utah, U.S.A. the behaviour of Tertiary silicic ash deposits has been likened to that of water filling pre-existing depressions and 'finding its own level' in vast plateaux and plains (Mackin 1960).

Several writers have described the exploitation of vertical fractures in acid volcanic rocks resulting in some instances in spectacular turrets, columns and towers. Those of the Chiricahua National Monument of New Mexico, U.S.A., for example, are well known for their detailed sculpture (Enlows 1955). Similarly, the City of Rocks and Giant of the Mimbres of New Mexico both consist of

groups of pinnacles and boulders, many with flared sidewalls, developed in an Oligocene rhyolitic tuff (Mueller & Twidale 1988). The New Mexico forms are, however, much smaller than those of the Gawler Ranges.

Ross and Smith (1961, p. 30) reported '...rounded knobs typical of exfoliating granite...' developed on a Cainozoic silicic welded tuff in southern Nevada, U.S.A.. They gave no indication of the scale of the 'knobs' or of that of the 'exfoliation', so that it is difficult to envisage the landscape to which they refer.

Where acid volcanics are interbedded and folded they tend to be associated with ridge and valley landscapes, depending on the relative resistance of the volcanic and adjacent formations, and on variations in composition and structure within the extrusive sequence. Thus in the Newcastle Range of northern Queensland, developed in Permian acid volcanics (felsite), columnar joints are prominent in river bluffs and regional scale vertical joints give rise to a rectangular drainage pattern, but the regional landscape is one of ranges and valleys that reflect the relative resistance of the volcanic layers (Twidale 1966; Branch 1966).

Thus, though the erosional landscapes developed on indurated acid volcanics are varied, those of flat-lying sequences like the Gawler Range Volcanics characteristically give rise to plains and plateaux. The only landscape known to the writer that is developed on acid volcanic rocks and is comparable to that of the Gawler Ranges has been described from the Ozark Mountains of Missouri, U.S.A. (Bretz 1965; Bickford & Mose 1975). There, conical peaks developed in Middle Proterozoic felsite and granite have been exhumed from beneath Palaeozoic sediments in the St Francois Mountains. Hayes (1961) noted the contrast between the rounded forms developed in granite and the angular nature of the felsite fragments and outcrops. However, a comparison of the United States Geological Survey topographic map of the Ironton Quadrangle with the geology map (Plate 1) in Tolman and Robertson (1969) indicates that many of the domical hills of the area are underlain by extrusive rocks. Grassy Mountain and Vail Mountain, for example, are eroded in Stouts Creek Rhyolite, and Hogan Mountain Rhyolite underlies both Russell Mountain and Taum Sauk Mountain.

Thus, the Gawler Ranges landscape is unusual in terms of its lithologic base. Various questions arise, but the crucial ones are how, why and when did the bornhardts evolve? This thesis is concerned to address these questions, and thus to resolve the problem posed by the development of bornhardts in the silicic volcanic rocks of the Gawler Ranges.

CHAPTER 2 BORNHARDTS OF THE GAWLER RANGES

2.1 INTRODUCTION

Bornhardts are most commonly developed in granitic and gneissic materials, but are also known from sandstone, conglomerate and limestone (Willis 1934; King 1949a; Verstappen 1960; Ollier & Tuddenham 1962; Twidale 1964, 1978, 1982a; Mainguet 1972; Twidale & Bourne 1978a). Only in the Gawler Ranges, and possibly in the Ozark Mountains, U.S.A., are they found in silicic volcanic rocks.

2.2 BORNHARDT CHARACTERISTICS

Though essentially domical, the bornhardts of the Gawler Ranges, like their counterparts in other areas, vary in their precise form. The tall, comparatively narrow variety, like the Sugarloaf of Rio de Janeiro, Brazil (Lamego 1938), is however, lacking. Individual hills in the Gawler Ranges rise to a maximum of 200 m from the surrounding valleys or plains, though low rises only a few metres or tens of metres high are also common (Pl. 1.4B, 2.1). Isolated forms are up to 2 km in diameter. Many bornhardts, however, form interconnected groups, together measuring up to 10 km in diameter (Fig. 2.1). Though the bornhardts are typically rounded or elliptical in plan, the linked domes are irregular or elongate.

Like bornhardts in other areas, the Gawler Range residuals are developed in rocks that are hard, compact and impermeable. They are also essentially massive, with few open joints. Joints are present, but most are tightly closed and weathering agents, particularly water, are unable to penetrate the rock.

The bornhardts are developed within blocks defined by fracture sets which together produce orthogonal, rhomboidal, or, less commonly, triangular shapes (Pl. 1.3A; see Chapter 5). Smaller-scale fracture systems occur within the major blocks, and, in addition, sheet fractures (Chapter 6) are well and widely developed (Pl. 2.2), though they appear to be confined to near-surface zones. Columnar joints (Chapter 7), a manifestation of the volcanic origin of the rock, are also well developed (Pl. 2.3).

A sharp break of slope known as the piedmont angle commonly separates bornhardts from the adjacent plain or pediment. In the Gawler Ranges, as elsewhere, the piedmont angle is formed in bedrock, and in some instances, it takes the form of a clear cut angular junction between the hill and

the plain. More commonly, however, it is represented by a narrow zone of concave-upward curvature linking the bornhardt and the plain or valley floor (Pl. 1.4A, 2.4).

Bornhardts are widely considered to be associated with arid to semiarid climates, and the study area is, indeed, of this type, for the climate of the Gawler Ranges varies from semiarid in the south to arid in the north (e.g. Nonning 240, Moonaree 190, Kokatha 159 mm per annum). In fact, however, bornhardts are azonal, having been reported also from a wide range of conventionally defined climatic regions including hot humid, temperate and cool lands (e.g. Wilhelmy 1958; Twidale & Bourne 1978b).

Bornhardts invariably occur in multicyclic landscapes, i.e. in regions in which there is evidence of more than one geomorphic cycle (Obst 1923; Jessen 1936; King 1949a; Twidale 1982a, p. 207-208, 1982b). The landscape of the Gawler Ranges is of this type, for the bevelled summits of the bornhardts of the southern Gawler Ranges (Pl. 1.4) can be construed as remnants of a former planation surface developed during a previous cycle which was terminated by relative uplift of the region and erosion of the present valley floors (Chapter 3).

2.3 ORIGIN OF BORNHARDTS

To be acceptable, any explanation of bornhardts must account for their salient features. As has been described in the previous section, the bornhardts of the Gawler Ranges, whether they occur as isolated hills or as parts of larger massifs, are essentially the same and they are similar to bornhardts described from other parts of the world. The theories that have been advanced in explanation of bornhardts are now discussed, with particular reference to the domical residuals of the Gawler Ranges.

2.3.1 Faulting

Many bornhardts are located within faulted massifs. Thus the well-known morros of the Rio de Janeiro area, Brazil, stand on the Tijuca Massif which is intrinsically a horst block (Birot 1958), and some, like the famous Sugarloaf, bordering Rio harbour, are partly delimited and are otherwise affected by faults (Lamego 1938). None is however, demonstrably upfaulted. On the other hand, a few bornhardts are considered to be upstanding because of faulting. They are, in fact, minor horsts, and are therefore tectonic forms. Barbier (1957), for example, has shown that the Pic Parana in southeastern Brazil is bounded by faults that were active in the Late Cainozoic, and that it is an

upfaulted mass. Choubert (1949) has also described some of the pitons of French Guyana in similar terms.

The bornhardts of the Gawler Ranges are located within fracture-defined blocks, but there is no evidence that they are upfaulted. Turner (1975) suggested that the hills of the Uno area in the eastern Gawler Ranges are defined by faults, but there is no evidence of planes of dislocation delimiting each hill. Certainly there is no suggestion that the fractures defining the blocks within which the bornhardts have developed are large-dislocation faults. Indeed, to explain the bornhardts of the Gawler Ranges as upthrust blocks would call for a very peculiar mechanism whereby, within each and every fracture-defined block the central core was uplifted; and of that there is no evidence.

2.3.2. Metamorphic differentiation

Brajnikov (1953) suggested that the morros of southeastern Brazil represent cores that are also zones of compression related to volume increase consequent on metasomatism. In these terms the bornhardts are huge discrete corestones or 'floaters' that lack structural continuity in depth: in Brajnikov's terms they are not enracinés. No examples of detached masses of inselberg proportions coincident with metamorphic zones have been located. The gneissic inselbergs of Zimbabwe, for example, display concentric zonation but there is no evidence that they are detached (Layshon 1973).

Moreover, this explanation is clearly inapplicable to the bornhardts developed in the layered volcanic sequence of the Gawler Ranges, as well as to the numerous examples from unmetamorphosed granitic exposures.

2.3.3. Igneous plutons

Holmes and Wray (1912, 1913) suggested that some of the inselbergs of Mozambique are in reality the exposed margins of igneous masses and that their form closely reflects the shape of projections or apophyses developed at the margins of stocks and batholiths. Du Toit (1939, p. 53) suggested that Gorongoza, also in Mozambique, is of this type and there are other examples for which the suggestion seems to be apposite. For instance, Twidale (1982a, p. 128, 1982b) has described from central Namibia a dome of Donkahoek Granite surrounded by schist into which it is intruded and fragments of which remain attached to the sides of the granitic mass. The granite domes of the Encounter Bay, South Australia, area could be of similar type for their outlines appear to be generally coincident with the outlines of the stocks to which they are related.

The nubbins of the Hiltaba-Kondoolka and Kokatha areas of the western Gawler Ranges are developed in granite that both field relations and radiometric dating show were intruded into the Gawler Range Volcanics. The emplaced granite masses seen in section beneath the volcanics, for example near Hiltaba O.S. (Out Station) and around Kondoolka H.S. (Pl. 2.5), are comparable in size and shape to the granite nubbins that rise from the adjacent valley floors. This suggests that the nubbins are basically protruberant stocks that have been exposed by weathering and erosion of the host volcanics.

On the other hand, such an explanation cannot apply to sedimentary bornhardts or to those innumerable examples where both hill and plain are developed in a granitic mass that is intrinsically homogeneous and that has been deeply eroded. Similarly, this explanation is not appropriate to the bornhardts of the Gawler Ranges that have evolved in layered volcanic rocks.

2.3.4. Compositional variation

Some bornhardts are upstanding because they are composed of material that is manifestly different from, and implicitly more resistant than, that which underlies the adjacent plains. Falconer (1911) and Holmes (1918) described examples from Nigeria and Mozambique respectively where granitic inselbergs rise from plains eroded in gneiss. The stressed minerals of the gneiss are more susceptible to weathering, and hence erosion, than are the unstressed minerals of granite (Turner & Verhoogen 1960, p. 476). Hurault (1957) attributed the implied resistance of inselbergs in French Guyana to their being of a resistant leucogranite, and Dumanowski (1968) makes a similar point with regard to upstanding areas of the Polish Carpathians. Lester (1938) attributed the resistance of Stone Mountain, Georgia, U.S.A., to the granite being more resistant than the adjacent biotite schist. This is only partly correct for though the hill-plain junction is, in places, coincident with the granite-schist contact, elsewhere the granite underlies the plains as well as the higher ground (Herrmann 1957; Twidale 1982a, p. 125-131).

The suggestion that some hills are upstanding by virtue of their being underlain by rocks that are more resistant to weathering and erosion than those in which the adjacent plains are eroded, is similar in principle to the suggestion that inselbergs are essentially apophyses developed at the margin of an emplaced mass; it is merely that the causation of compositional contrast is different. And

like that suggestion, the explanation involving compositional variations is applicable in some specific instances.

But the Gawler Range Volcanics consist of layered units of varied petrology (Fig. 1.3), and although there is some suggestion of zonation within individual units, the variations are in vertical section and not laterally as ought to be the case if the bornhardts are due to their being of a more resistant variety of volcanic rock. Also, the bornhardts display a similar limited morphological range whether developed in dacite, rhyodacite or rhyolite, or even in andesite and basalt (e.g. northwest of Kokatha H.S.). There is no evidence to suggest that the rock of which the bornhardts are built is mineralogically and texturally different from that which underlies the adjacent valleys and plains.

2.3.5 Environmental factors

Some workers consider that environment is the key to inselberg development. Bornhardt (1900, p. 34) briefly entertained the possibility that the inselbergs of East Africa are residuals of marine planation. An older generation of geologists (e.g. Ramsay 1846; see also Barrell 1920) believed that ocean waves are capable of regional planation, but it is now realised that there are inbuilt limits to the extent to which the sea can erode the land, save in special circumstances, namely where there is a constant relative rise of sea level. Otherwise, the broader the marine platform, the more wave energy is dissipated in crossing the platform. For this reason shore platforms are unlikely to be more than about 0.8 km wide (Bird 1968). On the other hand, Cushing (1913) has described from southeastern India a coastal plain, with quartzitic inselbergs, that is attributed to marine erosion and which is some tens of kilometres wide. Marine processes have exposed some inselbergs, as for example in several parts of southern Australia and in the Rio de Janeiro area (Biro 1958), but this is coincidental rather than central to their development, for the residuals are basically of structural origin. So far as the Gawler Ranges bornhardts are concerned, there is no evidence of marine incursion, so the question does not arise.

Many workers, impressed by the inselberg landscapes of semiarid and arid lands, have assumed that their development is linked to those climatic environments. Indeed, Passarge's (1904) classification of inselberg landscapes is based in climate. The plains of his Banda type, for example, are, according to Passarge, eroded by the wind (cf. Keyes 1912; Jutson 1914). Nowadays, however, regional planation by the wind is discounted. Many workers consider that bornhardts are zonal or climatic forms. Bloom (1978, p. 325) is a recent worker who embraces this thesis, but the wide favour

enjoyed by this environmental hypothesis is demonstrated by examining the placement in most standard texts of the discussion of bornhardts in the section on deserts. Yet some of the best-known and earliest-described bornhardts occur in the humid tropics (e.g. southeastern Brazil; see Darwin 1846), and domical inselbergs were long ago described from such cold areas as the Sierra Nevada of California (Le Conte 1873; Matthes 1930). They also occur in various parts of the arctic and subarctic zones (e.g. Schrepfer 1933; Kieslinger 1960; Oen 1965; Kaitanen 1985). Indeed bornhardts have been reported from a wide range of climatic environments (see e.g. Wilhelmy 1958; Twidale & Bourne 1978b; Twidale 1982a, p. 136-137). Climatic inheritance could, of course, be invoked but such an explanation calls for climatic changes of a character and chronology unsupported by the evidence. Thus, if Ayers Rock were an arid zone feature, desertic conditions ought to have obtained throughout its period of development. It became upstanding in the late Mesozoic when humid and warm conditions prevailed in central Australia (e.g. Twidale & Harris 1977; Kemp 1978; Frakes *et al.* 1987). The Rock developed its steep-sided morphology during the Cainozoic, also mainly in torrid climatic conditions. In central Australia aridity is a later Cainozoic feature (e.g. Kemp 1978; Frakes *et al.* 1987).

Within the Gawler Ranges the climate varies from semiarid in the south to arid in the north. There is no discernible morphological change coincident with this variation. The area is, however, too limited to demonstrate whether bornhardt development varies with climate.

Thus, some of the concepts and interpretations reviewed above are valid in respect of specific cases, but they cannot be considered general explanations. Only two hypotheses fall into this category. Both have received widespread support.

2.3.6. Scarp retreat

Many workers, and a majority of modern workers, follow King (1942, 1949a) in interpreting inselbergs in granite and other rocks as the last remnants surviving after long-continued scarp retreat (Fig. 2.2). The general concept of parallel scarp retreat can be traced back to Fisher (1866, 1872) and more recently to Lehmann (1933) and Wood (1940). It was first used in the interpretation of granitic inselbergs by Holmes (1918) and was later adopted by Jessen (1936) and King. Pugh (1956) and Selby (1977) may be cited as examples of modern workers who have found the concept satisfactory in granitic terrains, and Ollier and Tuddenham (1962) as some who have applied the idea to sedimentary

forms. But the concept has been most vigorously and persistently applied to inselberg landscapes by King (e.g. 1942, p. 42, 1949a, 1953, 1962, p. 137, 1966).

Most workers who believe in the mechanism favour the arid and semiarid context. King (1957, 1962), however, remained adamant that scarp retreat (and pedimentation) are prevalent wherever the land surface is, or has been, shaped by running water, i.e. everywhere except the glacial regions and the dune deserts.

Scarp retreat undoubtedly takes place in caprock situations and especially in dissected, flat-lying sedimentary sequences, or where duricrusts are preserved. Many assemblages of plateau, mesa and butte in the platform and basin regions of Australia are of this origin. Scarp retreat is also facilitated by arid and semiarid conditions and hence is linked with the environmental concept discussed previously. In arid and semiarid areas, where the soil is thin and the vegetation cover sparse especially on the drier and higher ground, little or no moisture is retained. But on the lower slopes where there is more moisture, and also more vegetation, there is a tendency to greater weathering and erosion. Thus the lower slopes tend to be steepened and the scarps tend to retreat parallel to themselves (Twidale 1983).

Bornhardts are well developed in granitic rocks that lack an obvious caprock. Yet, theoretically, the mechanism could operate in granitic terrains because of the contrasted stability of granite in wet and dry conditions. Barton (1916), Bain (1923) and others have derived evidence to suggest that granite in contact with water is rapidly altered, whereas dry granite is stable. Thus, the upper zones could act as a caprock.

But this is theory, and the field evidence, both in the Gawler Ranges and elsewhere, suggests that inselbergs are not the penultimate residuals surviving after long distance scarp retreat (Boyé & Fritsch 1973; Twidale 1982a, p. 138, 1982b).

According to the scarp retreat hypothesis, inselbergs should be no older than the duration of a cycle of erosion. Estimates of the duration of a cycle vary widely (see Gilluly 1955; Linton 1957; Schumm 1963; Twidale 1976a), but there is general agreement that, even allowing for isostatic readjustment, large areas of high land would be reduced to a plain of low relief in about 35-40 My. Thus, in terms of scarp retreat, no inselberg ought to be older than this; in other words, no inselberg ought to predate the Oligocene. As is discussed in Chapter 3, the Gawler Ranges bornhardts appear to be at least 60 My old and are probably older, which is inconsistent with the scarp retreat hypothesis.

Also, as is illustrated in Fig. 2.2B, the bornhardts ought to be the last residuals surviving after long distance scarp retreat. In several parts of the world (see e.g. Thomas 1965, Twidale 1982a, p. 139-140, 1982b) bornhardts are located either in the sidewalls of comparatively narrow valleys, or in the valley floors, which suggests that they are not the result of scarp retreat. The field evidence in the Gawler Ranges is also inconsistent with this hypothesis. Whatever their location in the drainage basin, bornhardts in the Gawler Ranges display a similar range of morphology, as would be expected in terms of scarp retreat. In keeping with the concept, however, the areal or plan extent of residuals ought to diminish down valley, or, conversely, those remnants surviving in the headwater regions of river systems ought to be larger than those in the lower reaches (Fig. 2.2B). The field evidence shows that this is not so. The size of the bornhardts is related to the distribution of the regional scale orthogonal fractures and not to their location within a drainage basin. In addition, there are no examples of pillars, or tall, relatively narrow remnants, representative of the penultimate phase in the parallel retreat of slopes.

Also, in terms of scarp retreat, the bornhardts ought to be restricted to major divides. In the Gawler Ranges they are found throughout the drainage basins, even adjacent to the major drainage lines. For example, Lake Gairdner occupies an alluviated valley. The alluvium is some 19 m thick (Johns 1968), so that the islands of Gawler Range Volcanics that stand some 50 m above the surface of the saline crust are surely the crests of bornhardts some 70 m high and located close to the axis of the old valley.

Thus the bornhardts of the Gawler Ranges, like those of many other regions, cannot be satisfactorily explained in terms of scarp retreat.

2.3.7. Subsurface two-stage development

The other hypothesis that finds strong support amongst field workers is due to Falconer, who in a seminal statement wrote:

"A plane surface of granite and gneiss subjected to long-continued weathering at base level would be decomposed to unequal depths, mainly according to the composition and texture of the various rocks. When elevation and erosion ensued, the weathered crust would be removed and an irregular surface would be produced from which the more resistant rocks would project. Those rocks which had offered the greatest resistance to chemical weathering beneath the surface would upon exposure naturally assume that

(1911)

configuration of surface which afforded the least scope for the activity of the agents of denudation. In this way would arise the characteristic domes and turtle-backs ..."
(Falconer 1911, p. 264).

Falconer's is a structural concept, for he suggested that inselbergs are developed on resistant masses. In addition, he not only recognised the importance of chemical weathering, but clearly attributed the inselbergs to weathering beneath the land surface followed by erosional exposure; in other words he stipulated a two-stage development. Furthermore, he cited the view of Merrill (1898, p. 245) to the effect that the outlines of the residuals are determined by strain in the rocks (see Chapter 5). Compositional variation would undoubtedly lead to differential subsurface weathering, with the weathering front (Mabbutt 1961) deeper and the regolith thicker on weak rocks and shallower and thinner respectively on resistant materials (Fig. 2.3). Another significant factor alluded to by Falconer, concerns fracture density for, as was recognised by Le Conte (1873) and Mennell (1904) and has since been demonstrated in several parts of the world (Linton 1952, 1955; Twidale 1964, 1971, 1982a, p. 131-135; Büdel 1977, p. 108-109), the rocks of inselbergs lack open joints - they are massive - whereas those that underlie the plains are well fractured. The reason for such contrasts in fracture density between adjacent compartments may be related to the distribution of stress and related strain (see e.g. Lamego 1938; Twidale 1981b, 1982a, p. 134-135, 1982b).

This two-stage hypothesis finds support in the field evidence from many parts of the world. There are demonstrable contrasts in fracture density as between inselberg and plain (e.g. at Ucontitchie Hill on Eyre Peninsula) and these contrasts at the present surface can also be taken as indicative of the fracture patterns in the eroded masses (Blès 1986; Twidale 1987). The incipient bornhardts reported beneath the natural land surface and exposed by excavation (see Boyé & Fritsch 1973; Twidale 1982a, p. 142) are explicable as features which have attained only the first stage of their development.

Several lines of evidence point to the Gawler Range bornhardts having evolved in this manner. First, the summit surface preserved as the bevelled domes of the region constitutes evidence of an old planation surface beneath which the deep differential weathering could have taken place.

Second, the bornhardts are based on fracture-defined blocks. The linearity of the valleys and their regular geometrical pattern are suggestive of development along fractures (see Section 4.2). These fractures are zones of weakness along which water could have penetrated into the otherwise

impermeable rock. The fracture zones could have been the loci of particularly deep weathering. In some areas, particularly in the east of the Ranges, geophysical investigations have demonstrated the presence of what are interpreted to be dolerite dykes intruded along the fractures (Tucker *et al.* 1986; Fig 1.4). These dykes, being of more basic composition than the acid volcanic rocks, are theoretically more susceptible to weathering and erosion. Thus in some instances, this compositional weakness may reinforce the effect that the fractures have had on the development of the bornhardts. The hills, on the other hand, are massive, i.e. they lack open fractures, and are therefore resistant to weathering. Thus fracture patterns could have led to the weathering front becoming irregular.

The rounding of the hills could be attributed to preferential weathering which is more effective on the corners and edges of the blocks than on the plane faces (MacCulloch 1814, p. 74-75; Logan 1849, p. 24; Merrill 1898, p. 244; Mennell 1904, p. 74; Falconer 1911, p. 246; White 1945). Some workers, however, would relate the domical form of the hills basically to the presence of sheet fractures (see Chapter 6).

Third, on the upper slopes and summits of the volcanic hills, the rock is essentially fresh with only minor patches of regolith preserved in depressions (Pl. 2.6). This is not because the Gawler Range Volcanics are immune to weathering, for, as is discussed in Chapter 3, weathering has occurred to considerable depths in the major valleys and remnants of a former regolith are preserved on the bornhardts. These weathering products are interpreted as an indication that the entire surface has been weathered, though all but a few remnants have since been stripped. This is consistent with the two-stage hypothesis.

2.4 CONCLUSION

On balance, the bornhardts developed in Gawler Range Volcanics are best explained by two-stage development, the subsurface differential weathering being fracture-controlled and having taken place beneath a stable land surface. There is considerable evidence that is consistent with the mechanism, and nothing that is grossly incompatible with it. The bornhardts, *pro tempore*, are construed as etch forms that developed first by differential subsurface weathering followed by stripping of the regolith and exposure of the unweathered bedrock forms.

To test this suggestion, and to ascertain when and why the postulated evolution took place, it is necessary, first, to investigate the pattern of weathering of the Gawler Range Volcanics and to

ascertain whether there is evidence of the etch nature of the bornhardts; second, to determine the age and evolution of the planation surface beneath which weathering took place (Chapter 3); and third, to ascertain the age and origin of the different fracture sets that have been exploited by weathering and which have thus contributed substantially to the shaping of the bornhardts of the Gawler Ranges (Chapter 4-7).

CHAPTER 3 DENUDATION CHRONOLOGY

3.1 INTRODUCTION

From a geomorphologic point of view, the summit surface of the Gawler Ranges is second only in importance to the bornhardts of the upland. It is widely distributed (Fig. 1.5) and takes the form of distinct bevels located on the crests of many of the bornhardts (Pl. 1.4, 2.1). The bevelled crests were first noted by Dickinson (1942) in the course of a groundwater study on Moonaree Station (Fig. 3.1). He wrote that '... this feature suggests that the hills were once part of an old uplifted land surface which has been dissected by a long and continuous erosion process to a stage of full or late maturity'. The present analysis suggests that Dickinson's interpretation is simplistic, for, though the bevels are manifestly related to some form of old, now uplifted and dissected, planate land surface, the evidence suggests that they were not originally part of a surface of low relief.

The summit surface is essentially devoid of regolith (Pl. 2.6). Rocky outcrops comprising clusters of intrinsically fresh angular blocks and rounded boulders are separated by shallow depressions filled with skeletal soil that is presumably of recent origin. But no substantial remnants of a palaeosol are preserved on the summits.

Yet the Gawler Range Volcanics are susceptible to weathering, for the valley floors are underlain by a regolith up to 60 m deep (see below). Moreover, in the southern Gawler Ranges, some remnants of a regolith, in the form of corestones set in a matrix of weathered material, remain perched on valley side slopes (see Section 3.3.2).

Also, most surfaces of low relief are underlain by a regolith, for a plain frequently implies stability and time for rock alteration by meteoric waters. Extensive bedrock plains lacking a regolithic veneer are unusual. However, they undoubtedly exist. Examples include the Meekatharra Plain of central Western Australia, which is cut in Archaean migmatite, and the Bushmanland Surface of Namaqualand, eroded in granite, gneiss and sandstone (Twidale 1983). The Bushmanland Surface is certainly of etch type (Partridge & Maud 1987; Twidale 1990), and the Meekatharra Plain may be so, though it may be interpreted as an ultiplain, a surface of virtually nil relief that represents an even more advanced stage of erosion than the peneplain (Twidale 1983). Such extensive bedrock plains are, however, rare. More commonly, surfaces of low relief carry a regolith of greater or lesser thickness. Such varied concepts make it necessary to consider whether the Gawler Ranges summit

surface was produced by processes active at the land surface, or whether it is an etch feature developed beneath a higher surface that no longer exists.

Various planation surfaces, including the widespread summit surface, and others of limited extent, were identified, described and discussed by Smith (1976). The work reported in this thesis largely corroborates her findings, though the ages and origins she assigned to some of the surfaces have been revised in the light of new data and concepts. This illustrates the advantages of identifying surfaces by local or regional names, rather than by a postulated age or age-range, for, in such instances, ages can readily be adjusted in accordance with new evidence.

The surfaces are discussed in chronological order. The morphology of the Scrubby Surface, the oldest so far identified in the region, is indicative of fracture-controlled weathering of the Gawler Range Volcanics in Middle Proterozoic times. The Nott Surface is not only the most prominent, but is also critical to the evolution of the bornhardts of the Gawler Ranges. The Spring and Beck surfaces (the latter additional to those named by Smith) are interpreted as genetically related to the Nott Surface. The later surfaces, which were treated separately by Smith, are taken as a group because their development impinges only marginally on the development of the bornhardts.

3.2 THE SCRUBBY SURFACE

The Scrubby Surface is of limited extent and is restricted to the area around Scrubby O.S., some 35 km north of Nonning H.S. It is rolling or undulating and is eroded in, and therefore younger than, the Gawler Range Volcanics. It is consistently associated with remnants of the Pandurra Formation, a fluvial deposit laid down in troughs some 1424 Ma (million years ago). The bedrock plain consists of low (1-2 m high) domical hills separated by shallow valleys that are developed along linear fracture zones, demonstrating that the partings, which belong to the orthogonal system, predate Pandurra times. Outcrops of Pandurra Formation, characteristically with a well-developed silcrete capping, stand as low mesas and plateaux adjacent to the Scrubby Surface (Pl. 3.1). In some places a regolith, some 2 m thick, is preserved between the bedrock plain and the sedimentary formation (Fig. 3.2), but elsewhere the contact between the Pandurra Formation and the volcanics is clean.

The regolith shows that the Scrubby Surface was eroded and weathered prior to the deposition of the Pandurra Formation. The surface is therefore older than the Pandurra sedimentary episode that took place about 1424 Ma, yet must be younger than the materials in which it is weathered and

eroded. Thus it is of Middle Proterozoic age. Where the bedrock has been exposed by the stripping of the old regolith, it is of etch type for it is an exposed weathering front. Elsewhere, however, it is evidently exposed by the removal of the Pandurra Formation, and there it is of exhumed type.

3.3 THE NOTT AND RELATED SURFACES

3.3.1 The Nott Surface of Smith (1976)

The bevelled domes located near Lake Gairdner and depicted by Dickinson (1942) are excellent examples of the genre, but are only typical of many such features preserved in the Ranges, and particularly in the southern areas. The summit bevels were interpreted by Smith (1976) as being part of a once coherent, but now dissected surface which she called the Nott Surface (Fig. 1.5).

The crestal bevels stand some 380-460 m above sea level and some 120-180 m above the adjacent valley floors. The crests of the higher hills such as Mt Fairview (450 m) and Mt Nott (430 m) stand above the general level of the summit surface. The surface is erosional rather than structural in origin because it cuts across various layers in the volcanics. For example, in the southern Gawler Ranges the surface transects areas of Yardea Dacite, Paney Rhyolite and Eucarro Dacite (Fig. 1.3).

In the southern part of the Gawler Ranges, in the Paney Upland in particular, there are remnants of a planation surface approximately 30 m lower than the bevelled crests of the Nott Surface, and standing some 100 m above the present valley floors. It was considered separately, and named the Spring Surface by Smith (1976). It is fragmented and restricted in area (Fig. 3.3), and is represented by the bevelled spurs which project from the crests that are part of the Nott Surface, and also by accordant crests of some of the lower hills (Pl. 3.2). Smith noted a 2-4° southerly slope away from the remnants of the Nott Surface. The Spring Surface is erosional since it cuts across the different units of the Gawler Range Volcanics, for example, east of Paney H.S. (Fig. 1.3). The nature of the Spring Surface is very similar to that of the Nott Surface. It dips away in all directions from the remnants of the Nott Surface, rather than consistently to the south as was suggested by Smith.

Smith considered the Spring Surface to be the same age as the Nott Surface but formed by vigorous south-flowing streams during uplift of the area in the manner of a perched peneplain as described by Kennedy (1962). The existence of the two surfaces can also be taken to result from phased uplift of the Ranges. In this case the Spring Surface, being 30 m lower than the Nott Surface, would represent a later period of weathering under stable conditions, followed by renewed uplift, and

erosion of the weathered material. Alternatively, the Spring Surface may have been formed as a weathering front at the same time as the Nott Surface, but at a lower level because weathering penetrated to greater depths, possibly due to a higher fracture density.

3.3.2 The nature of the Nott Surface

Smith restricted the Nott Surface to the summit bevels, and this is reasonable if the surface is interpreted as an epigene form. If the possibility of its being of etch character is taken into account, however, the morphology of the former weathering front must be considered more closely. Weathering beneath the old land surface may well have extended to greater depths along fracture zones - the present valleys - so that the etch surface would have consisted of two broad morphologic elements, the summit surface and the valley side slopes or the flanks of the bornhardts. In these terms, the Nott Surface comprises two elements, the summit bevels (Nott-S) and the hill slopes (Nott-H).

In the Gawler Ranges at present, evidence of significant deep weathering of the bedrock only occurs in major valley floors. The material exposed in the excavation of dams, for example, consists of white clay with grains of quartz and feldspar. Bores sunk in the unconsolidated material in the Moonaree area show that there is a thin layer of weathered material overlying relatively unaltered but fractured rock (Dickinson 1942). Logged boreholes (South Australian Department of Mines and Energy, bore general file, Yardea bore location plan) indicate that within the Ranges, weathered material frequently extends down to 10 m and in some places to depths of 60 m or more.

In addition to valley floor weathering, one bornhardt, Mt Cooper, an outlier of Gawler Range Volcanics located 70 km southwest of the Ranges proper, displays shallow but intense weathering of the crest and flanks. The regolith, up to 2 m thick (Pl. 3.3), is exposed in quarries. It consists of small corestones set in a kaolinitic matrix. The rock below the weathering front (Fig. 3.4A, sample 1) contains predominantly quartz and feldspar (microcline and albite) with microcline more abundant than albite. Minor amounts of mica (probably biotite) and hematite are also present. Quartz is dominant in all samples analysed, but in the samples of weathered rock (2 to 4) the feldspars (F), especially albite (A), are reduced towards the surface as weathering proceeds, kaolinite (K) appears in sample 2 and increases towards the surface and biotite (B) is absent from all the weathered samples. Hematite (H), present in the fresh rock, is depleted through most of the profile, but is present in the surface zone (see Fig. 3.4B). The corestones possess a weathering rind in which a zone of iron oxide concentration is

prominent, a feature characteristic of many weathering fronts (see below). In granitic rocks, such a concentration of iron may be as much as three times that in fresh rock (R.I. May & A.R. Milnes, personal communication 1981; S.M. Kraemers & A.R. Milnes, personal communication 1981).

Most Gawler Range bornhardts, however, are devoid of regolith, although most carry thin ferruginous skins. Exceptional remnants of an old regolith are found in two areas, one 7 km east of Nonning H.S., and the other in a small area between Yardea, Thurlga and Paney homesteads. The regolithic remnants at the latter site consist of altered Yardea Dacite mottled white, red and brown, and with corestones set in the finer matrix (Pl. 3.4A). The corestones are up to 50 cm in diameter, though most are of the order of 25 cm. Many display spalled margins, with shells 1-3 cms thick arranged concentrically around the kernel (Fig. 3.5). Within the kernels preferential weathering of feldspar phenocrysts has taken place. Some of the shells are stained red, suggesting concentrations of iron oxide.

These regolithic remnants with corestones are preserved on mid slope (Pl. 3.4B), sites at which they could not develop under present conditions. It is only low in the relief, beneath valley floors, that such intense chemical attack is taking place. The valley side occurrences are interpreted as remnants of a regolith that formerly covered and filled not only the entire valleys, but also extended over the present summit surface. In other words, they are parts of the regolithic cover that developed beneath the land surface and beneath which both the summit and valley side elements of the Nott Surface evolved as a weathering front.

No remnant of the hypothetical surface below which the Nott Surface developed is known to survive. Yet there must have been such a surface in order for the present exposed weathering front, and the imputed regolith, to have developed. Its morphology must have been similar to that of the bevelled crests, i.e. it must have been an extensive surface of low relief (Fig. 3.6). It was thus morphologically different from the complete Nott Surface and also stood at a higher level. Because of this difference in morphology, as well as in origin and age, the planation surface below which deep weathering took place and beneath which the Nott Surface evolved is referred to by a distinct and separate name. It is the Beck Surface, named after Lance Beck, a long time friend and keen amateur geologist for whom the Gawler Ranges hold special interest.

3.3.3 The ferruginous patina and its significance

A veneer or patina of purplish-brown material, predominantly hematite (Pl. 3.5), is frequently found on the crests and upper hillslopes in the Gawler Ranges. It is approximately 1 cm thick and is frequently associated with a pitted surface, and with laminations (Barton 1916; Twidale & Bourne 1976). Similar ferruginous concentrations have been noted elsewhere, for example on Yarwondutta Rock and Tcharkuldu Hill on Eyre Peninsula and at Mt Monster in the Southeast of South Australia, associated with a suite of minor landforms initiated at or near the weathering front (Twidale 1986a; see also Milnes *et al.* 1987). Pavich (1986) and Whitehouse *et al.* (1986) have noted similar features from U.S.A. and New Zealand, and Morin (1982) has recorded iron concentrations in basalt weathering profiles from West Africa. Comparisons with these occurrences suggests the possibility that the hematite skins of the Gawler Ranges are derived from such weathering front accumulations. Their association with lamination and pitting is consistent with this interpretation.

But if this is so, the iron oxide concentrations, already two or three times greater than in the unaltered rock, must have been further concentrated. This could have occurred, after stripping of the kaolinitic cover and exposure of the iron oxide, by capillary action or by the activities of lichens or algae (Fry 1926, 1927; Scheffer *et al.* 1963; see also Dorn 1984). Alternatively, the material may have recrystallized on exposure and desiccation, much as does laterite (Alexander & Cady 1962). If these rinds are features formed at the weathering front, then the implication is that there has been only minimal weathering and erosion of the bornhardts since their exposure from beneath the regolith.

3.3.4 The age-ranges of the surfaces

The ages of the Nott and Beck surfaces can be determined by correlation with the stratigraphic sections exposed in the Eromanga Basin to the north and northeast of the Gawler Ranges.

Deposition in the southern part of the Eromanga Basin began in the Late Jurassic with the Algebuckina Sandstone, a fluvatile sandstone laid down on a weathered (kaolinised) surface eroded in Proterozoic and Palaeozoic rocks (Wopfner 1969; Wopfner *et al.* 1970; see Fig. 1.3). The Algebuckina Sandstone is unconformably overlain by the marine Cadna-owie Formation of Early Cretaceous (Neocomian-Aptian) age. The Cadna-owie Formation includes the fluvatile Mt Anna Sandstone Member, a cross-bedded feldspathic sandstone that contains pebbles of porphyritic silicic volcanics derived from the Gawler Ranges. Not only does the petrology of the pebbles match that of the Gawler Range Volcanics, but both thickness measurements and analysis of current directions

indicate a southerly provenance (Wopfner 1969; Wopfner *et al.* 1970). In the lower parts of the Mt Anna Sandstone the volcanic pebbles are highly weathered, in contrast with those from higher in the sequence where the proportion of intrinsically fresh volcanic material increases (Wopfner *et al.* 1970).

The Mt Anna Sandstone is clearly derived from a regolith developed in the Gawler Ranges, at a time when the latter had been reduced to low relief. Conditions must have been stable, allowing widespread, relatively deep weathering, particularly along fracture zones where, judging from the depth of the present valleys, the regolith must have extended to depths of 120 m or more. The distribution of weathered and fresh volcanic pebbles in the sequence is consistent with the erosion, first of the upper intensely weathered zone of the regolith, and then of the deeper less weathered zone. The Mt Anna Sandstone is of Neocomian-Aptian age suggesting that the stripping of the regolith developed beneath the Beck Surface took place in the Early Cretaceous. Thus the Nott Surface is, in this sense, also of Early Cretaceous age. On the other hand, its preparation or initiation by differential subsurface weathering occurred earlier, certainly during the later Jurassic, but possibly extending back into the Triassic: this is also the imputed age of the Beck Surface.

The stripping of the regolith to expose the Nott Surface was probably achieved by the end of the Cretaceous. The presence of relatively unweathered pebbles of volcanic material in the higher levels of the Mt Anna Sandstone suggests that the Gawler Ranges had been stripped to the deeper levels of the regolith by Aptian times. The erosion of the present valleys in the Ranges appears to have been essentially completed by the Early to Middle Tertiary, for silcrete accumulations of that age have formed on the valley floors, for example north of Nonning H. S. (Hutton *et al.* 1978). A more precise age has been suggested by Firman (1983) for silcrete near Chundie Swamp, west of Ceduna, which had already formed prior to the deposition of the overlying Miocene sediments. This silcrete may be correlated with that from the Gawler Ranges, and if so, an Early Tertiary age is indicated.

In addition, whereas the Pandurra Formation and the Mt Anna Sandstone Member demonstrate the reality of erosion of the volcanic upland during the Middle Proterozoic and Early Cretaceous respectively, no such distinctive sediments derived from acid volcanic material have been identified in Cainozoic sequences adjacent to the Ranges. For example, deposition in the Eromanga Basin ceased with the early Late Cretaceous Winton Formation (Moore 1986) and the Eocene and Miocene sediments in the Narlabby-Corrobinnie Depression to the south consist almost entirely of quartz sand from a granitic source (Binks & Hooper 1984). Sediments from the Gawler Ranges are

likely to be present, indeed must be present, because many rivers, including older, more active rivers such as the Thurlga Palaeochannel drainage (Blissett *et al.* 1988), flow or flowed into the Depression, but their deposits are masked by detritus of granitic provenance. The paucity of sediment derived from the Gawler Range Volcanics in the adjacent sedimentary basin suggests very strongly that erosion of the uplands over the past 60-100 My has been minimal.

The Beck Surface appears to have been part of a widely developed Mesozoic landscape, remnants of which are found in parts of central and southern Australia (e.g. Woodard 1955; Twidale 1980; Mabbutt 1966, p. 95; Wopfner & Twidale 1967). Remnants of such a planation surface are preserved, for example, in the Gulfs region of South Australia where they are lateritized (Campana 1958; Daily *et al.* 1974; Twidale 1976b). The age of this laterite is controversial, but it is indubitably a Mesozoic feature. To the east of the Gawler Ranges, the Arcoona and Simmens surfaces stand high in the relief. They are of Late Cretaceous (or earlier) age, being truncated by faults active in Late Cretaceous time (Johns 1968; Twidale *et al.* 1970).

3.3.5 Conditions during the development of the Beck and Nott surfaces

Several factors were conducive to deep weathering beneath the Beck Surface. First, the region was tectonically stable. There is no evidence of significant tectonic events in the Gawler Ranges during the Jurassic, and it seems that the stable land surface of low relief in the Eromanga Basin, on which the Algebuckina Formation was deposited, extended also into the Gawler Ranges area.

Evidence from sediments, fossils and oxygen isotope data suggests that globally the climate of Mesozoic times was appreciably more equable than that of today, with no polar icecaps (Hallam 1975, 1985; Frakes 1979, p. 156). Frakes (1979, p. 168) concluded that there is little doubt that the Jurassic climates were warm. Whether they were arid or moist, or perhaps seasonally moist, is more debatable. In Australia, for at least a part of the Jurassic, when the Mesozoic land surfaces of Australia, including the Beck and the Nott surfaces developed, a warm dry climate is suggested (e.g. Quilty 1984, p. 155; Frakes *et al.* 1987, p. 3). The presence of dreikanter, on the one hand, and of conglomerate lenses and cut and fill structures, on the other, in the lower Algebuckina Sandstone (Jurassic) was possibly due to episodic flooding in a seasonally arid climate (Wopfner 1969, p.147). The upper unit of the Algebuckina Sandstone is, however, well sorted with large scale angular current beds. Although this unit has been interpreted as due to aeolian deposition and desert conditions

(Brown *et al.* 1968, p. 250), it is most likely indicative of energetic and uniform conditions of fluvial transport such as occur under a moist, subtropical climate (Wopfner 1969, p. 147). Such conditions would favour the silicification of plant impressions found near the top of the unit near Mt Anna (Wopfner 1969, p. 147, 1978, p. 137, 1983), and also the development of lignite in the Upper Jurassic of the Poldas Basin further south (Brown *et al.* 1968, p. 251). Any arid phases of the Jurassic were apparently only minor aberrations, and after the desiccation, humid conditions quickly resumed (Frakes *et al.* 1987, p. 3).

The vegetation of Jurassic times was more primitive and less provincial and diverse than that of today (Hallam 1975, p.221). Ferns and gymnosperms of the period, signifying subtropical to warm temperate conditions, extended to 60° palaeolatitude (Hallam 1985). Humid conditions provided for prolific plant growth and maintained high groundwater tables during deposition of the Late Jurassic Algebuckina Sandstone in the Great Artesian Basin (Wopfner 1983). These conditions were conducive to groundwaters of low pH which promoted kaolinization.

Although the Gawler Ranges were probably reduced to a surface of low relief close to base level, the Jurassic shoreline was located well to the north (Veevers 1984, p. 265), while to the south Antarctica and Australia had not yet separated. Marine erosion in the Gawler Ranges is, therefore, ruled out. The equable climate excludes the possibility of glacial erosion, and also of wind action, except perhaps for limited periods. In any event, the efficacy of the wind in erosional work is restricted to minor amounts in hard rocks, though in weak unconsolidated strata yardangs of considerable amplitude are developed (e.g. Bobeck 1969). Streams draining north to the Eromanga Basin (Veevers 1984, p. 265) were apparently the dominant agents of erosion and deposition.

Such a drainage pattern continued during the Cretaceous when the sea transgressed into the Eromanga Basin and the marine Cadna-owie was deposited there. The deposition of the fluvial Mt Anna Sandstone Member involved not only retreat of the sea, but also a change in calibre of the sediments. The deposition of the pebbles of Gawler Range Volcanics implies increased erosion in the Gawler Ranges. Dissection of the Beck Surface and stripping of the regolith formed beneath it, thus had their counterpart in the deposition of the Mt Anna Sandstone Member. The change in denudation conditions has been attributed to a major tectonic uplift of the Gawler Ranges along their northern margin in Early Cretaceous time (Wopfner *et al.* 1970; see also Mount 1982). If the uplift occurred along the southern margin as suggested by Twidale *et al.* (1976), the abrupt southern rampart of the

Ranges and their northerly tilt are also explained. Uplift of the Ranges would account for the remnants of the Nott Surface now standing high in the relief, a feature which is not explained if either downfaulting within the Eromanga Basin or a change in climatic conditions was suggested as an explanation for increased erosion in the Gawler Ranges.

Thus the tectonic stability and climatic conditions of Jurassic times were conducive first to planation and production of a surface of low relief. Second, the conditions were suitable for deep weathering beneath the Beck Surface. The weathering beneath the Beck Surface was not of uniform depth. The subhorizontal Nott-S components may reflect the general position of the former water table whilst the steeper slopes, the Nott-H elements, represent the margins of deeper weathering coincident with fracture zones (Fig. 3.6).

No remnants of the Beck Surface have survived and hence it is not possible to compute the thickness of the old regolith. However, regoliths in excess of 100 m thick have been reported from such warm, humid regions as Brazil and northern Australia (Branner 1896; Thomas 1966; Ollier 1969, p. 121). What can be said is that the regolith was at least 120 m thick in the valleys. This is not excessive, given the estimated rate of weathering. Velbel (1985), for example, estimated that in the central Appalachians, U.S.A., a regolith 6.1 m thick developed in about 100,000 years.

3.4 POST-NOTT SURFACES

Because of the presence of silcrete of Early Middle Tertiary age at approximately the same level as the present valley floor 6 km north of Nonning H.S. (Hutton *et al.* 1978), Smith considered the present valley floors and almost horizontal plains between the upland remnants to be of Early Middle Tertiary age. Similar silcrete remnants cap low rises at several sites around the Gawler Ranges, e.g. in the Buckleboo area south of the Ranges, and an Early Tertiary age is suggested for some (Firman 1983). These silcreted surfaces within the Ranges and to the south of the Ranges were termed the Nonning and the Uno surfaces respectively by Smith, and her names are retained. The present valley floors and pediments which form the Nonning Surface are widespread and are extending and developing, albeit slowly, at the expense of the upstanding residuals. The Uno Surface south of the Ranges has been dissected by up to 6 m, whereas the Nonning Surface has been preserved, probably because it is far removed from base level fluctuations.

The Early Tertiary age of the Uno and Nonning surfaces is confirmed by remnants of ferricrete (the Koongawa Surface of Smith 1976) developed at a lower level than the silcreted surface to the south of the Ranges. The ferruginization is considered to be of late Pliocene or early Pleistocene age, by extrapolation from similar ferricretes in the southern Mt. Lofty Ranges and northern Yorke Peninsula (Horwitz & Daily 1958, p. 57; Crawford 1965, p. 39-41). Because the silcrete is slightly higher than the ferricrete, it is also older.

Lowering of base level during the Quaternary resulted in the formation of a modern surface of erosion which was differentiated by Smith (1976) according to the various rock types over which it is developed. The Wudinna Surface, developed across weathered granite south of the Ranges, the Gilles Surface developed on metasediments and granites on the margins of Lake Gilles, the Kingoonya Surface developed on Cretaceous sediments and Gawler Range Volcanics north of Lake Gairdner, and the Peterby Surface developed across Gawler Range Volcanics in restricted areas on the southern margins of the Gawler Ranges, for example near Peterby Tanks and at Coralbignie Rocks, are all equivalent.

3.5 PEDIMENTS AND THE PIEDMONT ANGLE

The Peterby Surface consists of coalesced pediments, i.e. inclined bedrock surfaces which are separated from the bornhardts by a sharp break of slope or a narrow zone of curvature known as the piedmont angle (Tator 1952, 1953; Whitaker 1973, 1979; Pl. 1.4). Most of the pediments are of the mantled variety, being covered by only a thin layer of rock fragments and material derived primarily from weathering in situ. The distal parts of some pediments near the valley axes, especially those in the broader valleys, are covered by alluvium up to 4 m thick. They are therefore covered pediments (Twidale 1981b). The pediments meet the backing scarps in an abrupt break of slope or a zone of curvature known as the piedmont angle, the origin of which has given rise to considerable controversy.

Some early workers suggested that the piedmont angle originated at the junction of fault blocks (Lawson 1915). This hypothesis does not explain the maintenance of the piedmont angle as weathering and erosion proceed, and although the mechanism may contribute to the development of the piedmont angle in some areas like the American Southwest, it is of no significance in the Gawler Ranges where faulting at the scale and frequency required - the implication is that each bornhardt is defined by large displacement faults - has not been demonstrated.

Johnson (1932) proposed that the piedmont angle is due to lateral corrasion by streams debouching from the upland to the plain. In the Gawler Ranges, as elsewhere, there is no evidence of streams being diverted along the upland front. The scarp fronts are rectilinear, with no evidence of indentations or scalloping by meandering streams. Also, streams leaving the upland tend to continue on directly toward the valley axis or basin centre. In addition, some residuals are too small to generate streams, as opposed to wash, so that the piedmont angle cannot be explained by stream action: the piedmont angle is as well developed in scarp foot zones lacking streams as it is adjacent to drainage channels.

King's (1949b, 1953) suggestion that the piedmont angle is due to a change in the nature of flow from turbulent to laminar consequent on a change in gradient has about it a chicken and egg element, for it requires that the piedmont angle be already in existence. Moreover, the pediment surfaces are typically stony and covered with vegetation, and it is unlikely that laminar flow could be maintained for any length of time over such a wide area.

Twidale (1967) argued that the piedmont angle is basically of structural origin: the abrupt break of slope is found at structural boundaries, typically the junction between compartments of contrasted fracture density. The structural effect is reinforced by differential weathering and erosion, for moisture is concentrated in the highly jointed rock beneath the valley floor, whilst the hills are massive and are therefore resistant to weathering and erosion. If the weathered material is stripped the exposed rock pediment is an etch form. Once the hill plain junction has formed, reinforcement, or positive feedback, effects come into play (Twidale et al. 1974).

On the granitic inselbergs of northwestern Eyre Peninsula and elsewhere (Twidale 1967, 1982a, p. 131) excavations reveal that the piedmont angle is coincident with the structural boundary between the massive granite of the inselbergs and the densely fractured granite of the plains. The structural contrast results in a variation in the rate of weathering and erosion. The densely fractured compartments are worn down and pediments are formed on them. Most carry a veneer or mantle of weathered granite augmented by minor amounts of detritus washed from upslope. Any increase in erosion results in stripping of the regolith and exposure of the weathering front as a rock pediment.

This structural interpretation is readily applicable to the piedmont angles developed in the Gawler Ranges, for, although no exposures of fresh rock underlying the plain and the hill plain junction have been found, there is strong inferential evidence that the valleys are coincident with fracture

zones. The valley floors have been weathered whereas the uplands remain fresh. Also, none of the other explanations is consistent with the field evidence.

In addition, flared slopes are developed in the Ranges both on volcanic and granitic rocks. Flared slopes are a particular type of the piedmont angle. They are not generally developed on volcanic rocks in the Gawler Ranges, occurring at only a few sites in the neighbourhood of Paney H.S., at Mt Sturt (Pl. 3.6B) and at Coralbignie (Houlderoo) Rocks 10 km southwest of Nonning H.S. They are also found at Mt Cooper, 70 km southwest of the Ranges. The flared forms rise up to 2 m above the present valley floors.

The most spectacular development of flared slopes in Gawler Range Volcanics is at Coralbignie Rocks. The rock is a porphyritic rhyolite. A series of fracture-defined blocks is preserved, on which is developed a suite of landforms representing every stage in the reduction of the blocks, from masses of rock surmounted by boulders, to conical forms shaped like coolie hats, and to rock platforms (Pl. 3.7). Most of these forms are characterized by flared sidewalls.

The flared slopes are due to pronounced subsurface, scarp foot moisture attack. They are two-stage, or etch, forms (Fig. 3.7). The concave-upward shape of the flare is most likely due to the drying out of the regolith near the surface and the persistence of moisture and hence of weathering at depth (Twidale 1962). It is notable that, though many granite residuals within the Ranges display flared basal slopes, they are developed on Gawler Range Volcanics only at or near the southern margin of the upland, bordering the Corrobinnie Depression, and in a zone of moisture accumulation. Basal flared slopes indicate that subsurface weathering has been active in bornhardt formation and that the bedrock slope has been exposed in stages. The scarcity of flares at higher levels suggests that phased exposure has not generally taken place. The flares are evidence of recent renewal of erosion and a minor modification to the bornhardt form. They demonstrate an increase in relief amplitude of the bornhardts as the valleys are eroded. Above all, however, they indicate the operation of scarp foot weathering as the mechanism responsible for the development of the piedmont angle in the Gawler Ranges.

3.6 CONCLUSION

The bornhardts in the Gawler Ranges developed by subsurface weathering beneath a Jurassic planation surface. The weathering extended to greater depths in fracture zones than in the fracture-

defined blocks. The stripping of the regolith and the exposure of the domical forms took place in the Early Cretaceous. Since then the bornhardts appear to have remained virtually unchanged. The bornhardts of this multicyclic landscape are thus of considerable antiquity.

CHAPTER 4 TECTONIC SETTING

4.1 INTRODUCTION

The Gawler Range Volcanics were extruded onto the Gawler Craton (Fig. 1.4), which is part of the tectonically stable Westralian Shield or Australian Craton. The present setting of the Volcanics can be regarded as stable, though not entirely devoid of tectonic activity, the Meckering Earthquake of 1968 (Everingham *et al.* 1969; Gordon & Lewis 1980), for instance, demonstrating that the Yilgarn Block or Province, one of the oldest segments of the Australian Craton, is still susceptible to faulting. But compared, for example, with the Adelaide Geosyncline to the east, the Gawler Craton is stable, experiencing only infrequent and minor diastrophism (Sutton & White 1968; Stewart *et al.* 1973).

The main body of the Gawler Range Volcanics is situated near the junction of geological provinces characterised by contrasted structural styles. The oldest rocks of the region are the Late Archaean to Early Proterozoic metasedimentary gneisses of the Mulgathing Complex, located to the northwest and west of the volcanic province, and the Sleaford Complex, situated to the southwest (Table 1.4; Fig. 1.3). These were intruded by Late Archaean to Early Proterozoic granitoids. To the southeast are exposed the Hutchison Group of sediments and the Myola Volcanics. Both were folded, metamorphosed and intruded during the Kimban Orogeny 1850-1600 Ma.

Middle Proterozoic sediments and volcanics, including the Gawler Range Volcanics, unconformably overlie the metamorphics and were gently folded during the Wartakan Event (Thomson 1969, p. 31). The sediments include the Tarcoola Formation and the Corunna Conglomerate, which are generally considered to have been deposited just prior to, or contemporaneously with, the effusion of the Gawler Range Volcanics (e.g. Preiss 1987, p. 35).

The post-tectonic Hiltaba Suite of granites intruded a variety of Middle Proterozoic and older rocks about 1585 ± 16 Ma (Creaser 1989, cited in Blissett *et al.* 1989). Consolidation of the crystalline basement of the Gawler Craton was completed about 1450 Ma (Preiss 1987, p. 37), and subsequent sedimentation adjacent to the Gawler Ranges was platformal. For example, the widespread Pandurra Formation, a fluvial felspathic sandstone (1424 ± 51 Ma: Fanning *et al.* 1983) was laid down to the east of the Gawler Ranges. Again, the flat-lying Tent Hill Formation, which gives rise to prominent plateau forms west of Port Augusta, is the lateral extension of the folded Late Proterozoic-Palaeozoic rocks of the Adelaide Geosyncline, but deposited on the stable Stuart Shelf (Fig. 1.4).

To the north and northeast of the Gawler Ranges, flat-lying Mesozoic (Jurassic and Cretaceous) sediments of the Eromanga Basin unconformably overlie Palaeozoic and older rocks, including the Gawler Range Volcanics.

Turning to geophysical characteristics, gravity trends of the Gawler Craton plotted by Wellman (1976) are meridional in the south but are oriented NW-SE in the area of the Gawler Ranges and become predominantly latitudinal to the north (Fig. 4.1). The outcrop of the Gawler Range Volcanics is coincident with a pronounced gravity high (South Australia, Department of Mines and Energy 1982a). The density of the Gawler Range Volcanics is, however, 2.65 compared with an estimate of about 2.8 for the surrounding rocks, suggesting that the gravity high is not related to the Gawler Range Volcanics, but possibly to a denser body, possibly gabbro, in the deeper crust or the mantle (K. Stewart, personal communication 1989).

Strong linear aeromagnetic anomalies trending NNW are a feature of the Stuart Shelf and shorter, less prominent linear anomalies of various trends can be discerned in what is a generally complex magnetic anomaly area (South Australia, Department of Mines and Energy 1982b).

Within and to the east of the Gawler Ranges the NNW trending magnetic anomalies are related to the Gairdner Dyke Swarm (Tucker *et al.* 1986), a series of dolerite dykes, provisionally dated as 1050 My old (Preiss 1987, p. 251). The dykes are inferred from aeromagnetic anomalies, but their presence is confirmed by drilling in several areas (see e.g. Elliott 1981) and by a rare outcrop in the central Gawler Ranges (N. Lemon, personal communication 1988). More detailed aeromagnetic surveys have located additional presumed dolerite dykes, some of which are coincident with NNW trending valleys within the Gawler Range Volcanics (D. Boyd, personal communication 1988). Two additional sets of dolerite dykes, one trending northeast and the other north, and extending as far west as Tarcoola and Streaky Bay, have recently been revealed by geophysical data. Their ages are unknown (R. Gerdes, personal communication 1989), so that their relationship with the Gairdner Dyke Swarm is not yet established.

The formations surrounding the Gawler Range Volcanics are traversed, and in some instances delimited, by major structures variously described as lineaments, hinge zones or faults. Though some, like the Torrens Hinge Zone of Johns (1968) and Thomson (1969, p. 25), have been shown to be faults (Fig. 4.2), most have been recognized from their presumed surface expression (see Appendix 2). For this reason, and for the sake of economy, the features are here referred to as lineaments. If

some, or all, of these lineaments are fractures, and if they are shear zones, they provide a possible explanation, not only for the orthogonal fracture systems at various scales, that have been identified within the Gawler Ranges, but also for sheet structure. These fracture systems are of fundamental importance in the development of the bornhardts. Horizontal dislocations along lineaments could produce sets of conjugate shears that are the regional and local fractures discussed in Chapter 5.

4.2 LINEAMENTS

4.2.1 Terminology

Hobbs (1904, 1911) applied the term lineament to significant lines in the landscape which reflect the presence of buried features of the rock basement. Hills (1946, 1961, 1963, p. 455) also used the term for topographic features that are essentially linear or only gently arcuate, that are of regional scale, and that reflect linear forms of various kinds in the underlying bedrock. Features giving rise to such forms include foliation, strike, faults and joints. Joints are fractures along which there has been no discernible displacement, whereas faults are fractures along which displacement has occurred. O'Leary *et al.* (1976, p. 1463) discussed the varied, and in some instances confusing, definitions of the term lineament recorded in the literature, and concluded that a lineament is best understood as 'some surface expression of a buried feature'. Lineaments so defined are not the same as geophysical lines derived from various geognostic features such as gravity anomalies (Wellman 1976), or geomagnetic trends and geological ingredients (O'Driscoll 1983, 1985). These geophysical features have no surface expression, even though they may be related to the structural grain of the area. Lineaments are intrinsically straight, of regional scale and are surface manifestations of deep-seated structures (Hobbs 1904, 1911; Hills 1963, p. 455; O'Leary *et al.* 1976). As they are straight or gently arcuate over long distances it can be assumed that they are essentially vertical in disposition.

Some authors, e.g. Ramberg *et al.* (1977), have suggested that the term lineament be restricted to features between 10 and 100 kilometres in length, referring to linear surface features less than 10 kilometres long as linears, and calling those greater than 100 kilometres long megalineaments. This convention is adopted here.

4.2.2 Global pattern

Lineaments have been recognised in all continents and their presence has also been demonstrated on the ocean floors (O'Driscoll 1980). They are particularly prominent in continental

cratons but are not restricted to them. They have been identified from quite varied terrains such as the tectonically active Western Cordillera of North America (e.g. Maughan & Perry 1986), and from more stable riverine lowlands (e.g. Sternberg & Russell 1952; Stauffer & Gendzwill 1987).

Plotting the patterns of lineament trends from many regions shows that certain orientations are widely developed; in particular NE-SW and NW-SE lines are prominent, though latitudinal and meridional elements are also significant (see e.g. Hobbs 1911; Hills 1963, p. 40; Thomas 1976; Holmgren 1976; Dikkers 1977; Johnson & Frost 1977). Whether the patterns identified in various parts of the world constitute elements of a global network is still debated. Vening Meinesz (1947), for example, showed a megalineament field occupying the entire Earth's surface dominated by diagonal (i.e. NW-SE and NE-SW trending) lines (Fig. 4.3) and O'Driscoll (1980) identified major trends which originate from the poles and spiral around the Earth. On the other hand, some workers have concentrated on lineaments developed within various specific regions (e.g. Daniels 1975; Thomas 1976).

4.2.3 Australian lineaments

The recognition and plotting of Australian lineaments resulted from Hills' construction of a relief model of the continent (e.g. Hills 1956; see Fig. 4.4). These lineaments fall into four major trends, namely NNW, NNE, ENE, and WNW. The WNW lineament is dominant in the crystalline rocks of the Shield, though the NNW trend is dominant overall. Hills' (1946, 1956, 1961, 1963) analysis suggested that most of the major features of the continent, e.g. major river channels, basin margins, mountain chains, coastlines, etc., are defined by lineaments.

4.2.4 Gawler Craton tectonic framework

A bewildering array of lineaments has been identified within and bordering the Gawler Craton (Dickinson & Sprigg 1953; Crawford 1963; Parkin 1969, p. 26; Thomson 1970; Firman 1974; Harrington *et al.* 1982; O'Driscoll 1986: Fig. 4.1, Fig. 4.5; see Appendix 3). In some degree the varied results can be understood in terms of the different sources of data (e.g. topographic maps, geologic maps and aerial photographs), and the different methods of analysis. But even allowing for such factors, it is difficult, in some instances, to determine what was plotted. If lineaments reflect structures in the underlying bedrock, then the results ought to be in substantial agreement. The various patterns obtained indicate the subjective nature of lineament studies.

Lineaments have been identified in the study area on topographic maps, geologic maps and aerial photographs, including satellite imagery (Fig. 4.6; see Appendix 2). The lineaments are of varied orientation but the dominant feature of the pattern is a set of north to NNW to NW trending megalineaments spaced some 20-30 km apart and traversing the entire area (a - g on Fig. 4.6; see also Fig. 4.7). The analysis of lineaments by number (Fig. 4.7A) shows the dominant trend falls within the range 145-150° (SSE; 150° i.e. the maximum trend within this range is 150° or SSE; see Appendix A2.1). Subdominant trends fall within the ranges 0-10° (N; 5°), 120-130° (SE; 125°) and 100-105° (ESE; 105°). Minor peaks occur at 75-80° (E; 80°) and 35-45° (NE; 35°). A similar result is obtained when the lineaments are analysed by length (Fig. 4.7B). The dominant trend falls within the range 130-155° (SSE; 150°), again with the mode at 150°. Subdominant trends range from 0-5° (N; 5°) with minor peaks at 100-105° (ESE; 105°), 75-80° (E; 80°) and 35-40° (NE; 40°).

The N-S trending megalineament located to the east of the area, (a on Fig. 4.6) and known as the Torrens Hinge Zone, is a well established fracture zone (Johns 1968). The NW trending lineament (f), along which is developed the Corrobinnie Depression, is also, almost certainly, related to fractures (Bourne *et al.* 1974), and the plots and rose diagrams of lineaments on the one hand (Fig. 4.6, 4.7) and faults on the other (Fig. 4.2, 4.8) are comparable. All these megalineaments may be genetically related as there is a gradual swing in orientation from north in the east, to NNW in the centre and NW in the western part of the area. But the nature of many lineaments remains unexplained.

4.3 ORIGIN AND AGE OF LINEAMENTS

Various planetary theories, involving stresses induced by variations in the behaviour of the Earth as a planet (e.g. Badgley 1965, p. 117; Thomas 1976; Ramberg *et al.* 1977; O'Driscoll 1980, 1982; Wopfner 1985), have been invoked to account for lineaments. Some workers, like O'Driscoll, considered that planetary stresses are capable of initiating them. Others, like Badgley, were more conservative, and suggested that planetary stresses are only capable of rejuvenating such fractures once they have formed. Some authors, and particularly Soviet geologists (e.g. Belousov 1961; Belousov *et al.* 1989; see also Hills 1946, 1963, p. 357; Brock 1966; Burns & Shepherd 1976; Kisvarsanyi & Kisvarsanyi 1976) relate major deformations of the crust including lineaments, to vertical dislocations arising, for example, from density variations. Most workers, however, attribute

lineaments, as well as folding, faulting and some joints, to large-scale horizontal movements (e.g. Moody & Hill 1956; Badgley 1965; Holmgren 1976; Thomas 1976; Wopfner 1985).

Large-scale disruptions have been described from many areas. They include strike-slip faults like the San Andreas Fault of California, U.S.A., and the Alpine Fault of New Zealand (Billings 1972, p. 261-276) that are active at present. Many others, however, can be regarded as dormant and are subject to only minor disruptions.

Major dislocations have also been described from various parts of Australia (Hills 1946; Rod 1966; Daniels 1975, p. 438; Katz 1976). For example, Austin and Williams (1978) suggested that for late Precambrian to Mesozoic times the pattern and style of the Australian continent could be explained in terms of dextral shear and/or compressive stresses between major subcontinental blocks. Again, Veevers (1984, p. 278) described the deformation of the continent along the Tasman Line (the boundary between the Precambrian terrains to the west and the wholly Phanerozoic terrains to the east) that took place 650-575 Ma, in terms of horizontal movements associated with regional dextral shear followed by plate divergence.

Whatever the ultimate causes of lineaments and irrespective of their azimuth, the presence of such features is likely to have influenced later deformations. Depending on the stress regime, systems of fractures decreasing in scale are likely to develop as stress accumulates. Their patterns will be geometrically and genetically related to the preexisting zones of dislocation. Lineaments are, in this sense, the fundamental elements of the tectonic framework of a region.

The age of these lineaments is nowhere precisely defined, though many workers intuitively believe them to be of great antiquity, viz. of Proterozoic or earlier age (e.g. Hills 1946; Rod 1966; Daniels 1975, p. 438; O'Driscoll 1983). Within and surrounding the Gawler Ranges, lineaments affect rocks of a considerable age range. Materials that are older than the Gawler Range Volcanics are affected as are younger strata. It could be suggested that lineaments are comparatively youthful developments - even very youthful, for lineament trends have been plotted, for example, in Miocene sediments of the Murray Basin (Firman 1974). On the other hand, the development of lineaments in such young formations could be attributed to underprinting from the basement (i.e. resurgent tectonics - see Hills 1963, p. 365). In the present context, perhaps the best argument for the antiquity rather than youth of the lineaments, is that both the extrusion of the Gawler Range Volcanics and the intrusion of the Hiltaba Granite were controlled by fractures that form part of the lineament pattern

(Blissett 1985). Likewise, the geometry of the Gairdner Dyke Swarm and of the regional scale fractures of the Gawler Ranges (see Chapter 5) may be related to that of the lineaments. The Gairdner Dyke Swarm is about 1050 My old, and the regional scale orthogonal fractures predate the Pandurra Formation, i.e. pre 1424 Ma (see Chapter 5), for the Pandurra was deposited in NW-NNW trending grabens. Thus, the regional fracture systems and the associated lineaments must be at least of Middle Proterozoic age.

The lineaments are, therefore, considered as the primary features of the regional tectonic framework. Dislocation, particularly shearing, along these fractures, may have imposed strain in the adjoining blocks, resulting in smaller scale fractures, namely the orthogonal systems, some columnar joints and possibly also the sheet fractures.

Each fracture system has been exploited by weathering and erosion, and has thus contributed to the shaping of the bornhardts. These systems are described in order of scale, from largest to smallest. This sequence is not the same as their order of formation, for some, at least, of the columnar joints must have formed in the Middle Proterozoic as the volcanic material cooled and contracted and thus predate the orthogonal systems. The age of the sheet fractures is more difficult to determine, as their age relationships are dependent on their interpreted mode of origin; but it seems likely that sheet fractures were present as early as the Jurassic, when deep weathering of the volcanic massif took place.

CHAPTER 5 ORTHOGONAL FRACTURES

5.1 INTRODUCTION

Whether viewed from space or from an aeroplane flying at high altitude, the most striking feature of the Gawler Range Volcanics is the subdivision of the uplands by linear valleys that together form square, rectangular, rhomboidal or occasionally triangular patterns. Such systems aligned normal to one another (or approximately so) are conveniently referred to as 'orthogonal' (i.e. at right angles to each other). The shape and size of the hills and ranges thus isolated is determined by the geometry of the linear or gently arcuate valleys that are inferentially developed on the orthogonal fracture systems (Fig. 5.1; Frontispiece, Pl. 1.3).

The straightness of the valleys and the patterns they form (Fig. 5.2) are also, in some degree, evident in the field, but because all major valleys are underlain by regolith it is not possible to observe the bedrock beneath. Hence the reason for the linearity of the valleys cannot be ascertained. The most obvious explanation for such linear depressions is that they are due to the exploitation by weathering and erosional agencies of fracture zones. The reality cannot be observed so the validity of this claim cannot be tested. On the other hand, it is difficult to envisage any other causative factor on a regional scale.

As has been pointed out by Hills (1963, p. 365) it is frequently difficult to determine whether a fracture is a fault or a joint. This is particularly so in crystalline rocks lacking the compositional layering that can indicate the amount and sense of dislocation. Some displacements of volcanic layers have been mapped in the Gawler Ranges, e.g. southwest of Yardea H. S. (Blissett 1987; Fig. 1.3). Overall, the regional scale fractures, although termed joints by some (e.g. Smith 1976; Blissett 1985), probably involve at least minor dislocations and are therefore faults. Elastic rebound (or dislocation characterised by a return to the original position of the blocks relative one to another) may be involved. Apart from two fragments of quartz breccia found in the Uno area by Turner (1975), no geological or topographic features characteristic of faults, apart from the linear clefts themselves, have been found in any of the valleys.

Thus it is concluded that major valleys coincide with regional scale orthogonal fracture systems which are widely developed in brittle rocks such as granite (e.g. Hodgson 1961a; Nickelson & Hough 1967; Gerrard 1974; Engelder & Geiser 1980).

5.2 GEOMORPHOLOGIC SIGNIFICANCE OF FRACTURES

Most geomorphologists agree that the presence of fractures is a significant factor in the evolution of the landscape. For example, Rognon (1967, p. 275) wrote that '*...les diaclases gardent un rôle primordial en influencent le modélé granitique...*' and Birot (1952, p. 301) has stated that '*...le facteur le plus important de l'érosion différentielle paraît être la densité des diaclases et la multiplicité des lignes de fracture.*'

In addition to the direct effect of mechanical destruction of the rock, fractures or fracture zones are avenues along which meteoric waters can penetrate and in which groundwaters can circulate. They are thus planes along which weathering takes place. How readily depends on whether the fractures are open or tight.

The relative significance of the fractures depends on the permeability of the bedrock in which they occur. Fractures attain their greatest significance in rocks of low permeability such as granite and crystalline limestone. The Gawler Range Volcanics are also of this type. Fractures diminish in importance in materials that are permeable, but everywhere they are significant in the geomorphologic context.

In some instances minerals are precipitated within the fracture or fracture zone, so that the latter become impregnated and resistant, giving rise to major or minor ridges, the box-work pattern of which reflects that of the fractures (e.g. Young 1988). But far more commonly fractures are zones of weakness along which water-related weathering is concentrated. Solution, hydrolysis and hydration are prominent (see e.g. Loughnan 1969; Birkeland 1974, p. 52-80; Nesbitt 1979; Nesbitt *et al.* 1980; Beavis 1985). In addition, chemicals and biota, both of which achieve or contribute to the alteration of rocks (see e.g. Trudinger & Swaine 1979; McFarlane & Heydeman 1984), are carried in the groundwaters.

The rocks adjacent to fractures are altered and weakened and when the regolith is evacuated clefts (or slots) or valleys are developed coincidentally with the fracture traces, depending on the scale of the feature involved. The blocks between fracture zones remain upstanding, though, because of the preferential attack of their corners and edges, blocks tend to become rounded.

The earliest study of the geomorphologic significance of fractures is due to Daubrée (see Hobbs 1911), and since then there have been many studies concerned with the relationship of fractures to drainage patterns and topography (Judson & Andrews 1955). It has long been recognized that stream

directions are strongly controlled by fracture trends (e.g. Hobbs 1905; Sheldon 1912; Zernitz 1930; Auden 1954a, 1954b; Gerrard 1974; Aghassy 1970; Bannister 1980). In contrast, Pohn (1983) has demonstrated that in New York and Pennsylvania, U.S.A., the streams in flat-lying rocks are generally joint-oblique. Nevertheless, more commonly there is a close relationship between drainage and fracture patterns.

Fractures are patently crucial to the two-stage development of bornhardts, since it is the fracture systems which have determined the course of weathering. The compartments of rock have been differentially weathered according to their fracture densities: massive compartments remain intact and project into the base of the regolith. Stripping of the regolith has exposed the projecting masses as bornhardts. The genesis and age of the bornhardts are therefore related to the fracture systems on the one hand, and to differential weathering on the other.

5.3 CHARACTERISTICS OF THE REGIONAL SCALE ORTHOGONAL FRACTURE SYSTEMS

Major valleys are developed along regional scale orthogonal fractures which thus define the blocks on which the bornhardts are developed. In this manner, the fractures control, in a general way, the maximum size and the shape of the residuals, but the actual dimensions and rounded plan form reflect the differential weathering of the fracture-defined blocks. Other fractures determine the orientations of lake margins and sections of the drainage network (Fig. 5.2).

Some of the regional scale orthogonal fractures coincide with lineaments (Fig. 4.6; see Appendix 2). The NNW trending lineament southwest of Lake Gairdner (d on Fig. 4.6) is an example, for it is present on both the lineament and the fracture plots. Other fractures are oriented parallel to lineaments; some are aligned at an acute angle to them.

Their pattern is especially apparent in the more rugged topography, where the hills are higher and the valleys narrower than in areas of more subdued relief. But even in the latter, for example northeast of Barker Hill, the pattern of wide valleys alternating with low hills is in alignment with the fracture system in the adjacent more rugged terrain (Fig. 5.1).

The fracture pattern transects without interruption the gently inclined layered rock units and also extends without break through various members of the volcanic sequence. This is particularly evident in the southern Gawler Ranges where the fractures are continuous through the Nonning Rhyodacite, the Eucarro Dacite and the Yardea Dacite. The orthogonal fracture pattern also extends from

exposures of Gawler Range Volcanics into the Hiltaba Granite. For instance, in the Kondoolka area a single coherent fracture system subdivides the Eucarro Dacite and Yardea Dacite as well as the granite (Fig. 5.3). Even where the granite topography is more subdued and the valleys between the hills are broader, as in the Hiltaba area, a similar continuity of fracture patterns between volcanics and granite can be identified.

The dominant trend of regional scale orthogonal fractures in the Gawler Ranges (Fig. 5.1; Fig. 5.4; see Appendix 2) analysed by total number is 135-155° (145°), i.e. 135-155° from grid north with the mode at 145°. Subdominant trends at 165-200° (185°) and 30-50° (45°) also occur. The dominant trend analysed by total length is again 135-155° (145°) with a subdominant trend at 5-45° and a minor peak at 170°.

The regional scale orthogonal fractures of the Gawler Ranges are thus concentrated in NW-NNW (135-155°) and N-NE (5-55°) preferred orientations. They are generally spaced 1-5 km apart and range from 1-10 km in length. Their linearity and distribution are consistent with a vertical attitude. Though most are orthogonal, the preferred development of one or other of these sets, or of an additional set of diagonal fractures, in some areas has produced triangular or rhomboidal patterns.

The fracture pattern varies regionally throughout the Gawler Ranges (Fig. 5.1). A detailed analysis of linears i.e. fractures less than 10 km long (Fig. 5.5; see Appendix 2) for selected upland areas (Fig. 5.6), indicates that the NE and NNW sets are represented in most of the uplands, but the relative importance of each set varies in each of the seven hill regions analysed. For example, in the Kolendo Upland the dominant trend is NE (40-45°), with NW and NNW orientations also important. In the Moonaree Upland the dominant trend is north (0-5°) with NE and NNW trends subdominant. In some instances the patterns grade imperceptibly from one region to the next. For example, the north, NE, east and NW trends in the Yardea Upland gradually change towards the Hiltaba Upland where NW and northerly trends are dominant (Fig. 5.5, 5.6).

5.4 ORIGIN

Several geologists and geomorphologists have discussed the pattern of regional fractures in the Gawler Ranges in general terms.

Turner (1975) interpreted the fractures defining the valleys in the Uno area, in the southeastern Gawler Ranges, as faults. The attitude of columnar joints which are now slightly inclined, but which

were presumed originally to have been vertical, suggested to Turner that the blocks had been tilted. Quartz-cemented breccias present at two sites in valleys between the uplands were interpreted as fault breccias. Thus Turner suggested that the regional linear fractures defined blocks which had subsided en echelon and were tilted to the south and west about a WNW trending axis.

Smith (1976) discounted Turner's (1975) interpretation. She pointed out that nowhere else in the Gawler Ranges is there evidence for large-scale differential movement along the fractures, and suggested that the fractures are due to shear and developed in the manner described by Cloos (1955), i.e. as a result of compression and tension from two orthogonally opposed directions.

The terminology used by Smith is misleading, as shear fractures involve relative displacement of the blocks on either side of the fracture. They are therefore faults. This confusion of terms is repeated in Blissett (1985) who referred to the features as joints, but also described them as conjugate fracture zones, thus apparently recognizing the possibility of some dislocation.

As with lineaments, it is difficult to identify what caused the regional scale orthogonal fractures. Planetary stresses (see Chapter 4) and either vertical or horizontal stresses generated within the Earth may be responsible. If vertical stresses were responsible, they must have been of very small amplitude, for there is no evidence of large-scale vertical dislocations such as have occurred, for example, along the Darling Scarp, Western Australia (Playford et al. 1975, p. 227).

The pattern of regional fractures is consistent with their being due to horizontal stresses in the crust. The stress fields responsible for fracture patterns can be resolved by classifying the fractures into sets according to their orientation, attitude and surface features such as striations and fillings (see Davis 1984, p. 348). Conjugate fractures form under plane strain conditions of brittle failure in an environment of differential stress. The stress acting on a point can be referred to three mutually perpendicular axes known as the principal (sic) stress axes, Θ_1 , Θ_2 and Θ_3 , with Θ_1 the greatest and Θ_3 the least principal stress. The classic interpretation is that conjugate fractures intersect in the axis of intermediate stress (Θ_2), with the axis of greatest principal stress (Θ_1) splitting the acute angle between the conjugate fractures (Fig. 5.7). Such fractures are due to shear, and are, strictly speaking, faults, for dislocation is involved. Tensional fractures (Fig. 5.7) that form during brittle failure, on the other hand, are disposed at right angles to the direction of least principal stress (Θ_3).

These conventional methods for relating stress and strain apply to a homogeneous, unfractured medium. If the crust is segmented, the deformations are reoriented according to the zones of

weakness present (see e.g. Thomas 1974). The results of experimental analyses, for example by Mead (1920) and Cloos (1955), cannot readily be extrapolated to a particular field area.

In the Gawler Range Volcanics the regional scale fractures are not visible, and, in the absence of fracture-related features such as veins and striations (Davis 1984, p. 333), it is impossible to differentiate between fractures originally due to tension or to shear. It was also found impossible to determine the relative age of the fractures by offsets in plan pattern. As there is no proof of equal age of apparently conjugate sets, their angles of intersection cannot be used as a basis for interpretation of the mechanics of their formation.

Movements along a major shear zone can result in second order shears which are aligned at various angles to the primary shear (Willis 1923; McKinstry 1953; Enlows 1955; Billings 1972, p. 274). Dislocations resulting in second order fractures both in parallel with, and at an angle to the major fractures have been described. In French Guyana, for example, Choubert (1974) cited fracture patterns parallel to lineaments, and Johnson and Frost (1977) described various fault sets diagonally disposed to wrench faults such as the great Glen Fault of Scotland. Moody and Hill (1956) showed that in addition to second order shears, third order shears can be developed from a single primary compressive stress orientation.

These studies demonstrate that the origin of the regional scale orthogonal fractures of the Gawler Ranges is complex. The testing of the various hypotheses is beyond the scope of this study. All that can be said is that the fractures are, most probably, due either to tension or to shear. Although there is ample opportunity for the direction of stress to rotate and, at each new orientation, a new set of tension joints to be formed, a simpler explanation, and the one that is favoured in light of the many examples cited both in Australia and overseas, is that the fractures are related to shearing along lineaments.

In addition to the fractures which form part of the regional scale network, and must, therefore be due to some general and widespread effect, some features may be due to more localized factors. For example, Lake Acraman may occupy the site of a meteorite impact (Williams 1986, 1987), and the apparently circular structures centred on Lake Acraman (Fig. 5.8) may be correlated with shock wave depressions. Radial fractures are not present. They are found associated with some impact structures, e.g. the Steen River astrobleme, Alberta, Canada (McCall 1977, p. 214) and the Wells Creek structure, Tennessee, U.S.A (McCall 1977, p. 314), but are not invariably found in association

with impact craters. Moreover, only the lower zones of deformation related to the Acraman impact survive. Also, the Yardea Dacite is highly fractured, so that the stresses that may have produced radial fractures may have been dissipated. Yet, it seems reasonable to find radial fractures in the Yardea Dacite.

An alternative explanation for the circular structures is that they are due to caldera collapse associated with the extrusion of volcanic material (Crawford 1963, see Fig. 4.5B; Giles 1977; Branch 1978), although to date no centres of eruption have definitely been located to test this theory (Blissett 1985).

The circular structures can also be interpreted as comprising linked linear sectors of the various orthogonal, rhomboidal or triangular systems (Fig. 5.9). This idea is implicit in the description by Mainguet (1968) of corridors in the Borkou area, southern Sahara, French Equatorial Africa, in the formation of which a series of straight joints has been exploited by water and wind erosion to form curvilinear depressions and corridors.

5.5 AGE

If the localized effects, i.e. meteorite impact and caldera collapse, were responsible for the formation of some of the orthogonal fractures, the implied age of the features is relatively simple to determine. The Lake Acraman meteorite is believed to have impacted 600 Ma as fragments of the Gawler Range Volcanics were ejected and deposited some 300 km to the east in the 600 My old Bunyeroo Formation in what is now the Flinders Ranges (Gostin *et al.* 1986). Or, if the fractures are related to caldera collapse they must have formed soon after the extrusion of the Gawler Range Volcanics, and are therefore of Middle Proterozoic age.

On the other hand, if the fractures are due to tension or shearing associated with lineament dislocation, their age is more difficult to define, if only because of the possibility of underprinting, or resurgent tectonics. The fractures must be younger than the material in which they are developed, but are older than any intrusives emplaced along them. Thus, rhyolite dykes, associated with, and of the same age as the Gawler Range Volcanics are intruded along NNW trending fractures in the Corunna Conglomerate and Hutchison Group, south of the Ranges (Parker *et al.* 1985, p. 36), so that the fractures are younger than the Corunna Conglomerate and the Hutchison Group respectively, but predate the Gawler Range Volcanics. Again, dykes of silicic composition, and considered to be

comagmatic with the Hiltaba Granite, intrude rocks even as young as the youngest units of the Gawler Range Volcanics. They are intruded along fractures that trend north and NE in the Childara area (Blissett 1980); NNW in the Glenloth area; NNW and NNE between Kokatha H.S. and Lake Gairdner; and NNE near Everard H.S. (Blissett 1985). All of these fractures are younger than the latest stage of the Gawler Range Volcanics but are older than the Hiltaba Granite.

To the east of the Gawler Ranges, the Pandurra Formation was laid down on a surface that was already differentially weathered and eroded in the Gawler Range Volcanics. Fracture-controlled valleys were in existence and deposition was concentrated in NNW trending grabens. These fractures must therefore postdate the Gawler Range Volcanics in this area and predate the Pandurra Formation, (i.e. 1424 Ma; Preiss 1987, p. 37). Again, the Gairdner Dyke Swarm was intruded along preexisting NNW trending fractures about 1050 Ma. Thus, many, probably most, of the fractures were in existence by the Middle Proterozoic.

5.6 SMALLER-SCALE ORTHOGONAL FRACTURE SYSTEMS

The slopes of many of the bornhardts of the Gawler Ranges are scored by minor valleys. They are large enough to be visible on aerial photographs (scale 1:80,000), but are not readily apparent on satellite imagery (scale 1:500,000). The valleys are linear, and because of their geometric relationship to each other and to the regional scale orthogonal fracture systems, they also are interpreted as related to fractures (Fig. 5.10, 5.11). The linear valleys in the Spring Hill, Kolendo and Yardea East areas were plotted from contoured maps at 1:100,000 scale and from aerial photographs at 1:86,000 (Fig. 5.10) and rose diagrams were drawn illustrating the analysis by number and by length.

The dominant trend of these inferred fractures at Spring Hill, when analysed by number, falls within the range $130-175^{\circ}$ (145°) with a subdominant trend within the range $45-60^{\circ}$ (45° ; Fig. 5.11A1). When analysed by length a similar result was obtained with the dominant trend again $130-175^{\circ}$ (145°) and with a minor peak at 55° (Fig. 5.11A2). In the Kolendo area, when analysed by number, the dominant trend of the inferred fractures is $90-105^{\circ}$ (105°) with a subdominant trend within the range $135-155^{\circ}$ (140° ; Fig. 5.11B1). When analysed by length the relative importance of the peaks is altered with the dominant trend within the range $50-55^{\circ}$ (50°), and with subdominant trends at $135-140^{\circ}$ (140°) and $150-160^{\circ}$ (160°) and a minor peak at $90-105^{\circ}$ (90° ; Fig. 5.11B2). In the area east of Yardea H.S. the dominant trend is $75-110^{\circ}$ (95°), with a subdominant trend from $45-55^{\circ}$ (50°)

and a minor peak at 150-155° when analysed by number (Fig. 5.11C1), and when analysed by length the trend from 35-55° (50°) is dominant and the trend from 80-110° (95°) is only slightly less frequent (Fig. 5.11C2).

Whether these minor valleys are located along fractures, and therefore are directly related to them, can be determined in the field. The axis of many of the valleys, for much of their length, is marked by outcrops of relatively fresh material in which the pattern of vertical fractures is readily seen. Fractures are everywhere present, but the relationship of the valleys to the fractures is not, in many cases, a simple and direct one.

Several types have been observed (Fig. 5.12). First, in some valleys, for example Kolay Valley, the relationship is direct, for a fracture zone some 0.5 m wide and consisting of tens of parallel fractures several centimetres apart and oriented north-south, coincides with the axis of the valley (Pl. 5.1; Fig. 5.12A). A similar fracture zone marks the axis of the nearby NW-SE trending valley.

Second, the axis of some valleys is located at the contact between two steeply dipping sheet fractures (Fig. 5.12B). A vertical joint parallel to the valley axis is apparent at some of these contacts as, for instance, at Peterby Hill (Pl. 5.2).

Third, some minor valleys are located in or near the base of a synformal sheet structure (Fig. 5.12C). The clearest example of this type is in a minor valley in the west of Spring Hill (Pl. 5.3). This synformal structure is complicated by a repetition of at least three basin-like sheet structures aligned along the axis of the valley at progressively higher levels (Fig. 5.13). The trace of vertical fractures is readily apparent on the exposed sheets. The dominant features of the pattern are a system of pentagonal fractures which meet at Y intersections and a cross-cutting set of parallel fractures aligned perpendicular to the valley axis. Few fractures are aligned parallel with the valley axis (Fig. 5.14A). In other valleys the simple synformal relationship is apparent only in part of the valley, for example at Peterby Hill.

In many, perhaps most, of the minor valleys, vertical fractures making rectangular, rhomboidal or irregular patterns are evident on outcrops, but there are few examples of an obvious preferred orientation parallel to the valley (Pl. 5.4). An explanation for the location of these valleys is more difficult to determine. Those minor valleys not directly related to either parallel fracture zones, or to sheet structure may be located in zones of more intense fracturing than that on the valley sides and summits (Fig. 5.12D). This suggestion is not supported by site scale fracture analysis discussed in

Chapter 7. Or, the fractures in the valleys may be more open (less tightly closed) than on the slopes, and hence allow weathering and erosion to penetrate more readily into the rock (Fig. 5.12E). Or, the location of the minor valleys may reflect the disposition and nature of fractures that were present in the higher now eroded parts of the rock (Fig. 5.12F). In other words, the density of fracturing may vary with depth, as it does areally, and the river has persisted in its course. However, Blès (1986; see also Twidale 1987) has demonstrated that fractures in granite at the surface are comparable in orientation and density to those at depth, and a similar distribution may apply in the Gawler Range Volcanics.

Thus, some at least of the minor valleys are related directly to local scale vertical fractures. These local fractures are probably genetically related to the regional scale orthogonal systems, and, if so, were probably also formed during the Middle Proterozoic. The local fractures must have formed prior to the dissection and erosion of the major valleys which border the bornhardts (i.e. prior to the Early Cretaceous), since the rocks in the bornhardts must have been confined to have been placed under stress. Some of the valleys are related to sheet structure, which may also be of similar age (see Chapter 6).

At a smaller scale than the local orthogonal fractures, traces of site scale fracture systems are apparent on rock outcrops on the crest of bornhardts, on valley side slopes and in minor valley floors (Fig. 5.14; Pl. 5.4). These site scale fractures are predominantly vertical, and commonly occur in parallel sets or form complex orthogonal systems. The traces of columnar joints that meet at triple point, or Y intersections are clearly discernible at some sites (Fig. 5.14A). Nonsystematic joints are also present. Many of these joints have been exploited by weathering and are exposed in the landscape as columns and cliffs: they modify the detailed slope profile of the bornhardts. These columnar joints are described and discussed in Chapter 7.

CHAPTER 6 SHEET FRACTURES

6.1 INTRODUCTION

The domical profiles of the Gawler Ranges are associated with convex-upward curvilinear fractures that run approximately parallel to the land surface (Pl. 2.2, 6.1). In granitic terrains these convex-upward fractures, here termed sheet fractures, are characteristic of, and are apparently genetically related to inselbergs, and especially to bornhardts (e.g. Twidale 1982a, p. 150). Their influence can also be seen in the boulder-strewn residuals known as nubbins or knolls (Twidale 1981a).

The characteristics of sheet fractures in granite have been widely discussed (e.g. Merrill 1898; Dale 1923; Ljunger 1930; Jahns 1943; Twidale 1964, 1971, p. 59-90, 1982a p. 49-55). Though well and commonly developed in granitic materials, they have also been reported from other plutonic rocks such as norite, syenite and diorite, from metamorphic terrains and from sedimentary materials such as arkose, sandstone, conglomerate and limestone (Bradley 1963; Twidale 1973, 1978). Occurrences in volcanic rocks are, however, less well known.

Sheet structure is characteristically developed in massive rocks, i.e. in rocks which, though not lacking joints, do not display open fractures. In some places the slabs of rock are 10 m thick. Where exposed they tend to increase in thickness with depth (Dale 1923), but this is not everywhere the case. Sheet fractures have been observed to depths of at least 100 m in quarries (Dale 1923, p. 23; Twidale 1971, p. 63) and they occur in tunnels and mines at even greater depths beneath the surface (e.g. Moye 1958; Leigh 1967). They have been reported from all climatic regimes (Twidale 1964).

Sheet fractures have been described and discussed under many names. Flat-lying joints, gently dipping joints, Lägerklufte and Bankung, are frequently used to describe more or less horizontal primary fractures in intrusive masses, but structures en gros bancs, stretching planes, shells, pseudobedding, offloading joints, relief of load joints, topographic joints, pressure release joints, exfoliation and sheeting joints have also been used in a more general context (Price 1966, p. 160; Twidale 1973, 1982a, p. 49). Some of these terms have obvious genetic implications (e.g. offloading joints) and a purely descriptive term such as sheet fractures is preferable. The rock mass which is divided by sheet fractures into slabs or sheets, is said to display sheet structure.

Sheet fractures are not to be confused with thin laminae, i.e. banks of closely spaced fractures defining flakes that vary in thickness from a millimetre to a few centimetres. These are frequently developed both in outcrop and at depth particularly in crystalline rocks, but also in quartzite. Such lamination has been attributed to expansion of biotite on weathering (Folk & Patton 1982), but this cannot be of universal application, for lamination is developed in rocks like quartzite lacking biotite or any other mica.

6.2 GENERAL CHARACTERISTICS

6.2.1 Relation to topography

Sheet structure is widely developed in the Gawler Range Volcanics. It occurs to a greater or lesser degree in all the hills observed. Hillslopes consist of banks of truncated or partially overlapping slabs. Some give rise to short convex-upward bedrock slopes bounded on the lower side by cliffs up to 10 m high in which vertical fractures defining columns of rock are well exposed (Pl. 6.1B). Others form rock benches bounded by debris covered slopes. Near the summit of the hills the sheet structure is exposed in horizontal benches. In the minor valleys which score the hills the fractures are generally synformal (Pl. 5.3), though in places, e.g. near Eucarro Dam and at Peterby Hill, convex-upward sheet fractures are exposed in the valley floors (Pl. 6.2; Fig. 6.1). In other minor valleys the sheet fractures dip towards the axis of the valley (Pl. 5.2). In the Gawler Ranges no examples are known of the converse, i.e. a topographic high being underlain by a structural low or synform, though such have been reported from other parts of the world (Twidale 1971, p. 66).

6.2.2 Geometry of sheets

The dip of sheet fractures varies, both in the one sheet and from one exposure to another, from almost horizontal to as much as 40° from the horizontal (Pl. 5.3), although more commonly the range is between $5-20^{\circ}$.

In some exposures the sheet fractures are disposed essentially parallel to one another, as reported from many other areas (e.g. Dale 1923; Bradley 1963), though a tendency to non-parallelism and wedging has been suggested at some sites (e.g. Twidale 1964). In the Gawler Range Volcanics there are significant departures from parallelism between adjacent fractures. In fact, sheet fractures commonly tend to divide the rock mass into a series of lenses (Pl. 6.3A), each lens being about 4-30 m across and 1-8 m high. In places the geometry of sheet structure is irregular (Pl. 6.3B). The floor of

a valley cut in Peterby Hill displays swells and angular depressions which reflect the varied local disposition of the sheet fractures (Fig. 6.1). The adjacent sheets, though of similar morphology, are offset, with the swells being located above the depressions of the lower sheet, and so on.

The maximum thickness of sheets developed in Gawler Range Volcanics is 3 m. Sheets cannot be said consistently to increase in thickness with depth. In many surface exposures, for example at Spring Hill (Pl. 6.4), sheets of about 1m thickness are underlain by thinner (10 cm) sheets. Moreover, deep exposures are rare, so that it is not possible to comment on either the existence of sheet fractures at depth, or any variation in thickness with depth. Evidence from Mt Cooper suggests that surface appearances may be misleading, however, for there sheet structure is well displayed in outcrop but is not obviously developed in quarry exposures (Pl. 3.3, 6.5).

6.2.3 Nature of sheet surfaces

The partings between the sheets are clean and essentially fresh, with little or no weathering of the adjacent rock. Polished surfaces, slickensides and the offsetting of columns have been noted at a few sites (e.g. Spring Hill, Pl. 6.4), suggesting that here at least, there has been lateral dislocation along the sheet fractures. Generally, however, there is no evidence of relative movement.

6.2.4 Relation to other fractures.

Joints of various types are ubiquitous in the volcanic rocks of the Gawler Ranges, and sheet joints are best developed where other joints, although present, are tightly closed (e.g. traces of vertical joints on the exposed benches which are coincident with sheet joints).

Though locally variable, sheet fractures tend to be essentially flat-lying on the crest of the domical hills and to increase in declination downslope towards the base of the hill, and thus towards the major valleys that are associated with linear fractures of the regional orthogonal system, or towards the minor valleys which score these hills and many of which are also fracture-defined (Fig. 2.1; Pl. 5.2). The confinement of sheet structure within these orthogonal blocks suggests that the sheet fractures are either contemporaneous with, or younger than the regional fractures.

The association of sheet fractures and vertical columnar joints (see Chapter 7) imparts a stepped profile to many of the hill slopes. The sheet fractures coincide with the treads of the steps, on which the traces of the columnar joints are readily apparent. Some sheet fractures terminate abruptly against the columnar joints, although many merge with the sheet fracture above or below (Pl. 5.3). At Spring Hill and Kolay Valley the sheet fractures cut through columnar joints the geometry of which

suggests that they are due to contraction on cooling. This relationship implies that sheet fractures postdate the formation of columnar joints and thus the consolidation of the lava. This is to be expected as fractures only form in brittle materials. At Peterby Hill sheet fractures transect columnar joints that are considered to be due to tectonism. Here, obviously, the sheet fractures must postdate the tectonic columns.

Other lines of evidence confirm this relative age. First, the columnar joints are consistently vertical and are not arranged radially within the lenticular masses defined by sheet fractures (Fig. 6.2A; Pl. 2.3, 6.3A). If the columns evolved after the formation of the sheet structure, they ought to be radially disposed and perpendicular to the sheet fractures, as would be expected if the vertical joints postdated the sheet fractures (Fig. 6.2B).

Second, the examples of offsetting of columnar joints by movement along the sheet fractures and the development of slickensides on the surfaces of contact indicate lateral movement. If this movement were associated with the formation of sheet fractures, as seems likely, then the vertical joints must have been in existence at the time of, or prior to, the formation of sheet fractures.

6.3 ORIGIN

6.3.1 Introduction

Many hypotheses have been suggested to account for sheet structure. However, most of the explanations are as implausible in the context of the volcanic bornhardts of the Gawler Ranges as they are in general. The suggestions that sheet fractures are related to insolation (Shaler 1869; MacMahon 1893; see also Lewis 1954; Ollier 1971; Winkler 1987; Folk & Patton 1982) or to chemical weathering (Blackwelder 1925, 1933), for example, are not supported by the field evidence. Some hypotheses are even less rational in the particular context of the volcanic province than they are in the general. Thus those explanations relating sheet structure to a mechanism of intrusion (e.g. de la Beche 1839; Holmes & Wray 1912, 1913; Brammall 1926; Kranck 1957) are irrelevant because the volcanics exposed in the Gawler Ranges are extrusive. Similarly, since the volcanics are unmetamorphosed, the suggestion that sheet fractures are related to metasomatic expansion (Brajnikov 1953) is inappropriate.

Two opposed major interpretations have arisen concerning the relationship between the shape of bornhardts and the geometry of sheet fractures. Some workers who support the offloading, or

pressure release hypothesis, argue that the topography determines the disposition of the sheet fractures, whereas those who attribute the sheet structure to lateral compression, believe that the structure gives rise to the form of the land surface. Plausible arguments have been brought to bear in support of both points of view (e.g. Twidale 1982a, p. 150-158).

In addition to these more general arguments, however, the setting of the Gawler Ranges has stimulated one explanation based on the structure of the volcanic sequences themselves.

6.3.2 Sheet fractures as boundaries to individual cooling units

Turner (1975) assumed that the low angle joints present in the Uno area '...formed in the plane of the cooling surface,' and, later, Giles (1980) suggested that sheet fractures are coincident with flow or cooling surfaces preserved within the Gawler Range Volcanics. The Gawler Ranges consist overwhelmingly of ashflow tuffs. These formed from pyroclastic flows ejected from vents at high temperatures. The flows consisted of solids and gases which, because of their high density flowed under gravity across the land surface. On deposition, various processes may have contributed to the development of vertical zonation. For example, some vertically zoned volcanic piles, including ash flow tuffs, reflect subtle variations in chemistry, mineralogy, degree of welding and in degree and rate of devitrification (Barker 1983, p. 174; Cas & Wright 1987, p. 223).

Overall the Gawler Range Volcanics do not display obvious zonation. The Yardea Dacite, the most widespread of the volcanic units, consists of two or more cooling units separated by a distinctive black dacite (Blissett & Radke 1980), but its composition is nevertheless remarkably uniform (Blissett 1975, 1985). Vertical layering is, however, discernible in the Eucarro Dacite of the Hiltaba area and in Toondulya Bluff, where the petrological zones are separated by gently dipping planes of regional extent that do not run parallel to the land surface. But, whereas the petrological partings or cooling surfaces are generally horizontal, the sheet fractures in places dip as much as 40° from the horizontal. Post-depositional tilting of individual blocks could account for the increased dip of many of the fractures, but this is ruled out because the sheet fractures are essentially symmetrical on opposed slopes of any given hill (Fig. 6.3), and there is no evidence of warping or faulting on the scale of the individual hills.

Also, whereas the cooling surfaces are of regional extent, sheet partings are essentially local in scale (Pl. 6.1). Flow boundaries are of an altogether simpler geometry than the sheet fractures, which suggests that the sheet fractures are not individual flow unit boundaries. In addition, because the

sheet fractures are geometrically related to, i.e. they dip towards, the regional scale orthogonal fractures, the sheet fractures either are contemporaneous with or they postdate the regional set. They cannot predate them, as is implied if the sheet fractures are interpreted as flow or welding features.

If the sheet fractures were cooling surfaces, it could be expected that the columns would develop normal to these surfaces and thus form a radial pattern (Fig. 6.2). This is not found; the columnar joints are consistently vertical and do not necessarily intersect the sheet fractures at right angles. This relationship provides further evidence that the sheet fractures are not the surfaces of individual cooling units.

6.3.3 Erosional offloading hypothesis

The erosional offloading hypothesis has been associated principally with the occurrences of sheet fractures in plutonic igneous rocks like granite. Granite masses were emplaced, cooled and crystallized at depths of several kilometres below the surface under conditions of high hydrostatic pressure. Many are now exposed, implying that several kilometres of rock have been eroded. Thus, in terms of the offloading hypothesis, the vertical load would decrease and the rock would tend to expand radially, inducing the development of fractures tangential to these stresses and thus in rough parallelism to the land surface. In detail, according to proponents of this hypothesis, the hills are rounded as a result of differential weathering, corners and edges of cubic blocks being weathered more rapidly than plane faces, and the sheet structure reflects the rounded form of the hills. The geometry of sheet structure is determined by the form of the land surface. The release of pressure due to removal of the superincumbent load is considered to cause the fracturing (e.g. Gilbert 1904; Matthes 1930; Jahns 1943; White 1946; Waters 1954; Harland 1957; Bradley 1963; Hack 1966; Price 1966, p. 160; Stapledon 1966; Spencer 1977, p. 50; Selby 1985, p. 190).

All fractures are, in some degree, due to erosional offloading. Skinner and Porter (1987, p. 147) asserted that jointing results when rock that has been deeply buried is slowly uncovered by erosion and is relieved of the confining pressure exerted by overlying material and so expands. All joints are predominantly opening mode fractures (e.g. Pollard & Aydin 1988), i.e. there has been a slight amount of movement normal to the fracture indicating an expansive stress. In addition, it is well recognized that joints do not persist indefinitely downwards from the surface as eventually the realm of plastic deformation is reached (e.g. Badgley 1965, p. 123). The offloading hypothesis of sheet fracture formation implies, however, that the arcuate fractures are due solely to such erosional removal of

superincumbent load. Certainly, the common parallelism of structure and surface makes this an attractive proposition. Also, as Lewis (1954) and Gage (1966), for example, have pointed out, fractures and slabs that follow around the detailed morphology of recently developed glacial forms are most readily comprehended in terms not of erosional offloading, but as a consequence of unloading due to the melting of glacial ice.

The general parallelism of sheet fractures with the land surface in the Gawler Ranges is consistent with their development as a result of offloading or removal of the superincumbent load. The sheet fractures could have developed after the erosion of the regolith in Early Cretaceous times. Alternatively, it can be argued that differential fracture-controlled subsurface weathering could produce a series of convex-upward bedrock masses projecting into the base of the regolith. The density of the regolith would be less than that of the fresh bedrock, so that expansion consequent on unloading could have taken place at the weathering front. In these terms, the sheet fractures result, not from removal of the superincumbent load by erosion, but by reduction of the density of the overlying material by weathering. Indeed, sheet structure has developed beneath the surface at other sites (e.g. Paarlberg, South Africa - see Twidale 1982a, p. 15). In either case, the few available sections suggest that only one or two sheets developed, and not the thick banks of multiple slabs seen in some other places. It could be argued that more were originally present and have since disintegrated and been eroded, for although patches of an iron oxide patina are present on the sheets, suggesting development at the base of the regolith, the weathering front could have been diffuse to the extent that groundwaters penetrated along the sheet fractures.

The evident restriction of sheet structure to the superficial zones of such occurrences as Mt Cooper can be interpreted in several ways. First, it could be argued that the sheets, if a manifestation of erosional offloading, ought to have developed continuously during pressure release, so that at any one time there ought to be a bank of sheets beneath the land surface. On the other hand, if, as is believed, the morphology of the bornhardts that form the Gawler Range massif has been little altered since the Cretaceous, then there is no need to invoke a continuous development of sheets since that time.

Second, it could be suggested that, because of the compact and cohesive nature of the volcanics, offloading has allowed only a few sheet fractures to develop.

Yet some of the evidence, both general (see e.g. Twidale 1982a, p. 150-158) and specifically from the Gawler Ranges, suggests that the offloading hypothesis must be questioned.

First, the increase in thickness of the sheets with depth is considered by many to support the offloading hypothesis, because at depth the vertical loading is still present and sheet fractures have not yet developed to their full extent. However, it is difficult to explain the reverse, i.e. thin sheets beneath thick ones, in terms of this hypothesis. There are many examples in the Gawler Ranges, e.g. at Spring Hill and Yandinga Hill (see Pl. 6.4), where this condition applies.

Second, although the sheet fractures in the volcanic bornhardts are, in general parallel with the land surface, there are many examples where the convex-upward fractures occur in valleys. For example, within a valley west of Yandinga Hill, the sheet structure is convex-upward and dips at 30° into the hill (Pl. 6.2). Again the bulbous protruberances defined by sheet fractures near the bottom of a west-facing valley in Peterby Hill (Fig. 6.1) are convex-upward, and in addition, the fractures defining these protruberances overlap asymmetrically the sheet fracture immediately below, which indicates a strain which is impossible to explain as a result of expansive stress due to erosional offloading.

6.3.4. Lateral compression hypothesis

Although lateral compression may result from other causes (e.g. compression during emplacement of a pluton or from recrystallization during metamorphism), lateral compression due to former or present tectonism can be widely demonstrated. These stresses lead to the formation of folds, faults and joints of various kinds. The primary orthogonal sets of fractures in intrusive masses have been explained in terms of lateral compression (e.g. H. Cloos 1922, 1936; E. Cloos 1936) and some workers have endeavoured to explain sheet fractures in similar terms, i.e. as strains that are manifested as arcuate fractures after the removal by erosion of the confining superincumbent load (e.g. Merrill 1898, p. 245; Dale 1923; Bain 1931; Meunier 1961; Twidale 1964, 1971, p. 62 ff, 1973, 1982a, p. 155).

The suggestion that sheet structure is an expression of lateral compression finds support in general arguments (see e.g. Twidale 1982a, p. 150-158). For example, direct measurements of stress (Denham *et al.* 1979) and of deformation in mine shafts (Isaacson 1957; Moye 1958; Leeman 1962; Alexander *et al.* 1963) indicate that rocks are not only under considerable stress, but also that the horizontal stresses exceed both theoretical expectations and the vertical loading.

Measurements of stress at site scale suggest that surface rocks are strained (Twidale 1986b). A suite of minor landforms (A-tents, overlapping slabs, horizontal wedges and blisters) developed on inselbergs and with sheet structure also preserved has been attributed to the local release of compressive stress (Coates 1964; Jennings & Twidale 1971; Twidale 1971; Twidale & Sved 1978; Twidale 1982a, p. 327, 1986).

The extension of gently arched slabs of granite consequent on their release, was measured on granite outcrops on northwestern Eyre Peninsula (Twidale 1986b). Because such slabs are absent on the Gawler Range Volcanics, it has not been possible to take direct stress measurements, but several lines of evidence suggest that the region has been in compression. First, within the Gawler Ranges there are numerous faults (Fig. 4.2), some of which result from compression in the crust (Blissett 1987), so that there is a rational link between compression and sheet structure in the volcanic rocks.

Second, the general increase in dip of the sheet fractures towards the vertical fractures which define the blocks on which the hills develop, or towards the valleys within the hills, suggests that there is a genetic connection between the vertical fractures and the sheet fractures. If the vertical fractures are tectonic then the sheet fractures may also be tectonic. The postulated shearing, resulting in the orthogonal system of fractures, involves the development of compression within the blocks so defined (Twidale 1980b), so that lateral compression is a logical corollary.

Third, columns are offset along sheet fractures at Peterby Hill and Spring Hill (Pl. 6.4) and slickensides are developed along sheet fractures at Spring Hill. Both these features indicate differential movement along the sheet fractures, which suggests stress in the horizontal plane.

Fourth, although there are no known examples of A-tents in Gawler Range Volcanics, A-tents, and also blisters and wedges, occur in the Hiltaba Granite outcrops within the Gawler Ranges. Sheet structure is common to the volcanics and the granite, and it is likely that compressive stress is also common.

Whether sheet fractures result directly from lateral compression when this stress reaches a critical value, or from some allied stress situation such as induced tensile stress in an overall compressive situation (Gramberg 1965; Price 1966, p. 162; Brunner & Scheidegger 1973), or from the relaxation of stresses under a condition of residual stress (Bridgman 1938; Hills 1963, p. 157; Kieslinger 1960), is not known. Nevertheless, the association of sheet fractures with lateral compression is demonstrated in the Gawler Ranges.

However, there are several problems with this lateral compression concept. First, if the sheet fractures are due to lateral compression, it is difficult to explain why they are not better developed at depth. It could be argued that sufficient superincumbent load has not yet been removed to allow the stresses to be expressed as fractures.

Second, the bulbous protruberances in the valley in Peterby Hill (Fig. 6.1), that are impossible to explain in terms of the offloading hypothesis, are no less difficult in terms of lateral compression. No explanation is offered for these irregular forms.

If sheet structure is due to offloading, then it is of Jurassic age or younger, as the bornhardts are considered to date from that time. On the other hand, if sheet structure is due to lateral compression and the topography of the bornhardts reflects the internal structure, then sheet structure must predate the Jurassic, for bornhardts were shaped by subsurface weathering in the (? late) Jurassic (see Chapter 3). In these terms, sheet structure must have developed prior to the Jurassic.

Sheet structure is certainly younger than the columnar joints, for the columns, both those due to cooling and to tectonism (see Chapter 7), are dislocated along sheet fractures, e.g. at Spring Hill and Peterby Hill. Sheet structure is also confined within the regional orthogonal blocks. If it is accepted that the sheet structure and the regional scale orthogonal fractures are due to the same stresses, then the sheet structure is either contemporaneous with the orthogonal fractures or later than them, i.e. they are of Middle Proterozoic age or younger.

The Pandurra Formation, though originally possessing physical characteristics very different from those of the Gawler Range Volcanics, is, nevertheless, not deformed by stresses related to the orthogonal fractures. Hence the sheet structure must be older than the Pandurra Formation. Therefore the sheet structure is of Middle Proterozoic age. On this basis, the bornhardts have their roots in the Middle Proterozoic.

6.4 CONCLUSION

Most of the explanations for sheet structure so far suggested appear to be inapplicable to the volcanic rocks of the Gawler Ranges. The sheet fractures are not coincident with surfaces of individual cooling units. Some of the field evidence argues against pressure release, but other features (e.g. the common parallelism of fractures and topography) are consistent with the concept and all fractures are, in part, an expression of offloading.

On the other hand, though there is no direct evidence that lateral compression is responsible for sheet structure in the Gawler Ranges, this hypothesis is consistent with much of the field evidence and, in particular, offers a comprehensive view of the preservation of the bornhardts and of the sheet structure which is widely associated with them. The sheet fractures are apparently related to the regional orthogonal fractures and were possibly formed at the same time and by the same process. Thus, if the orthogonal fractures are tectonic then the sheet structure may be also. It has been suggested that the orthogonal fractures are due to shearing (see Chapter 5). This is consistent with the sheet structure being due to compressional stress, for shearing involves the development of both compression and tension, the contrasted stress fields being disposed at right angles to one another. If shearing were responsible for the sheet structure, an asymmetrical distribution of sheet fractures on different sides of each hill might be expected. Although sheet structure is not equally developed on all aspects, there is no consistent relationship, and, as far as can be ascertained, the distribution is not regularly asymmetrical with respect to each upland (Fig. 6.3).

The occurrence of antiformal structures in valleys can be understood in terms of local variations in stress resulting in the irregular geometry of sheet structure - antiforms and synforms that are offset in the vertical.

The lithological and climatic azonality of sheet structure make sense also, for stress is independent of the latter, and is manifested in this form in massive brittle rocks, rather than in a particular rock type or types. The occurrence of sheet structure in the cratonic setting of the Gawler Ranges is comprehensible, for this now tectonically stable region has been subjected to tectonism and stress in the past.

Whatever their origin, sheet fractures are a characteristic and prominent feature of bornhardts in the Gawler Ranges, as indeed they are on all domical inselbergs. The sheet structure of the study area is characteristic in some respects but atypical in others. It is closely related to the convex-upward form of the residuals, but whether the link between morphology and structure is cause or effect, is not clear.

CHAPTER 7 COLUMNAR JOINTS

7.1 INTRODUCTION

The profiles of the volcanic hills of the Gawler Ranges commonly include prominent and precipitous walls consisting of numerous juxtaposed columns of rock up to 20 m high. The columns are defined by steeply inclined - commonly vertical - joints, the spacing of which varies but is usually less than a metre. These joints are known as columnar joints, a term used in this study to refer to a system of jointing which delimits columns of various shapes and sizes, with no implication as to the origin of the fractures. Typically these groups of columns occur within lenticular masses defined above and below by sheet fractures (Pl. 6.3). The association of sheet fractures and vertical joints imposes a stepped morphology on the profiles of many of the hill slopes. The steps, or risers, are formed by banks of columns: the treads of the steps coincide with sheet fractures in sloping, usually slightly convex-upward benches of bare rock. On these benches the traces of the vertical joints are readily apparent. Where the sheet fractures are less well defined the benches are irregular and consist of the exposed ends of innumerable columns of slightly varied lengths. Columnar joints are developed on all aspects and at all levels of the domical hills, including the crests. Unlike in some volcanic areas (e.g. the Giant's Loom, Giant's Causeway- Tomkeieff 1940, Fig.2), however, discrete columns, or banks of columns, are not found on summits in the Gawler Ranges.

Columnar joints developed in the volcanic rocks of the Gawler Ranges are of two types. Some systems of joints meet in what are called three-point, or Y intersections and make angles of approximately 120° with each other (Fig. 7.1A). Where exposed on horizontal benches these joints form a pattern of polygons commonly with five sides (Pl. 7.1). These are analogous to columnar joints in igneous rocks reported from other areas (e.g. Spry 1962). The second type of joint is much more common: vertical fractures form commonly two, but in places three, parallel sets that meet in four-point, or X, intersections of variable geometry, and which define columns of triangular or quadrangular cross-section (Fig. 7.1B). Slabs are formed where one set of closely spaced vertical fractures is dominant (Fig. 7.1C, Pl. 7.2).

7.2 CHARACTERISTICS OF COLUMNAR JOINTS IN IGNEOUS ROCKS

7.2.1 Rock type

Columnar joints in igneous rocks have been reported from a variety of materials, but they are most common in basaltic flows (e.g. James 1920; Tomkeieff 1940; Spry 1962). Examples in extrusive andesites and rhyolites have been described, for example, from the United States and New Zealand (Boyd 1961; Ross & Smith 1961; Lipman & Christiansen 1964; Ewart & Healy 1966).

A few workers (e.g. Sosman 1916; Fuller 1938; Smedes & Lang 1955; Lafeber 1956) have noted an intracolumnar variation in chemical composition, but most analyses (Spry 1962) indicate uniformity within the columns.

7.2.2 Dimensions of columns

Columns are generally about 0.5 m in diameter and several metres in length, although ignimbrite columns with a diameter of 10 m are reported (Enlows 1955) from the Chiricahua National Monument, Arizona, and Geikie (1953, p. 149) reported columns up to 200 feet (62 m) long in thick lava flows. The basaltic columns of the Tasman Peninsula, Tasmania, rise some 300 m from the sea.

Lavas with columnar structure commonly display an upper colonnade (a-b in Fig. 7.2), a middle entablature (c in Fig. 7.2) and a lower colonnade (d-e in Fig. 7.2), each separated by a definite line of demarcation, but not necessarily by a fracture. The columns of the entablature are more slender and more irregular than those of the colonnade. Each zone is, however, complex and the nomenclature used in many studies varies (e.g. Tomkeieff 1940; Spry 1962; Long & Wood 1986).

7.2.3 Shape of columns

Columnar structure is ideally defined by a system of vertical fractures each disposed at 120° with each other. Three fractures radiate out from numerous evenly distributed centres (Fig. 7.3). In nature, the cross-section shape varies. Beard (1959), for example, reported some prisms with as few as three sides, others with eight, and with representatives of all shapes in between. In addition, in some lavas the ideal hexagonal pattern is modified by the development of prominent master joints which extend for some distance and form the boundary of several columns. Shorter columnar joints meet the master joint at right angles (Spry 1962).

Columns are almost invariably cut by cross joints (Fig. 7.4A) running normal, or at an angle to the long axis of the column (e.g. Thomson 1879; Sosman 1916). Unlike in the Gawler Ranges (see

below), they rarely extend from one column to the next. Some cross-joints are curved, concave- or convex-upward, in which case they are termed ball and socket joints (Preston 1930; Fig. 7.4B).

7.2.4 Disposition

Inclined columnar joints have been reported by Waters (1960), for example, in Columbia River basalt flows, northwestern U.S.A. These joints are consistently inclined and are at a uniform angle of inclination, apparently related to the flow of the molten lava. Curved columns are also widely reported. Fragments of columns are found at the base of steep slopes, for example at Devil's Postpile, California (Williams & McBirney 1979, p. 115), where they have apparently fallen from higher up the slope, due to unbuttressing and gravity.

7.2.5 Minor features

The faces of columns are essentially smooth and planar, though curved columns are reported, e.g. on the Island of Staffa, Scotland (Spry 1962; see also Hunt 1938). Some curved columns vary in thickness along their length: pinch and swell structure. Chisel marks disposed perpendicular to the long axis of the columns are developed in some lavas (Fig. 7.5). They comprise parallel, discontinuous bands 2-5 cm wide and including irregular curved lines similar to those made by roughly chiseling wood. De Graff and Aydin (1987) noted that each chisel mark contains a single plumose structure. Plumose structure consists of minute ray-like ridges and troughs which diverge from a central axis. The ridges and troughs on one fracture surface are matched by the troughs and ridges on the one adjacent (Fig. 7.6). The direction of propagation is indicated by the direction of convergence of the markings: the markings converge towards the point where the fracture originated (Roberts 1961; Hodgson 1961b).

7.3 CHARACTERISTICS OF COLUMNAR JOINTS IN THE GAWLER RANGE VOLCANICS

7.3.1 Rock type

Columnar joints are well developed throughout the Gawler Ranges, but are particularly prominent in the Younger Gawler Range Volcanics, and in particular in the thick and extensive Yardea Dacite, Eucarro Dacite and Nonning Rhyodacite (Blissett 1987). Columns are not so apparent at Mt Sturt and Coralbignie Rocks, each of which is eroded in rocks that are, unlike most of the volcanics, possibly of shallow intrusive origin (Blissett 1988).

Most of the columns are apparently of uniform composition throughout, and there is no preferred orientation of phenocrysts within the columns. The principal minerals are quartz, microcline and albite. A compositional variation within columns that are defined by fractures that meet in three-point intersections has been recognized at Spring Hill and Yandinga Hill. Each column consists of a core surrounded by a narrow sheath approximately one centimetre thick. The sheath is composed predominantly of albite, with lesser amounts of microcline and quartz. Where these columnar joints are exposed on benches the sheaths are marked by shallow depressions (Pl. 7.3).

Such a variation in composition within the columns was considered by some workers to be the result of convectional circulation in the still liquid lava (Sosman 1916; Lafeber 1956). Albite, the predominant mineral in the sheath, would be one of the first minerals to crystallize from a melt of the composition of the Gawler Range Volcanics, so that it is reasonable to suggest differentiation by crystallization on the margins of convection cells. The general arguments against the development of convection cells (see e.g. Spry 1962), however, preclude this hypothesis.

Albite is also one of the first minerals in the Gawler Range Volcanics to be affected by chemical weathering, so that the minor topographic depression which coincides with the sheath on the benches can be explained by differential weathering. The effect of weathering is also indicated by more abundant hematite (microscopic examination and XRD analysis) and the presence of kaolinite on the borders of the columns. But the sheath is itself not a weathering phenomenon. Fuller (1938) and Smedes and Laing (1955) attributed a similar variation in composition to deuteric alteration related to the already present cracks. Phenocrysts observed under the electron probe (e.g. inclusions and replaced margins- H. Rosser, personal communication 1988) display features that are consistent with compositional alteration by hydrothermal fluids which migrated towards or along the contraction cracks before the material had completely cooled (J. Foden, personal communication 1988).

7.3.2 Dimensions of columns

The size of the columns is comparable with the reported dimensions of columns in other areas. The maximum observed height is 20 m, in the Uno area (Turner 1975), but the exposed length is generally much shorter. The columns are up to 2 m in diameter, e.g. at Spring Hill (Fig. 5.14A). Those at Kolay Valley are much smaller (21 cm; Pl. 7.1). The mode is about 0.5 m. The size of columns is approximately uniform in any given area.

The reason for the size variation is obscure. It has been suggested that the diameter of the columns is related to the composition of the rock (Sosman 1916), the thickness of the lava flow, and hence its rate of cooling (e. g. Spry 1962; Macdonald 1968), the location of the columns in the various zones (colonnade, entablature) of the lava flow (Tomkeieff 1940), the degree of welding (Ross & Smith 1961), and the method of formation (Sosman 1916). In addition, Spry (1962) and Macdonald (1968) suggested that joints in many flows develop in a definite sequence: master joints, forming large columns, are formed first and are the most prominent; then each master column is subdivided by fractures into megacolumns up to 5 m in diameter; these are in turn broken down to normal columns about 0.3 m in diameter. Not all stages of joint formation can be recognised in every exposure and in some the fracturing ceases at the megacolumn phase. None of these suggestions is consistent with the evidence in the Gawler Ranges. Nor has differentiation into colonnade and entablature been recognized in the study area.

7.3.3 Shape of columns

In the Uno area Turner (1976) noted that the columnar joint sets define four- and five-sided columns. Smith (1976) surveyed several groups in the southern Gawler Ranges and noted that three- to seven-sided columns occur, with five sides being the most common. Hexagons are rare.

Three- and four-point intersections of columnar joints are general. A set of joints making three-point intersections and with the angle of intersection approximately 120° (Y junctions) are formed, for example, at Spring Hill (Fig. 5.14A), Yandinga Hill and Kolay Valley (Pl. 7.1). At Spring Hill a secondary set of parallel fractures forms some of the boundaries to columns. Perpendicular intersections (T junctions) are also found. Throughout the Ranges four-point intersections (X junctions) of variable geometry are much more widespread than Y intersections.

The pattern made by the traces of all vertical joints at several sites was analysed by the circle-inventory method of Davis (1984, p. 342; see Appendix 2). At Spring Hill the dominant joints trend $150-160^{\circ}$ (155°), i.e. $150-160^{\circ}$ from grid north with the mode at 155° . A subdominant set from $134-140^{\circ}$ and minor peaks from $25-40^{\circ}$, $85-90^{\circ}$ and $120-125^{\circ}$ also occur (Fig. 7.7).

At a site in a valley floor in Yandinga Hill the joints trend $20-40^{\circ}$ (25°). Subdominant trends occur at $105-110^{\circ}$ and at $160-175^{\circ}$ (165°) with minor peaks from $120-125^{\circ}$ and $80-85^{\circ}$.

The Fossil Hill site is on the western side of a major valley trending 145° . The dominant trend of these site scale fractures is $80-90^{\circ}$ (85°), and subdominant trends occur from $170-190^{\circ}$ (175°) and $15-20^{\circ}$, with minor peaks at $110-115^{\circ}$, $30-35^{\circ}$ and 160° .

The Yardea East site is on a bornhardt adjacent to the Yardea Corridor which, in this area, trends 50° . The dominant joint orientations are $85-95^{\circ}$ (90°). A subdominant trend of $140-145^{\circ}$ and minor peaks from $50-55^{\circ}$ and $105-110^{\circ}$ are also present.

All of these sites show parallel sets of joints and also many nonsystematic joints. Joints with Y intersections were present at only the Spring Hill site.

The joint densities are not significantly or consistently greater in the valley sites than on the hillslope stations. The dominant joints at each valley site (Spring Hill and Yandinga Hill) are not arranged parallel to the local scale fractures along which the minor valleys are located, although some joint sets may coincide with elements of the local scale fracture pattern. The dominant joints are nearly normal to the valley trend.

The pattern of joints at the hill slope sites (Fossil Hill, Yardea East and Yandinga Hill) indicates some joints sets are parallel to the adjacent major valley, but there is no close correspondence between the joint pattern at these sites and the pattern of fractures which control the minor valleys in the same area.

Not all of the joints analysed define columns. A system of vertical orthogonal joints subdivides many of the columns along their length (Pl. 7.4).

Many of the columns are truncated or subdivided by sheet fractures. Though the sheet fractures are locally undulating, the in situ columns are, in most cases, consistently vertical and are only coincidentally perpendicular to the sheet fractures, namely on crests and troughs of the undulations (Fig. 6.2A). The vertical columns generally extend from one sheet to the next (Pl. 7.5). At some sites however, e.g. Spring Hill and Peterby Hill, the columns are displaced laterally along the sheet fractures, i.e. they are offset relative to those in the sheet below (Pl. 6.4).

Some of the columns are subdivided by subhorizontal joints which are approximately parallel to, and presumably related to, sheet fractures. Whereas most of the sheet fractures cut across many columns, some of these subhorizontal joints are discontinuous (X on Pl. 7.6). Other columns are subdivided by oblique joints dipping up to 30° from the horizontal (Y on Fig. 7.6).

A few exposures consist of a series of rounded tops of columns. These differ in their detailed morphology from ball and socket joints (Fig. 7.4B), and are presumably a result of fracture-controlled weathering (Smith 1976).

7.3.4 Disposition

Most of the columns are vertical. Inclined columnar joints of uniform inclination, and curved columns are not known. Fragments of columns are found at the base of steep slopes. As distinct from these, toppled columns are commonplace (Goodman 1980, p. 258; Hoek & Bray 1981, p. 257). These are columns that were originally upright, but which have fractured normal to the long axis of the columns and the upper part of which, above the fracture, now leans away from the vertical. They are found, for example at Yandinga Hill and Peterby Hill (Pl. 7.7A, 7.7B). Toppled slabs, as distinct from columns, are also found, for example at Yardea East Hill (Pl. 7.7C).

The toppled columns, termed inclined columns by Smith (1976), were attributed by her to unbuttressing and gravity. There is evidence of unbuttressing of the columns in the deep valleys which have been worn into the rock mass, and the toppled columns are associated with steep slopes, so that there is no doubt that these factors contributed to their disposition. Not all exposed walls of columns, however, show evidence of toppling, and toppled columns are apparently not reported from any other area where columnar joints are developed.

Ollier (1964) suggested that dirt cracking was capable of enlarging vertical tension cracks, but the mechanism is unlikely to generate sufficient force to dislodge the columns. There is no evidence that undermining by weathering and erosion (Evans 1981) has been responsible for toppling. Goodman (1980, p. 257) suggested that toppling is frequently initiated by sliding along inclined planes at the base of the columns. Such relative movement along a steeply inclined sheet fracture could have triggered the toppling process in the Gawler Ranges.

Whatever the origin of the sheet structure, the toppled columns occur on steeper, rather than gentle, slopes where sheet fractures also tend to be steeper. The two may be genetically related and this association could explain why the columns remain vertical where the sheet fractures are horizontal or only gently dipping, as at Kolay Valley, or where sheet fractures are absent, as in most other volcanic terrains.

7.3.5 Minor features

The faces of the columns are generally smooth. Neither chisel marks nor pinch and swell structure have been observed, though Turner (1975) and Smith (1976) reported, but did not locate, examples of chisel marks.

Many of the columns show pronounced steps (Pl.7.8): some increase, others decrease in diameter with depth, varying in thickness by as much as 5cm (Fig. 7.8, Pl. 7.8). Some faces have curved steps. Others show plumose markings (Pl. 7.9) which indicate the direction of joint propagation perpendicular to the long axis of the columns, or more commonly, from the base upwards. The plumose structure, in some places greater than one metre in length, indicates large increments in joint propagation.

Kinematic characteristics can be deduced from some joint-related features, such as veins or striations (see Davis 1984, p. 333) but none were observed. There has been no discernible dislocation along these fractures: therefore they are properly termed joints.

7.4 THEORIES OF ORIGIN

7.4.1 Introduction

The origin of columnar joints in igneous rocks interested naturalists as long ago as the seventeenth century. Longchambon's (1913) bibliography on the subject includes items dating from 1693. As might be expected several different hypotheses have been put forward in explanation of the joints. These hypotheses invoke either crystallization, concretion, convection, contraction or tectonism. Mallet (1875), Geikie (1882), Iddings (1909), Sosman (1916), Tomkeieff (1940) and Spry (1962) have discussed these theories as general explanations of columnar joints in igneous rocks.

Some of the explanations proposed for columnar joints in igneous rock are implausible, both generally and in the Gawler Ranges context. Thus the crystallization hypothesis (Glen 1873, p. 156; O'Reilly 1879) and the concretion hypothesis (Watt 1804; Jukes 1862; Thomson 1864) are rejected on general grounds. As noted earlier, the variation in composition within the columns was considered by some workers (Sosman 1916; Lafeber 1956; see also Kantha 1981; Hsui 1982) to support convective circulation in the still liquid lava. The general arguments against the development of convection cells in lavas (see Spry 1962), however, preclude this hypothesis.

Columnar joints have also been described from metamorphosed sedimentary rocks (e.g. Glen 1873; Sussmilch 1922; Spry & Solomon 1964; Branagan 1968, see also 1973, 1983). Their origin in these rocks has generally been related to contact metamorphism, an origin which could possibly apply to igneous rocks. As the volcanic rocks of the Gawler Ranges have not been metamorphosed except locally adjacent to granite intrusions, and columnar joints are not preferentially developed in these zones, contact metamorphism cannot have been the cause of the columnar joints in the study area.

Columnar joints in igneous rocks are generally considered to be due to contraction on cooling of the molten lava, and it has been widely accepted that in the Gawler Ranges columnar joints formed in this way (Jack 1912; Corbett 1972; Turner 1975; Smith 1976).

7.4.2 Contraction hypothesis

The contraction hypothesis was first suggested by Raspe in 1776 (Tomkeieff 1940). Considering the columnar basalts of the Giant's Causeway, Ireland, Raspe suggested that they are due to the rapid chilling of fluid lava as it flowed into the sea. Although subaerial cooling of the lava was later shown to be sufficient to produce columnar joints, this hypothesis is now almost universally accepted as the explanation for columnar joints in igneous rock (see e.g. Mallet 1875; Iddings 1886; James 1920; Tomkeieff 1940; Spry 1962). Peck and Minakami (1968), for example, working in the Hawaiian Islands, have observed columnar joints forming in the Kilauean lava lakes and have explained them in terms of the contraction hypothesis.

According to proponents of this hypothesis columnar structure is a result of thermal stresses induced during the cooling of a lava. A joint is initiated when the contraction (thermal stress) overcomes the tensile strength of the rock, and the joint then extends in a plane normal to the direction of contraction.

The columnar joints are considered to form in a stationary lava flow of uniform composition, broad extent relative to thickness and at high temperatures. The lava loses heat by conduction from both the upper and the lower surfaces. Loss of heat by radiation, and by convection where water penetrates down fractures, is also possible from the upper surface.

The amount of thermal stress at any point in a cooling lava depends on many complexly interrelated factors, such as conductivity, coefficient of expansion, rate of cooling and shape of the lava flow (e.g. Spry 1962; Price 1966, p. 354). In addition, once a crack has formed the stress distribution is altered (Jaeger 1961).

Iddings (1909) and Billings (1954, p. 115) proposed mechanisms which involve the instantaneous development of the pattern from a series of equally spaced centres over the surface of the lava (Fig. 7.3; see also Smalley 1966). Spry (1962), on the other hand, favoured a method of fracture propagation which is continuous, with the cooling rock broken into progressively smaller parts (Fig. 7.9).

Most workers suggest that the hexagonal prism is the ideal shape of the columns no matter which mechanism of fracture propagation is favoured (see e.g. Holmes 1965, p. 100), though the reasons for the hexagonal symmetry are not understood (see e.g. Hewes 1948; Simpson 1948), and it is not everywhere the most common.

Theoretical and experimental studies on fracture propagation have demonstrated the feasibility of the contraction hypothesis (e.g. Ernsberger 1960; Ryan & Sammis 1978). The various features characteristic of columnar joints in igneous rock have been demonstrated to be feasible, if not precisely explained, in terms of this mechanism (e.g. chisel marks - De Graff & Aydin 1987; curved columns - Spry 1962). Finally columnar joints have actually been observed in process of formation in a molten lava as it cooled and contracted (Macdonald 1968, p. 40; Peck & Minakami 1968).

Thus, although many of the details of the mechanism of propagation of the cracks remain obscure, most workers agree that thermal contraction is the cause of the columnar joints in igneous rocks.

Some of the joints which define columns in the Gawler Ranges have probably originated in this way, for they display many of these characteristics.

The columnar joints at Spring Hill, Yandinga Hill and Kolay Valley, for example, (Fig. 5.14A; Pl. 7.1), which consist of a set of joints with three-point intersections, and with angles between the joints approaching 120° are typical of columnar joints in igneous rock described from other areas. Additional examples of similar patterns of joint traces can be found on rock benches in various places throughout the Gawler Ranges. The rock type, dimensions and shape of the Gawler Range examples are similar to those of columns that have been attributed to contraction on cooling from an igneous melt.

Many examples of columnar joints in the Gawler Ranges, however, depart from this typical pattern. First, studies in other areas have related local variations in pattern to variations in thermal stress in the cooling lava. These are due to such factors as variations in the rate of cooling, shape of

the lava flow and conductivity (e.g. Spry 1962). The essential uniformity of composition of the units within the Gawler Range Volcanics, and the formation of each at one time rather than as a series of eruptions, suggests that variations in thermal stress over short distances ought not to be common. But such variations in pattern are characteristic.

Second, four-point intersections are more common than three-point intersections. Although cooling joints with four-point intersections have been reported, for example by Engelder (1987, p. 52) from the Moruya Batholith, near Tuross Heads, New South Wales, and by Ross and Smith (1961) in welded ashflow tuffs in southwestern U.S.A., joints with three-point intersections are much more common, especially within the interior of cooling bodies. Associated with this feature, the angles made by the joints vary from around 60° to 180° , rather than about 120° which is typical of cooling joints. Also the joints in the Gawler Ranges trend in two or three dominant directions (Fig. 7.7) rather than having no preferred orientation, which is more typical of cooling joints.

Third, the Gawler Range columns lack such features as chisel marks, ball and socket joints, pinch and swell structure and differentiation of the material into colonnade and entablature with the consequent difference in pattern of the columnar joints. The absence of all of these typical characteristics throws some doubt on the contraction hypothesis.

On the other hand, some features apparently suggest that contraction has not contributed to the development of columnar joints in the Gawler Ranges to any major degree. First, the pronounced steps in the face of many of the columns resulting in either an abrupt increase or decrease in the column diameter with depth, are difficult to explain in terms of incremental joint propagation related to the migration of the cooling front inward into the solidifying material.

Second, plumose markings on the columns indicate joint propagation from the base upwards. These markings are known only from columns bounded by joints making four-point intersections. If they were related to cooling, then they must have originated at the base of the cooling mass. Presumably, all the joints that originated at the surface and progressed downwards must have been eroded or otherwise obliterated. It is perhaps surprising that none, in a deposit of several hundred metres of exposed depth, should be preserved. The few instances noted, for example at Yandinga Hill, of plumose structure indicating joint propagation perpendicular to the long axis of the columns are inconsistent with the requirements of the contraction hypothesis. In addition, the size of the plumose markings, in places more than a metre in length, is not consistent with the slow cooling rate generally

demonstrated for columnar structure, and far exceeds the scale of plumose markings on chisel marks (DeGraff & Aydin 1987).

Third, there are numerous occurrences of plate-like vertical slabs of rock several centimetres thick (Pl. 7.2). Because of their shape these cannot be explained by contraction due to thermal stress. Similarly, the secondary vertical fractures which subdivide the columns and occur in parallel sets or orthogonal systems, as at Spring Hill (Fig. 5.14A), cannot be explained in this way.

7.4.3 Tectonic hypothesis

Although the columnar joints in the base of the Rhyolite Canyon Formation of Chiricahua National Monument, Arizona, were originally attributed to contraction of the rhyolite (ignimbrite) on cooling, Enlows (1955) considered them to be due to tectonic forces associated with shear movements along normal faults. These columns are predominantly square or rectangular in cross-section. The joints occur in intersecting sets, extend from one member of the formation vertically into another, and are related to steeply dipping faults. For Enlows, these features were suggestive of tectonism rather than cooling and contraction.

Many of the columnar joints in the volcanic rocks of the Gawler Ranges can reasonably be explained in terms of tectonism. The absence of chisel marks, ball and socket joints, pinch and swell structure and colonnade and entablature differentiation is consistent with the tectonic hypothesis. So too are the variations in number of sides to the columns; the four-point intersections of columnar joints; the variations in size of the angles made by the intersecting joints; the development of one or more sets of joints as well as others of more variable bearing; the unequal development of each; the development of joints which bound several columns; the pronounced steps in the faces of many of the columns; the plumose markings which suggest instantaneous development of the order of one metre or more in length, and their propagation from the base upwards, or in a direction perpendicular to the axis of the column.

7.5 CONCLUSION

Some columnar joints in the Gawler Ranges are typical of those reported in igneous rocks in various parts of the world. Others show features that are atypical.

Various theories have been suggested to account for columnar joints in other settings. The deducible consequences of crystallization, concretion, convection and contact metamorphism are

inconsistent with the field evidence in the Gawler Ranges. Some columns, for example those at Spring Hill, Yandinga Hill and Kolay Valley which are bounded by joints with triple point intersections, are due to contraction on cooling of the molten rock. Others, for example those showing plumose markings, those with pronounced steps to their faces and those that are bounded by intersecting joint sets, are most likely due to tectonic activity. Some individual columns at Spring Hill are defined by both types of vertical joint. Some of the columns due to contraction on cooling, e.g. those at Spring Hill (Fig. 5.14A), have been subdivided by later joints due to tectonism.

The columnar joints due to contraction on cooling formed soon after the extrusion of the volcanic material. Those due to tectonism, including those that subdivide the columns, must post-date those due to cooling, since they must have formed after the solidification of the rock. They are considered to be of the same age as the regional scale and local scale orthogonal fractures which were discussed in Chapter 4.

Thus, columnar joints of varied origin are well developed in the Gawler Range Volcanics. The banks of columns add to the bornhardts a distinctive morphologic feature in part related to the volcanic origin of the country rock and found in few other bornhardt landscapes.

CHAPTER 8 DISCUSSION

8.1 INTRODUCTION

The analysis and interpretation of the bornhardts developed in Gawler Range Volcanics presented in the preceding chapters lead to the following conclusions:

1. The residuals evolved in two stages, the first involving differential subsurface weathering, the second the stripping of the regolith so formed to expose the irregular weathering front. The resulting domical hills, or bornhardts, are therefore etch forms.

2. The differential weathering was controlled by fractures. The fractures which are of major geomorphologic significance are

a) the regional scale orthogonal systems which have determined the size and shape of the bornhardts in plan,

b) the sheet fractures which, together with the rounding effects of weathering, have controlled the domical shape of the bornhardts,

and c) the orthogonal fracture systems of various scales and the columnar joints which have influenced the detailed slope morphology of the bornhardts.

3. The regional scale orthogonal fractures were possibly formed due to tension or to shearing resulting from movements along major lineaments. They developed during Middle Proterozoic times. The smaller scale orthogonal systems are probably related both in origin and age to these major fracture systems.

The origin and age of the sheet fractures are debatable. Some evidence suggests that they are due to lateral compression and, if so, they developed prior to the Jurassic and possibly as a result of the same Middle Proterozoic deformation that gave rise to the orthogonal systems. On the other hand, some evidence supports an origin due to offloading, and, if this be the case, the sheet fractures are of Jurassic age or younger.

Some of the columnar joints that introduce a unique morphologic element to the bornhardts of the Gawler Ranges, are due to contraction on cooling of the volcanic material soon after its extrusion. They are therefore of Middle Proterozoic age.

4. The initiation of the bornhardts as convex-upward projections into the base of the regolith took place during a period of weathering during the Late Jurassic, though it may have extended back into the Early Jurassic and even into the Triassic.

5. The stripping of the regolith to expose the domical projections as bornhardts was essentially complete by the end of the Early Cretaceous. Both the hills and the plains have changed but little during the succeeding 60-100 My.

8.2 WHY BORNHARDTS?

8.2.1 Introduction

Several aspects of this suggested evolution warrant further discussion. First, what factors are common to the domical forms of the Gawler Ranges and to bornhardts developed on granite and granitic gneiss in many parts of the world, and, less commonly, on some sedimentary sequences? Second, why have bornhardts evolved in silicic volcanic rocks whereas indurated acid volcanics in other areas most commonly give rise to plains and plateaux?

8.2.2 Common factors in bornhardt landscapes

Climate: There is nothing about the climatic regime of the region in and around the Gawler Ranges, past or present, that can be considered as especially conducive to bornhardt development. Domical hills that are congeners of the Gawler Range type have been widely reported from all major climatic regimes including cold, hot, humid and arid (e.g. Wilhelmy 1958; Twidale & Bourne 1978b) and the forms can thus be considered azonal: climatically-related processes are not common factors in their development.

Topographic setting: Location and topographic setting are not crucial to bornhardt formation. The Gawler Ranges are located in an interior continental situation, but elsewhere domes are found in coastal environments as well as in plains and mountainous contexts (see e.g. Twidale & Bourne 1978b).

Rock type: Bornhardts that are morphologically and apparently genetically similar to those evolved in Gawler Range Volcanics are well and widely developed, not only in granites but in other rock types also. In fact, granitic domes are well represented in the Kokatha (Pl. 8.1) and Hiltaba-Kondoolka areas within the western Gawler Ranges and numerous domical uplands cut in rocks of varying lithology stand above the gently undulating surface of northwestern Eyre Peninsula (Twidale & Campbell 1985 - Pl. 8.2), where gneissic forms, such as Caraptee Hill and Waddikee Rocks, are also developed. Mt Allalone (Pl. 1.1), immediately to the south of the Ranges, is conglomeratic, whereas Curtin Hill (Pl.8.3) and Barna Hill, both located southeast of Kimba on central Eyre Peninsula, are eroded in quartzite.

Turning to a wider perspective, the domes of the Hombori massif in Mali (Mainguet 1972) and Ayers Rock, central Australia (Twidale 1978), can be cited as examples of bornhardts in sandstone; and the Olgas complex, central Australia, and Mt Bresnahan in Western Australia, are examples of domical forms in conglomerate. Verstappen (1960) has also described conglomeratic domes in Indonesia, as well as residuals of similar morphology in limestone (Verstappen 1960). Cupolakarst also occurs in West Malaysia and Cuba (Lehmann 1954), and in Yucatan (Isphording 1977).

Multicyclic landscapes: Bornhardts are characteristically developed in multicyclic landscapes (Obst 1923; Willis 1934; Jessen 1936; King 1949a; Twidale 1964, 1978, 1982a, p. 207). The Gawler Ranges have in common with other regions a complex denudation chronology. But how does this multicyclic factor influence the development of domical forms? In some areas a surface of low relief has developed after a long period of weathering and erosion. Long-continued subsurface weathering has resulted in the exploitation of structural inequalities and in the differential weathering that is responsible for the initiation of the bornhardts as projecting masses of fresh rock.

In the Gawler Ranges the structural inequalities that have been exploited by weathering are related to fracture density and condition (whether open or closed). The valleys of the Gawler Ranges are so straight as to suggest a relationship with fractures of the regional orthogonal system. In addition, sheet fractures are well displayed on most of the hills. Vertical fractures at the local and site scale influence the detailed slope morphology, but are not directly related to the domical form. Banks of columns, many of them defined by joints due to contraction on cooling and therefore related to the volcanic origin of the rock, are unusual in the bornhardt context.

In the development of regional scale orthogonal fractures and sheet structure the Gawler Range domes are similar to bornhardts from other regions, both near and far. Many of the granitic domes of northern Eyre Peninsula are based in fracture-defined blocks, the fractures being members of orthogonal systems (Twidale 1982a, p. 140). Sheet structure is developed, at least at and near the surface, for shallow quarry exposures reveal sheet structure at depths of several metres. The low domes developed on Warrow Quartzite of Early Proterozoic age in the area southeast of Kimba are particularly interesting in respect of structural control of the landforms. Both Curtinye and Barna, as well as several other unnamed hills nearby, are eroded in quartzite with a north-south foliation dipping at 80° to the east. Strike ridges ought to develop on such materials, as indeed is the case in the Botenella Range further to the north. But sheet structure, though poorly exposed, is developed and is evidently enough to impose a domical form on the residuals. None of these quartzitic examples, as far as is known, is developed on fracture-defined blocks. Similarly, Mt Allalone is not obviously defined by fractures of the orthogonal system, though a weak, scarcely discernible sheet structure is present. This domical hill contrasts with the elongated Uno Range further to the east, which is also eroded in conglomerate.

Turning to occurrences from a wider area, many bornhardts have evolved on rock masses on which are developed orthogonal fractures at the regional scale, or well developed sheet structure, or both. Ayers Rock, for example, is constructed of a steeply dipping arkose, the bedding of which is responsible for the ribbed appearance of part of the residual. Sheet structure is nonetheless well developed, most notably in the Kangaroo Tail (Pl. 8.4), and has given rise to a dome, albeit bevelled. Ayers Rock is, however, not located on a fracture-defined block. Instead, it is a compartment that has been isolated by compression and possibly by cross-folding and developed within an elongate sedimentary formation (Twidale 1978). On the other hand, karst inselbergs are apparently developed on fracture-defined blocks, but sheet structure has not been widely reported from them (Sweeting 1972; Jennings 1985). Whether this reflects a true absence or a failure to observe the fractures is not known.

Overall, however, there is a close connection between bornhardts and fractures. Most bornhardts are defined by orthogonal fracture systems and many also display sheet structure. All apparently have one or the other of these fracture systems. In some, such as the Gawler Ranges bornhardts, Ucontitchie Hill on northwestern Eyre Peninsula, the Everard Ranges, central Australia

and the Kamiesberge of central Namaqualand (Twidale 1981a, Fig. 1a, and 1982b, Fig. 4), both orthogonal and sheet fractures are present and have markedly influenced the development of the domical hills.

8.2.3 Special features of the silicic volcanic rocks of the Gawler Ranges

The question as to why bornhardts have evolved in silicic volcanic rocks can now be broached. Most fields of Cainozoic ignimbrites give rise to plains and plateaux and, despite their occurrence in tectonically active areas like the American West and New Zealand, sheet structure is not well developed. It possibly occurs, for example, in the City of Rocks, New Mexico, but it is not well or widely developed. Though consolidated, these Cainozoic ignimbrites are not as compact as the Gawler Range Volcanics (C. R. Twidale, personal communication 1989), and lacking their brittleness, do not give rise to a well-developed sheet structure. In addition, the Cainozoic ignimbrites have not been deeply buried, so that there has been little or no offloading, and hence little development of sheet fractures.

The main reason for the development of bornhardts in the Gawler Range Volcanics is the variable resistance of the rock to weathering. On the one hand, linear fracture zones enable water to penetrate the rock and the progress of weathering is relatively rapid. The weathered material is readily eroded to form valleys. On the other hand, the intervening blocks are impermeable and impervious: the rock is compact and resistant to weathering and, in time, these blocks project upwards into the deeply weathered material. On stripping of the regolith, they stand out as bornhardts.

8.3 SURVIVAL OF THE BORNHARDTS OF THE GAWLER RANGES

The great age of the Gawler Range massif and of its component bornhardts is not unusual in the context of Australia and other Gondwana relics: palaeoforms of Mesozoic age are not rare (see e.g. King 1950; Twidale 1976a; Michel 1978;; Demangeot 1978; Partridge & Maud 1987; Twidale & Campbell 1988). Nevertheless, the preservation of these landforms requires explanation, for they are anomalous in terms of the deducible consequences of all the major models of landscape evolution.

The best known and most widely favoured model of landscape evolution is that of Davis (1899, 1909) whose cyclic scheme involves instantaneous uplift of a land mass and the consequent dissection and gradual lowering of the divides by rillwork, wash and wasting. Eventually the mass is

reduced to a surface of low relief; a peneplain, the penultimate form in the geographic cycle of erosion. Davis envisaged that the effects of running water extended to every part of a river basin: '...the river is like the veins of a leaf; broadly viewed it is like the entire leaf.' (Davis 1909, p. 267). The entire land surface was, therefore, lowered simultaneously. Any remnant of an uplifted and dissected palaeoplain, or any surviving palaeoform, is a denial of the effectiveness of rivers in lowering the interfluvies. In terms of Davis' model, the entire surface must be contemporary.

A similar difficulty is encountered with the models involving steady state development or dynamic equilibrium, such as the concept of the 'old from birth' peneplain (Davis 1922) and the noncyclic and time-independent scheme of Hack (1960). Steady state implies continuous and equal erosion of the entire land surface, such that all slopes are constantly being regraded and the land surface, like that of a peneplain, is essentially contemporary.

Models based on scarp retreat and pedimentation (e.g. King 1942, 1949b) are also cyclic as the end product is similar to the initial surface prior to dissection. Remnants of a high plain persist until late in the cycle, so that this model better explains the survival of palaeoforms, at least in the short term. But such remnants ought to be no older than the duration of a cycle, which, in the case of a region of continental or subcontinental extent, is of the order of 35-40 My (Gilluly 1955; Linton 1957; Schumm 1963; Twidale 1976a). In other words, no landform or surface ought to be older than Oligocene, unless, of course, it is exhumed.

The development of flared slopes at successively lower levels, for example on Yarwondutta Rock, Eyre Peninsula (Twidale & Bourne 1975), indicates that piedmont zones have changed location very little in time. This argues against significant scarp retreat in that area. Some flared slopes are developed on volcanic rocks in the southern Gawler Ranges and they are well developed at the base of granitic nubbins in the western Gawler Ranges. This, together with the arguments adduced in Chapter 2, suggests that scarp retreat has not been active in the Gawler Ranges. The presence of scarp-foot depressions similarly argues the relative stability of marginal slopes and weathering zones. Such depressions are found, for example, at Wattle Grove Rocks near Wudinna on northwestern Eyre Peninsula and are most likely due to the concentration of moisture and hence of weathering at the foot of the uplands (Clayton 1956; Pugh 1956; Peel 1960; Twidale 1982a, p. 262).

Thus, though the scarp retreat hypothesis offers a theoretical possibility for the survival of palaeoforms for perhaps 40 My, the evidence does not favour the mechanism. In any case, the landforms under discussion are older than the implications of scarp retreat allow.

Some of the possible reasons for the survival of palaeoforms have been adduced by Twidale (1976a). The persistence of the Gawler Range forms is not due to burial, as was the case with the relics of the Middle Proterozoic Scrubby Surface, for they have apparently been exposed since the regolith was originally stripped. There is no evidence that a laterite, silcrete or other duricrust, similar to the laterite of the Gulfs region of South Australia, had developed over the surface. Nor can the preservation of the bornhardts be due to the arid to semiarid climate in which the forms now exist. Corbel (1959) suggested that, although erosion in arid mountainous areas is rapid, arid lowlands tend to change only slowly, and this is corroborated by other studies (e.g. Judson & Ritter 1964). In any case, the present aridity in the Gawler Ranges is atypical of the climate of most of the period of bornhardt development and persistence.

One survival factor, discussed by Twidale (1976a) is the spatial variation in the work of rivers. In contrast to the ideas of Davis (1909, p. 267), various workers like Crickmay (e.g. 1959, 1968, 1971; see also Lees 1955, p. 224; Twidale 1972), have noted the contrast in the rate of lowering of divides and of stream beds. In the Gawler Ranges, this factor may have been important in the past, but it is apparent that neither the hill summits nor the valley bottoms have been reduced to any significant degree since at least the Early Tertiary, when silcrete developed in some of the valley floors. The localization of river erosion cannot explain the preservation of the bornhardts.

Several factors are relevant to the persistence of the Gawler Ranges landforms. First, the continental situation of the region has ensured that the landscape is far removed, or insulated, from base level fluctuations. Second, the stability of the region has allowed for the preservation of the bornhardts from diastrophic rejuvenation or significant uplift and accompanying increased erosion. Third, the Gawler Range Volcanics are physically hard, compact and of low porosity and permeability and they are of acid composition and are therefore resistant to weathering and hence to erosion (Goldich 1938). In particular, they are low in biotite which is, according to many workers (e.g. Ruellan 1931; Birot & Jeremine 1950; Velbel 1985), particularly prone to alteration through its reaction with water. Cleavage planes within mineral grains, for example in a stressed rock such as gneiss (Turner & Verhoogen 1960, p. 476; Gerrard 1988, p. 179), and especially within feldspars in porphyritic rocks

are considered to act as avenues for water and dissolved materials and thus result in an increased susceptibility to weathering (Evans 1988). None of the Gawler Range Volcanics, except those in the vicinity of Lake Acraman (see Williams 1986, 1987), shows evidence of significant stress at the crystal scale. In addition to the inherent strength of the rock, the bornhardts may represent the deep compressional cores of material tectonically deformed in Middle Proterozoic times. The survival of the bornhardts may also be enhanced by the hematite rind, and its possible induration after exposure and desiccation, or by impregnation of silica at the weathering front. Fourth, a reinforcement effect - or the fact that the bornhardts shed water and are dry for most of the time, whereas the valleys which receive moisture are readily weathered - has assisted materially in the preservation of the uplands. Such a reinforcement, or positive feedback effect (Twidale *et al.* 1974; Twidale 1976a) has been suggested to account for the preservation of landforms of different lithologies and in quite varied climatic settings.

8.4 CONCLUSION

The questions posed in Chapter 1 have now been answered. How were the bornhardts of the Gawler Ranges developed? They are etch forms, developed in two stages, involving first, differential fracture-controlled subsurface weathering and second, almost complete stripping of the regolith and exposure of the irregular weathering front, of which the domical forms are the upstanding parts. Why were they formed? Because of the contrast between the perviousness of the fracture zones and the impermeability, and hence resistance to weathering and erosion, of the intervening blocks. The landscape is overwhelmingly structural. When did the bornhardts develop? In the long term, the exploitation of the structural base which was established in the Middle Proterozoic and which is directly responsible for the modern landscape, probably took place throughout the Late Proterozoic and the Palaeozoic. The last phase of this exploitation, and the only one of which there is any evidence in the region, took place principally in the Mesozoic. The weathering which initiated the forms occurred in the Jurassic or earlier Mesozoic. The landforms were exposed in Late Cretaceous to Early Tertiary times.

The Gawler Range bornhardts developed beneath a widespread planation surface - the Beck Surface. Fold mountain regions, such as the Flinders Ranges to the east of the study area, which comprise ridge and valley in association with a summit surface, are said to be of Appalachian type. Could not those landform assemblages developed on crystalline rocks on which is developed a

summit surface also be given a special name? An appropriate term might be Eyrian relief, or Eyrian type relief, after the explorer who first described this interesting and distinctive landscape, and who correctly attributed the forms to the durability of the rock on which they are developed. But Eyrian suggests Lake Eyre or Eyre Peninsula, not the Gawler Ranges. Also, there is a potential for confusion with the already recognised Eyre Formation (e.g. in Wopfner *et al.* 1974). Thus, though Eyrian is apt, in many ways it is preferable to suggest that the relief be termed simply the Gawler Ranges type. Nonetheless, it is apposite to conclude with the quote from Peron which Eyre (1845, I, p. 201) cited as being '...singularly applicable to the Gawler range ...La dureté du roc paroît braver ici tous les efforts de la nature, et résister à ces mêmes moyens de décomposition qu'elle emploie ailleurs avec tant de succès.'

APPENDIX 1 ROCK HARDNESS

The Gawler Range Volcanics are resistant to erosion and are, therefore, implicitly hard and durable. A quantitative measure of rock hardness was considered necessary to relate the surface hardness of the rhyolites and dacites to that of other rock types, particularly those that crop out in nearby areas.

Two tests proved useful in this regard. First, the Los Angeles Abrasion test determines the abrasive resistance of an aggregate by tumbling a sample with steel spheres in the steel drum of a Los Angeles Machine. The result quoted is the percentage of the original sample broken down to minus 1.70 mm during the test (Table 1.2). These values were obtained from tests conducted by the South Australian Highways Department on rock aggregate proposed for use in road construction. The tests on Gawler Range Volcanics, except for the Mt Sturt dacite (sample 5), indicated a low percentage loss when compared with granite, gneiss, basalt, dolerite and calcrete.

Second, a Schmidt Hammer (Type N), on loan from the Department of Civil Engineering, University of Adelaide, was used both in the field and in the laboratory. The hammer measures the distance of rebound of a controlled impact on a rock surface. As elastic recovery depends on the hardness of the surface and on the compactness of the mass of which it is a part, the rebound number indicated is a measure of the hardness of the rock (Day & Goudie 1977; Day 1980). Ten measurements were taken on each sample and the range and mean were noted (Table 1.3). Tests were carried out on horizontal surfaces in the field and also on the horizontal faces of sawn blocks held in a vice in the laboratory. The tests on sawn faces gave results covering a narrower range of rebound numbers and a higher mean value than tests on the same rock type in the field (see e.g. samples 1 and 21 in Table 1.3). The rebound numbers obtained from the Gawler Range Volcanics were compared with those from a selection of other rock types (Table 1.3, samples 27-45). The low rebound numbers and the wide range in most of the samples is attributed to various factors such as variations in hardness of the constituent mineralst (e.g. augen gneiss, sample 41); lower rebound values on protruding crystals or otherwise rough surfaces (Calca granite, sample 37); a reduction in hardness on laminated or blistered rock (e.g. Eucarro Dacite, sample 16); local variations in hardness due to surface indurations of iron or silica (Yardea Dacite, samples 18 & 19; Eucarro Dacite, samples 7 & 8); or to partial weathering of the surface (Calca granite, sample 38; Eucarro Dacite, samples 11 &

12). Generally, however, the results obtained from the field and the laboratory on the same rock type are comparable. More importantly, the relative values are similar.

By both the Los Angeles Abrasion test and the Schmidt Hammer test, the Gawler Range Volcanics are very hard. Only the Darke Range metaquartzite is consistently harder (Table 1.2, sample 27).

APPENDIX 2 METHODS OF FRACTURE ANALYSIS

A2.1 LINEAMENTS

The lineaments of the Gawler Ranges and surrounding areas were plotted from Landsat imagery at a scale of 1:500,000 (Frontispiece). Sheets ALS 99-82, ALS 99-83 and ALS 100-82 were utilised. The band numbers used to produce the images and the filter colour used in exposing that band of the image are 4 blue, 5 green and 7 red. A tracing plot of linear features greater than 10 km in length was made on a clear plastic overlay of the coloured images. The lineament plot was transferred, with minor adjustments due to scale and projection variations across the images, to a Transverse Mercator projection base at the same scale. Most of these lineaments are also observable on geologic and topographic maps (Blissett 1987 and 1:250,000 topographic maps of the area) and on aerial photographs. The plot was photographically reduced to the scale of 1:1000,000. The orientation and length of each lineament on the map, excluding the arcuate features, were measured and the results tabulated. A directional frequency rose diagram of lineament trends was constructed, first for the percentage by number, and second for the percentage by length, in each class interval. The dominant trend is the direction range with the greatest percentage of occurrences. Subdominant trends are indicated by percentages less than the dominant trend but greater than 4% (arbitrarily chosen). Peaks on the rose diagram representing less than 4% of occurrences are referred to as minor trends.

A2.2 REGIONAL SCALE ORTHOGONAL FRACTURES

Features interpreted as regional orthogonal fractures were identified and analysed and rose diagrams were drawn in a method similar to that used for lineaments. Only features within the study area were included. Linear valleys and linear margins to uplands generally greater than 2 km and less than 20 km in length are readily discernible by colour changes on the satellite imagery. Some of the longer features coincide with lineaments. Some arcuate features, on the basis of the local pattern, can be subdivided into several straight segments, each of which is parallel to adjacent features, and each is treated as an individual straight feature.

A2.3 HIGH FREQUENCY LINEARS

High frequency linears were also identified from the satellite imagery according to the method employed by O'Driscoll (personal communication 1987). These linears are generally less than 2 km in length. Many coincide with regional scale orthogonal fractures, being also located along linear valleys and linear margins to uplands. The linears, however, are identified without extrapolation: each line of the plot represents a continuously visible colour change on the image. Thus, two linears in line may represent a single fracture not continuously visible on the image. Thus on Figure A2.1A, X - X may be a single fracture. There are other possibilities, however (O'Driscoll personal communication 1987). For example, the gaps in alignment (Y on Figure A2.1B) may represent a zone of more highly fractured rock or it may be a discontinuity.

Directional frequency rose diagrams of trends of high frequency linears were constructed for each of the upland areas within the Gawler Ranges, excluding the Kokatha Upland where few linears were identified (see Fig. 1.6, 5.6), using the circle inventory method described by Davis (1984, p. 339). The circle inventory method requires measuring all features that occupy a sampling circle. As described by Davis, the method is applied to measuring joints within a circle drawn by chalk on a bedrock outcrop. The orientation and trace length of all joints are measured. The method can also be adapted to a photogeologic approach, with the inventory circle drawn on an aerial photograph.

On the plot of high frequency linears for the Gawler Ranges, a circle of radius 1 cm, representing 10 km on the ground, was drawn in each of the upland regions (see Fig. 1.6), and the orientation of all linears within that circle was measured. The data were analysed only by total number, as the pattern is complex and intricate and there is little variation in the length of the linears.

A2.4 FAULTS

No original observations have been made on faults within the study area. The pattern of known or inferred faults was derived from geological maps at a scale of 1:250,000 (Johns *et al.* 1966, 1981; Dalgarno *et al.* 1968; Blissett 1977a, 1977b; Parker 1983; Daly 1985; Blissett *et al.* 1988; South Australia Department of Mines and Energy preliminary editions of Kingoonya and Streaky Bay sheets) and with additional information from Bourne *et al.* (1974), Turner (1975), Gerdes (1978), Flint *et al.* (1982), Flint (1984) and Blissett (1987). Rose diagrams of these faults were constructed using the same method as for lineaments. Whether the total number of faults in the Gawler Ranges and

surrounding areas (Fig. 4.2) is considered, or whether the total length in the various class intervals is analysed, the pattern is similar (Fig. 4.8). The dominant trend of faults by number (Fig. 4.8A) falls within the ranges $130-155^{\circ}$ and $175-200^{\circ}$ with a mode within each range at 145° and 185° (5°) respectively. The dominant trend of faults by length (Fig. 4.8B) is within the range $130-160^{\circ}$ (145°). A subdominant trend falls within the range $175-190^{\circ}$ (180°). Note that the plots and rose diagrams of lineaments (Fig. 4.6, 4.7) on the one hand, and faults (Fig. 4.2, 4.8) on the other, are remarkably similar.

A2.5 LOCAL SCALE ORTHOGONAL FRACTURES

Linear features coinciding with bornhardt margins, or with minor valleys which subdivide the uplands, were identified from aerial photographs (scale 1:86,000). They are related to local scale fractures. Three sites - Spring Hill, Mt Kolendo and Yardea East - were arbitrarily chosen. Rose diagrams indicating the trend of orthogonal fractures in these areas were constructed using the same method as for lineaments (Fig. 5.11).

A2.6 JOINTS

An analysis of the trend of joint traces at four sampling stations (Fig. 7.7) on horizontal rock outcrops was made using the circle inventory method of Davis (1984, p. 342; see section A2.3). A circle of radius 0.5 m was selected. Most of the joints visible dip vertically, or almost so. No joint-related structures, such as veins and striations, were present so that the joints could not be classified as to their kinematic characteristics. Compass bearings were corrected to grid north to enable comparisons with local scale and regional scale orthogonal fractures.

APPENDIX 3 LINEAMENTS IN THE GAWLER RANGES AREA

Within the Gawler Craton, and especially in and around the Gawler Ranges, a bewildering array of lineaments has been identified by previous workers. Hills (1946, 1956, 1961, 1963) was the first to broach the lineament problem in Australia and he recognised NNW-SSE features in the vicinity of the Gawler Craton (see Fig. 4.4).

Dickinson and Sprigg (1953) plotted a simple pattern of crustal shear lineaments which defined the Gawler Block, a quadrangular area contained within the Gawler Craton (see Fig. 1.4). Their Lincoln, Eyre, Gairdner and Pidinga diagonal lineaments and the meridional Torrens Lineament (Fig. 4.1, 4.5A) conform to the Australian and global patterns discussed by Hills (1963, p. 461). The Lincoln Lineament along the east coast of Eyre Peninsula consists largely of recognized faults. The northeastern boundary, the Gairdner Lineament of Dickinson and Sprigg, is coincident with the contact between the crystalline rocks of the Gawler Block and the sedimentary outcrops of the adjacent Stuart Shelf. It may, however, be ephemeral for crystalline rocks extend in the subsurface far to the northeast, into the Mt Woods Inlier, for example, and its location would thus be changed by the stripping of the sedimentary cover. The Pidinga Lineament in the northwest (not shown in Figs. 4.1, 4.5A) is coincident with the surface boundary between the crystalline rocks of the Gawler Block and the Tertiary sediments of the Eucla Basin, but the contact is difficult to locate because the area is covered by Cainozoic deposits. The southwestern boundary of the Block - the Eyre Lineament, along the west coast of the Peninsula is located largely on morphologic grounds, although the zone is characterised by seismic activity (Sutton & White 1968). This boundary of the Block is also ill-defined, however, because Proterozoic volcanic rocks, for example occur southwest of the Eyre Lineament, e.g. in the Nuyts Archipelago.

Crawford (1963) noted numerous lineaments with NW, WNW and ENE trends in the Gawler Block (Fig. 4.5B). He attributed many of them to faulting, as indicated by names such as Hiltaba Granite Graben, Yardea Graben, Moonaree Fault and Yartoo Fault. Crawford also noted curved features at various scales. Some are concentric in plan and are supposedly related to vents in the Gawler Range Volcanic Complex. These include a large so-called ring structure with concentric arcs of approximately 88, 112 and 160 km diameter and centred to the south of Lake Everard. According to Crawford, similar arcs determine the shape of the western shores of Lake Harris. The Paney Arc,

56 km in diameter and centred on Yardea H.S., was considered by Crawford to represent the edge of a cauldron subsidence. The Uno Arc was first noted by Crawford who postulated that it represented the northern part of a conical vent centred on an aeromagnetic high in Lake Gilles. Turner (1975), however, considered this to be part of a north-plunging faulted anticline. Some of the arcs identified by Crawford may be linked linear features, rather than genuine arcuate features.

Parkin (1969, p. 26) published a map showing the major lineaments (interpreted as faults, shear zones and hinge lines) recognised in South Australia. In the area under discussion, the dominant trends of these features are NW-SE, W-E and N-S (Fig. 4.1, 4.5A). Thomson (1970) - who compiled the map printed in Parkin (1969) - used information from the Tectonic Map of Australia (1:5,000,000) and grouped structural features on the basis of trend directions into diagonal, meridional and latitudinal features. In the Gawler Craton these features include the NW trending series of positive aeromagnetic anomalies (which are not strictly lineaments as they have no surface expression), the meridional Torrens Hinge Zone and the latitudinal Uno Fault (Fig. 4.5A).

The most detailed study to date of lineaments in the Gawler Ranges is that by Firman (1974). He plotted patterns for the whole of South Australia from aerial photomosaics. He analysed the directions and noted predominant NW and NE trends, as well as a minor concentration trending NNW. In addition, Firman compared his pattern with other known geologic and geophysical trends, and stated that his lineaments match, are closely aligned with, or fit the general pattern of known structural features.

Harrington *et al.* (1982; see also Moore & Simpson 1982) undertook an analysis of continental scale structures including lineaments, using a digital terrain model (DTM) of Australia. Besides confirming the presence of previously documented lineaments, several large features not previously detected appear in some computer-manipulated images of the DTM. The pattern of lineaments demonstrated by Harrington *et al.* (1982) included a major topographic discontinuity which was construed as an extension of the Gippsland Line of southern and western Victoria (Fig. A3.1). It extends northwestwards into South Australia, and is coincident with the Corrobinnie Depression, which has been interpreted as a fault-line feature (Bourne *et al.* 1974; Binks & Hooper 1984). Further to the west, it can be traced into the Ooldea Range located along a Miocene shoreline (Benbow 1986) at the northeastern margin of the Eucla Basin.

O'Driscoll (1986), using the methods and data of Hills, proposed that important Australian ore deposits are related to major lineaments. Besides the recognition of lineaments from geomorphic data, O'Driscoll showed that some of the lineaments can be located on Bouguer gravity maps, on geologic ingredient maps (maps of geologic boundaries without the distraction of colour), on magnetic trend maps and on aerial photographs. Plots of these data for the whole of Australia revealed a system of major transcontinental lineaments with preferred orientations trending WNW, NNW, NNE and ENE (O'Driscoll 1985). The lineaments transect rocks of various ages and are interpreted as fundamental basement fractures. O'Driscoll (1983) earlier showed that this system of transcontinental trends characteristic of the shield and orogenic areas could also be detected in the basins covered by sedimentary rocks, e.g. in the Eromanga Basin (see Fig. A3.2).

O'Driscoll (personal communication 1987), because of the implied reduction of subjectivity, favoured the use of high frequency linears defined from Landsat imagery. High frequency linears are indicated without extrapolation: each linear represents a continuously visible trace on the image. Thus, two or more linears in line may coincide with a single lineament not continuously visible on the image. The gaps between the linears may represent a continuation of the feature. Alternatively, a zone of different intensity of deformation may be indicated (see Fig. A2.1).

O'Driscoll devised a method of revealing additional structural features using high frequency linears identified from Landsat imagery. He demonstrated the occurrence of structural corridors which are relatively narrow belts or zones in which the density, not necessarily the trend, of linears stands in marked contrast with that of surrounding areas. These corridors serve as structural controls of basin development and sedimentation, and as conduits for intrusion or extrusion of magmas. In many areas the centres or edges of structural corridors are significantly related to mineral deposits, and it is in this context that the method was developed by O'Driscoll (see e.g. O'Driscoll 1981). The plot of linears in the Gawler Ranges is, however, too small and diffuse for much significance to be attached to any changes in density of linears.

The photolineaments shown on the tectonic sketch of the Yardea 1:250,000 geologic map sheet (Blissett 1987) were interpreted from Landsat imagery. They range in length from about 2-25 km and correspond with the lineaments interpreted in this study as regional scale orthogonal fractures and are not considered further.

Relatively few of the lineaments plotted by previous workers appear on all, or even on most, of the plots (Fig. 4.1, 4.5A, 4.5B, 4.5C). The NW-SE trending lineament defined by Harrington *et al.* (1982) corresponds with that of Crawford (1963) and that of Parkin (1969) located in the Corrobinnie Depression. The lineaments aligned parallel to this and running through Lake Gairdner appear on the plots of Dickinson and Sprigg (1953) and Parkin (1969). The west-east lineament coinciding with the Uno Fault is present on the Crawford (1963), Parkin (1969) and Thomson (1970) plots. Of the remainder, some lineaments correspond for part of their length and others are essentially parallel, e.g. the WNW lineament north of Lake Acraman, the Moonaree Fault of Crawford (1963), is parallel to a lineament located by Parkin (1969).

A closer examination of the relatively detailed plot of Firman (1974), and a comparison with the present study revealed some major discrepancies. The lineaments defined by Firman for the Gawler Ranges area were extracted by the author from the statewide study (Fig. 4.5C). Some lineaments shown on Firman's map cannot be found on the plot derived from satellite imagery (Fig 4.6), or on published maps, or on the ground. Also, some lineaments, including some major features discernible on satellite imagery, were not mapped by Firman. In addition, despite Firman's statement that his structural lineaments match, are closely aligned with, or fit the general pattern of known structural features, most in the Gawler Ranges area would be classed as only approximately parallel to known features. No close correspondence can be found for those indicated by X on Figure 4.5C. In some instances, a correspondence with known features is claimed by Firman, but no lineament occurs on his plot. Perhaps these are errors of omission, or they may be a reflection of preconceived ideas of what ought to be there. Apart from these discrepancies the lineament plot of Firman looks realistic and comprehensive. If his plot is concerned with surface expressions of major structures, there ought to be at least general agreement with the analysis of lineament trends derived from satellite imagery.

To facilitate a comparison with the author's plot, Firman's lineaments in the study area were analysed using the same directional frequency method (see Appendix 2). The dominant trends of Firman's lineaments (Fig. A3.3) analysed by total number fall within the ranges 125-145° (SE; 140°) and 35-45° (NE; 40°), i.e. SE and NE with maximum percentages at 140° and 40° respectively. The subdominant trends fall within the ranges 60-65° (ENE; 60°) and 155-160° (SSE; 160°). A similar result is obtained when these lineaments are analysed by total length within each class interval. The dominant trend falls within the range 125-145° (SE; 130°), and subdominant trends occur within the

ranges 35-45° (NE; 40°), 155-160° (SSE; 160°) and 60-65° (ENE; 60°). There are considerable discrepancies between the plots due to Firman and to the author. For example, the dominant (by number and by length) SE trend in Firman's plot (Fig. A3.3A, A3.3B) finds no exact equivalent in the author's analysis, which displays a prominent SSE trend (Fig. 4.7A, 4.7B), and the dominant (by number) and subdominant (by length) NE trend of Firman's plot is represented by only a minor peak in the author's analysis. These results are very similar to those for the whole of South Australia obtained by Firman, except that an additional subdominant trend (ENE) is also present in the study area.

If all of these studies are concerned with lineaments, i.e. straight features of regional extent reflecting structures in the underlying basement, the results ought to be in substantial agreement. In fact, of all the lineament plots by previous workers, remarkably few are similar. Some of the data used by earlier workers may have been imprecise or inaccurate. Differences in the plotting of lineaments from aerial photographs and satellite imagery may be due to a shadow illusion created by variations in the incidence of the Sun's rays, resulting in the suppression or emphasis of certain lineaments. But there can be no such excuses for all of the inconsistencies between the various plots. The varied results highlight the problems posed in identification, description and illustration of lineaments, and reflect the highly subjective nature of the interpretations.

A comparison of lineaments with the various scale fracture systems in the Gawler Ranges indicates that, in any one area, there is no close relationship between the orientation and pattern of the features at various scales. For example, a comparison of the dominant trends of lineaments, regional scale orthogonal fractures and faults analysed by number demonstrates the presence of a major trend in the range 135-155° in all three structural features. The dominant fault trend of 50-70°, however, does not appear in either the lineament pattern or the regional scale orthogonal fracture pattern, and the subdominant trend of 165-200° in the regional scale orthogonal fractures is not represented in either the lineament or the fault pattern. These discrepancies may reflect the small number of features analysed. O'Driscoll (personal communication 1987) has suggested that a close correspondence between the patterns of the different structural features cannot be expected, if only because the treatment at different scales calls for a different degree of generalization. It is possible, for example, that the lineaments represent fracture zones whose orientations differ from those of the constituent fractures. This is particularly true if the features being analysed are fractals.

A fractal is a mathematical term coined by Mandelbrot (1983) to refer to a set of geometrical shapes, e.g. curves or surfaces, the properties of which grow more and more irregular as the magnification of observation is increased. The shapes consist of a hierarchy of like elements at various scales. To apply this concept to structural features that appear on Landsat imagery, closer observation may reveal linear features to be composed of elements which are oriented at various angles to the overall trend. The possibilities are infinite (Sander 1987). As far as the features in the Gawler Ranges are concerned, as it is not possible to observe most of them in the field, it is not possible to ascertain which major trends are, indeed, composite features.

Thus, the relationship between the lineaments and the fractures at various scales is extremely complex and, although it is apparent that the features are genetically related, the details are as yet unknown.

REFERENCES

- Aghassy, J. 1970. Jointing, drainage and slopes in a West African epeirogenic savannah landscape. Association of American Geographers Annals 60: 286-298.
- Alexander, L. G., Worotnicki, G. & Aubrey, K. 1963. Stress and deformation in rock and rock support, Tumut 1 and 2 underground power stations. Fourth Australian-New Zealand Conference on Soil Mechanics and Foundation Engineering, Adelaide: 165-178.
- Alexander, L. T. & Cady, J. G. 1962. Genesis and hardening of laterite in soils. United States Department of Agriculture Technical Bulletin 1282.
- Auden, J. B. 1954a. Erosional patterns and fracture zones in peninsular India. Geological Magazine 91: 89-101.
- Auden, J. B. 1954b. Drainage and fracture patterns in northwest Scotland. Geological Magazine 91: 337-351.
- Austin, P. M. & Williams, G. E. 1978. Tectonic development of late Precambrian to Mesozoic Australia through plate motions possibly influenced by the earth's rotation. Geological Society of Australia Journal 25: 1-21.
- Badgley, P. C. 1965. Structural and tectonic principles. Harper and Row, London.
- Bain, G. W. 1931. Spontaneous rock expansion. Journal of Geology 39: 715-735.
- Bain, A. D. N. 1923. The formation of inselberge. Geological Magazine 60: 97-107.
- Bannister, E. 1980. Joint and drainage orientation of S.W. Pennsylvania. Zeitschrift für Geomorphologie 24: 273-286.
- Barbier, R. 1957. Aménagements hydroélectriques dans le sud de Brésil. Comptes Rendus Sommaire et Bulletin de la Société Géologique de France 6:877-892.
- Barker, D. S. 1983. Igneous rocks. Prentice-Hall, New Jersey.
- Barrell, J. 1920. The piedmont terraces of the northern Appalachians. American Journal of Science 49: 227-258, 327-362, 407-428.
- Barton, D. C. 1916. Notes on the disintegration of granite in Egypt. Journal of Geology 24: 382-393.
- Beard, C. N. 1959. Quantitative study of columnar jointing. Geological Society of America Bulletin 70: 379-382.
- Beavis, F. C. 1985. Engineering geology. Blackwell Scientific, Melbourne.
- Belousov, V. V. 1961. The origin of folding in the Earth's crust. Journal of Geophysical Research 66:2241-2254.
- Belousov, V. V., Rogozhin, E. A. & Sholpo, V. N. 1989. A mechanism of irregular holomorphic folding of the Great Caucasus. In Le Maitre, R. W. (ed). Edwin Sherbon Hills: Pathways in geology. Essays in his honour. Blackwell Scientific, Melbourne. (In press).
- Benbow, M. C. 1986. A palaeogeographic and palaeoclimatic model of the eastern Eucla Basin in the early/middle Miocene. Geological Society of Australia Eighth Convention, Adelaide Abstracts 15: 31-32.
- Bickford, M. E. & Mose, D. G. 1975. Geochronology of Precambrian rocks in the St Francois Mountains, southeastern Missouri. Geological Society of America Special Paper 165.
- Billings, M. P. 1954. Structural geology. First edition. Prentice-Hall, London.
- Billings, M. P. 1972. Structural geology. Third edition. Prentice-Hall, London.
- Binks, P.J. & Hooper, G.J. 1984. Uranium in Tertiary Palaeochannels, 'West Coast Area', South Australia. Australasian Institute of Mining and Metallurgy Proceedings 289: 271-275.
- Bird, E. C. F. 1968. Coasts. Australian National University, Canberra.
- Birkeland, P. W. 1974. Pedology weathering and geomorphological research. Oxford University Press, New York.
- Biro, P. 1952. Le relief granitique dans le nord-ouest de la Péninsule Ibérique. International Geophysical Union Seventeenth Proceedings, Eighth Assembly 301-303.
- Biro, P. 1958. Les domes cristallines. Centre Nationale de la Recherche Scientifique, Centre de Documentation Cartographique et Géographique Memoirs et Documents 6: 7-34.
- Biro, P. & Jérôme, E. 1950. Recherches sur la comportement de l'érosion différentielle dans les roches granitiques de Corse. Comptes rendus de la Congrès Internationale de Géographie (Lisbon): 243-253.
- Blackwelder, E. 1925. Exfoliation as a phase of rock weathering. Journal of Geology 33: 793-806.
- Blackwelder, E. 1933. The insolation hypothesis of rock weathering. American Journal of Science 26: 97-113.
- Blès, J. L. 1986. Fracturation profonde des massifs rocheuse granitiques. Documents du Bureau de Recherches Géologiques et Minières 102.

- Blissett, A. H. 1975. Rock units in the Gawler Range Volcanics, South Australia. Geological Survey of South Australia Quarterly Geological Notes 55: 2-14.
- Blissett, A. H. 1977a. Gairdner map sheet, 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Blissett, A. H. 1977b. Childara map sheet, 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Blissett, A. H. 1980. Childara, South Australia. Explanatory Notes, 1:250,000 Geological Series Sheet SH/53-14. Geological Survey of South Australia.
- Blissett, A. H. 1985. Gairdner, South Australia. Explanatory Notes, 1:250,000 Geological Series Sheet SH/53-15. Geological Survey of South Australia.
- Blissett, A. H. 1986. Subdivision of the Gawler Range Volcanics in the Gawler Ranges. Geological Survey of South Australia Quarterly Geological Notes 97: 2-11.
- Blissett, A. H. 1987. Geological setting of the Gawler Range Volcanics. Geological Atlas Special Series 1:500,000. South Australia Department of Mines and Energy.
- Blissett, A. H., Parker, A. J. & Crooks, A. F. 1988. Yardea map sheet. 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Blissett, A. H., Parker, A. J. & Scheffler, J. 1989. Gawler Range Excursion October 6-9th, 1989. South Australia Department of Mines and Energy Report Book 89/70.
- Blissett, A. H. & Radke, F. 1980. The Gawler Range Volcanics; a regional review. In Parker, A. J. - (compiler). Symposium on the Gawler Craton. Extended Abstracts. Geological Society of Australia Journal 27: 45-48.
- Bloom, A. L. 1978. Geomorphology; A systematic analysis of Late Cenozoic land forms. Prentice-Hall, New Jersey.
- Bobek, H. 1969. Zur Kenntnis der Sudlichen Lut. Mitteilungen der Osterreichischen Geographischen Gesellschaft 3: 155-192.
- Bornhardt, W. 1900. Zur Oberflächengestaltung und Geologie Deutsch Ostafrikas. Reimer, Berlin.
- Bourne, J. A., Twidale, C. R. & Smith, D. M. 1974. The Corrobinnie Depression, Eyre Peninsula, South Australia. Royal Society of South Australia Transactions 98: 139-152.
- Boyd, F. R. 1961. Welded tuffs and flows in the Rhyolite Plateau of Yellowstone Park, Wyoming. Geological Society of America Bulletin 72: 387-426.
- Boyé, M. & Fritsch, P. 1973. Dégagement artificiel d'un dôme cristallin au Sud-Cameroun. Travaux et Documents de Géographie Tropicale 8: 69-94.
- Bradley, W. C. 1963. Large scale exfoliation in massive sandstones of the Colorado Plateau. Geological Society of America Bulletin 74:519-528.
- Brajnikov, B. 1953. Les pains-de-sucre du Brésil: sont-ils enracinés? Comptes Rendus Sommaire et Bulletin de la Societé Géologique de France 6:267-269.
- Brammall, A. 1926. The Dartmoor Granite. Geologists' Association London Proceedings 37:251-277.
- Branagan, D. F. 1968. A tessellated platform, Ku-ring-gai Chase, New South Wales. Royal Society of New South Wales Journal and Proceedings 101:129-133.
- Branagan, D. F. 1973. A skin problem on cold shoulders? Eighth Symposium on Advanced Study of the Sydney Basin. University of Newcastle, Department of Geology Programme and Abstracts 14-15.
- Branagan, D. F. 1963. Tessellated pavements. In Young, R. W. & Nanson, G.C. (eds). Aspects of Australian Sandstone Landscapes. p. 11-20. Australian and New Zealand Geomorphology Group Special Publication 1.
- Branch, C. D. 1966. Volcanic cauldrons, ring complexes and associated granites of the Georgetown Inlier, Queensland. Australia, Department of National Development, Bureau of Mineral Resources, Geology and Geophysics Bulletin 76.
- Branch, C. D. 1975. The petrology and geochemistry of the Gawler Range Volcanics in the Kokatha area, and some economic implications. First Australian Geology Conference, Geological Survey of Australia, Adelaide Abstracts 59.
- Branch, C. D. 1978. Evolution of the Middle Proterozoic Chandabooka Caldera, Gawler Range acid volcano-plutonic province, South Australia. Geological Society of Australia Journal 25: 199-216.
- Branner, J. C. 1897. Decomposition of rocks in Brazil. Geological Society of America Bulletin 7: 255-314.
- Bretz, J. H. 1965. Geomorphic history of the Ozarks of Missouri. Missouri, Division of Geological Survey and Water Resources Report Series 2, 4.
- Bridgman, P. W. 1938. Reflections on rapture. Journal of Applied Physics 9: 517-528.

- Brock, B. B. 1966. The Rift Valley Craton. In Irvine, T. N. (ed). The World Rift System Symposium, Ottawa. September 1965. Geological Survey of Canada, Department of Mines and Technical Surveys Paper 66: 14.
- Brown, D. A., Campbell, K. S. W. & Crook, K. A. W. 1968. The geological evolution of Australia and New Zealand. Pergamon, Oxford.
- Brown, H. Y. L. 1908. Record of the Mines of South Australia. Fourth Edition. Government Printer, Adelaide.
- Brunner, F. K. & Scheidegger, A. E. 1973. Exfoliation. Rock Mechanics 5: 43-62.
- Büdel, J. 1977. Klima-Geomorphologie. Borntraeger, Berlin.
- Burns, K. L. & Shepherd, J. 1976. Satellite lineaments in southeast Australia. In Hodgson, R. A., Gay, S. P. & Benjamins, J. Y. (ed.) First International Conference on the New Basement Tectonics, Salt Lake City, Utah 1974 Proceedings. Utah Geological Association Publication 5: 354-368.
- Campana, B. 1958. The Mt Lofly-Olary region and Kangaroo Island. In Glaessner M. F. & Parkin, L. W. (eds). The Geology of South Australia. pp. 3-27. Melbourne University Press, Melbourne.
- Cas, R. A. F. & Wright, J. V. 1987. Volcanic successions; modern and ancient. Allen & Unwin, London.
- Chan, R. A., Craig, M. A., D'Daddario G. W., Gibson, D. L., Ollier, C. D. & Taylor, G. 1986. The regolith terrain map of Australia 1:5,000,000. Australia, Bureau of Mineral Resources, Geology and Geophysics Record 1986/27.
- Choubert, B. 1949. Géologie et pétrographie de la Guyane Française. Office de la Recherche Scientifique d'Outre-Mer, Paris.
- Choubert, B. 1974. Le Précambrien des Guyanes. Memoires du Bureau de Recherches Géologiques et Minières 81.
- Clayton, R. W. 1956. Linear depressions (Bergfussniederungen) in savannah landscapes. Geographical Studies 3: 102-126.
- Cloos, E. 1936. Der Sierra Nevada-Pluton in Californien. Neues Jahrbuch für Mineralogie, Geologie und Palaeontologie Beitrage-Band 76. B:355-450.
- Cloos, E. 1955. Experimental analysis of fracture patterns. Geological Society of America Bulletin 66: 241-256.
- Cloos, H. 1922. Der Gebirgsbau Schlesiens und die Stellung seiner Bodenschätze. Borntraeger, Berlin.
- Cloos, H. 1936. Plutone und Ihre Stellung im Rahmen der Krustenbewegungen. Sixth International Geological Congress Report 1: 235-253.
- Coates, D. F. 1964. Some cases of residual stress effects in engineering works. In Judd, W. R. (ed.). The state of stress in the Earth's crust. pp. 679-688. Elsevier, New York.
- Corbel, J. 1959. Vitesse d'érosion. Zeitschrift für Geomorphologie 3:1-28.
- Corbett, D. 1972. Geology and Landscape. In Nature Conservation Society. The Gawler Ranges. pp.16-18. Nature Conservation Society, Adelaide.
- Crawford, A. R. 1963. Large ring structures in a South Australian Precambrian volcanic complex. Nature (London) 197 (4863): 140-142.
- Crawford, A. R. 1965. The Geology of Yorke Peninsula, Geological Survey of South Australia Bulletin 39.
- Crickmay, C. H. 1959. A preliminary inquiry into the formation and applicability of the geological principle of uniformity. Crickmay, Calgary.
- Crickmay, C. H. 1968. Some central aspects of the scientific study of scenery. Crickmay, Calgary.
- Crickmay, C. H. 1971. The role of the river. Crickmay, Calgary.
- Cushing, S. W. 1913. The east coast of India. American Geographical Society Bulletin 45: 81-92.
- Daily, B., Twidale, C. R. & Milnes, A. R. 1974. The age of the lateritized summit surface on Kangaroo Island and adjacent areas of South Australia. Geological Society of Australia Journal 21:387-392.
- Dale, T. N. 1923. The commercial granites of New England. United States Geological Survey Bulletin 738.
- D'Algaro, C. R., Johnson, J. E., Forbes, B. G. & Thomson, B. P. 1968. Port Augusta map sheet, 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Daly, S. J. 1985. Tarcoola map sheet 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Daniels, J. L. 1975. Palaeogeographic development of Western Australia: Precambrian. Western Australia Geological Survey Memoir 2.
- Darwin, C. R. 1846. Geological observations on South America. Smith Elder, London.
- Davis, G. H. 1984. Structural geology of rock and regions. John Wiley & Sons, New York.

- Davis, W. M. 1899. The geographic cycle. Geographical Journal 14: 481-504.
- Davis, W. M. 1909. Geographical essays. Dover, Boston.
- Davis, W. M. 1922. Peneplains and the geographic cycle. Geological Society of America Bulletin 23: 587-598.
- Day, M. J. 1980. Rock hardness, field assessment and geomorphic importance. Professional Geographer 32: 72-81.
- Day, M. J. & Goudie, A. S. 1977. Field assessment of rock hardness using the Schmidt Test Hammer. British Geomorphological Research Group Technical Bulletin 18: 19-29.
- Degraff, J. M. & Aydin, A. 1987. Surface morphology of columnar joints and its significance to mechanics and direction of joint growth. Geological Society of America Bulletin 99: 605-617.
- De la Beche, H. T. 1839. Report on the geology of Cornwall, Devon and West Somerset. Geological Survey of England and Wales.
- Demangeot, J. 1978. Les reliefs cuirassés de l'Inde du Sud. (In Géomorphologie des reliefs cuirassés dans les pays tropicaux chauds et humides). Travaux et Documents de Géographie Tropicale 33: 97-111.
- Denham, D., Alexander, L. T. & Worotnicki, G. 1979. Stresses in the Australian crust: evidence from earthquakes and in situ stress measurements. Bureau of Mineral Resources Australia, Journal of Australian Geology and Geophysics 4: 289-295.
- Dickinson, S. B. 1942. The Moonaree Station saline ground waters and the origin of the saline material. Royal Society of South Australia Transactions 66: 32-45.
- Dickinson, S. B. & Sprigg, R. C. 1953. Geological structure of South Australia in relation to mineralisation. In Geology of Australian ore deposits. Fifth Empire Mineralogy and Metallurgy Congress, Melbourne 1: 426-448.
- Dijkers, A. J. 1977. Sketch of a possible lineament pattern in northwest Europe. Geologie en Mijnbouw 56: 275-285.
- Dorn, R. I. 1984. Cause and implications of rock varnish microchemical laminations. Nature (London) 310: 767-770.
- Dumanowski, B. 1968. Influence of petrographical differentiation of granitoids on land forms. Geographia Polonica 7: 93-98.
- Du Toit, A. L. 1939. Geology of South Africa. Oliver & Boyd, Edinburgh.
- Elliott, G. J. 1981. Interpretation of the detailed airborne magnetic survey, Fiddle Hill, Port Augusta sheet, South Australia. South Australia Department of Mines and Energy, Open file envelope 3994: 33-42.
- Engelder, T. 1987. Joints and shear fractures in rock. In Atkinson, B. K. (ed.). Fracture mechanics of rock. pp.27-69. Academic Press, London.
- Engelder, T. & Geiser, P. 1980. On the use of regional joint sets as trajectories of palaeostress fields during the development of the Appalachian Plateau, New York. Journal of Geophysical Research 85: 6319-6341.
- Enlows, H. E. 1955. Welded tuffs of Chiracahua National Monument, Arizona. Geological Society of America Bulletin 66: 1215-1246.
- Ernsberger, F. M. 1960. Detection of strength impairing flaws in glass. Royal Society of London Proceedings A 257: 213-223.
- Evans, J. P. 1988. Deformation mechanisms in granitic rocks at shallow crustal levels. Journal of Structural Geology. 10: 37-443.
- Evans, R. S. 1981. An analysis of secondary toppling rock failures - the stress distribution method. Quarterly Journal of Engineering Geology 14:77-86.
- Everingham, I. B., Gregson, P. J. & Doyle, H. A. 1969. Thrust faults in the Western Australian shield. Nature 223: 701-703.
- Ewart, A. & Healy, J. 1966. Mangakino - Geology. In Thompson, B. N., Kermode, L. O. & Ewart, A. (eds). New Zealand Vulcanology - Central Volcanic Region. New Zealand Department of Scientific & Industrial Research, Information Series 50:48-60.
- Eyre, E. J. 1845. Journals of expeditions into central Australia. Borne, London.
- Falconer, J. D. 1911. The geology and geography of Northern Nigeria. Macmillan, London.
- Fanning, C. M., Blissett, A. H., Flint, A. B., Ludwig, K. R. & Parker, A. J. 1986. A refined geological history of the southern Gawler Craton through U-Pb zircon dating of acid volcanics. Geological Society of Australia Abstracts 15: 67-68.
- Fanning, C. M., Flint, R. B. & Preiss, W. V. 1983. Geochronology of the Pandurra Formation. South Australian Geological Survey Quarterly Geological Notes 88: 11-16.
- Firman, J. B. 1974. Structural lineaments in South Australia. Royal Society of South Australia Transactions 98: 153-171.

- Firman, J. B. 1983. Silcrete near Chundie Swamps: The stratigraphic setting. South Australian Geological Survey Quarterly Geological Notes 85: 2-5.
- Fisher, O. 1866. On the disintegration of a chalk cliff. Geological Magazine 3:354-356.
- Fisher, O. 1872. On cirques and taluses. Geological Magazine 8: 10-12.
- Flint, R. B. 1984. The Gawler Craton. 1:1,000,000 map. South Australia Department of Mines and Energy.
- Flint, R. B. & Parker, A. J. 1982. Tectonic Map of South Australia 1:2,000,000 scale. South Australia Department of Mines and Energy.
- Folk, R. L. & Patton, E. B. 1982. Buttressed expansion of granite and development of grus in central Texas. Zeitschrift für Geomorphologie 26: 17-32.
- Frakes, L. A. 1979. Climates throughout geologic time. Elsevier, Amsterdam.
- Frakes, L. A., McGowran, B. & Bowler, J. M. 1987. Evolution of Australian Environments. In Dyne, G. R. & Walton, D. W. (eds). Fauna of Australia. pp. 1-16. Australian Government Publishing Service, Canberra.
- Fry, E. J. 1926. The mechanical action of corticolous lichens. Annals of Botany 40: 397-417.
- Fry, E. J. 1927. The mechanical action of crustaceous lichens on substrata of shale, schist, gneiss, limestone and obsidian. Annals of Botany 41: 437-460.
- Fuller, R. E. 1938. Deuteric alteration controlled by the jointing of lavas. American Journal of Science 35: 161-171.
- Gage, M. 1966. Franz Josef Glacier. Ice 20: 26-27.
- Geikie, A. 1882. Textbook of Geology. Macmillan, London.
- Geikie, J. 1953. Structural and field geology. Sixth Edition. Oliver & Boyd, Edinburgh.
- Gerdes, R. A. 1978. The Lake Hart Proterozoic Basin in the Gawler Platform. Geological Survey of South Australia Quarterly Geological Notes 67: 7-9.
- Gerrard, A. J. 1974. The geomorphological importance of jointing in the Dartmoor Granite. In Brown, E. H. & Waters, R. S. (eds). Progress in Geomorphology. pp. 39-51. Institute of British Geographers Special Publication 7.
- Gerrard, A. J. 1988. Rocks and landforms. Unwin Hyman, London.
- Gilbert, C. M. 1938. Welded tuff in eastern Canada. Geological Society of America Bulletin 49: 1829-1862.
- Gilbert, G. K. 1904. Domes and dome structures of the High Sierra. Geological Society of America Bulletin 15: 29-36.
- Giles, C. W. 1977. Rock units in the Gawler Range Volcanics, Lake Everard area, South Australia. Geological Survey of South Australia Quarterly Geological Notes 16: 7-16.
- Giles, C. W. 1980. Spring Hill, southern Gawler Ranges. Geological Society of Australia, South Australian Division Geological Monuments III: File E 20. (unpublished).
- Giles, E. 1889. Australia Twice Traversed. Low, Marston, Searle & Rivington, London.
- Gilluly, J. 1955. Geologic contrasts between continents and ocean basins. Geological Society of America Special Paper 62: 7-18.
- Glen, D. C. 1873. Notes from the island of Bute. Geological Society of Glasgow Transactions 5: 154-159.
- Goldich, S. A. 1938. A study in rock weathering. Journal of Geology 46: 17-58.
- Goodman, R. E. 1980. Introduction to rock mechanics. Wiley, New York.
- Gordon, F. R. & Lewis, J. D. 1980. The Meckering and Calingiri earthquakes, October 1968 and March 1970. Geological Survey of Western Australia Bulletin 126.
- Gostin, V. A., Haines, P. W., Jenkins, R. J. F., Compston, W. & Williams I. S. 1986. Impact ejecta horizon within Late Precambrian shales, Adelaide Geosyncline, South Australia. Science 233: 198-200.
- Gramberg, J. 1965. Axial cleavage fracturing, a significant process in mining and geology. Engineering Geology 1: 31-72.
- Hack, J. T. 1960. Interpretation of erosional topography in humid regions American Journal of Science 258 A: 80-97.
- Hack, J. T. 1966. Circular patterns and exfoliation in crystalline terrain, Grandfather Mountain area, North Carolina. Geological Society of America Bulletin 77: 975-986.
- Hack, S. 1857. Explorations by Mr. S. Hack. South Australia Parliamentary Paper 156: 1-10.
- Hallam, A. 1975. Jurassic environments. Cambridge University Press, Cambridge.
- Hallam, A. 1985. A review of Mesozoic climates. Geological Society (London) Journal 142: 433-4545.
- Harland, W. B. 1957. Exfoliation joints and ice action. Journal of Glaciology 3: 8-10.

- Harrington, H. J., Simpson, C. J. & Moore, R. F., 1982. Analysis of continental structures using a digital terrain model (DTM) of Australia. Australia Bureau of Mineral Resources. Journal of Australian Geology and Geophysics 7: 68-72.
- Hayes, W. C. 1961. Physiographic features of the St Francois Mountains. Guidebook to the geology of the St Francois Mountains area. Missouri Geological Survey and Water Resources Report of Investigations 26; 115-118.
- Herrmann, L. A. 1957. Geology of the Stone Mountain-Lithonia district, Georgia. Georgia Geological Survey Bulletin 61.
- Hewes, L. I. 1948. A theory of surface cracks in mud and lava and resulting geometrical relations. American Journal of Science 246: 138-149.
- Hills, E. S. 1946. Some aspects of the tectonics of Australia. Royal Society of New South Wales Proceedings 79: 67-91.
- Hills, E. S. 1956. A contribution to the morphotectonics of Australia. Geological Society of Australia Journal 3: 1-15.
- Hills, E. S. 1961. Morphotectonics and the geomorphological sciences with special reference to Australia. Geological Society of London Quarterly Journal 117: 77-89.
- Hills, E. S. 1963. Elements of structural geology. Methuen, London.
- Hobbs, W. H. 1904. Lineaments of the Atlantic border region. Geological Society of America Bulletin 15: 483-506.
- Hobbs, W. H. 1905. Examples of joint-controlled drainage from Wisconsin and New York. Journal of Geology 13: 363-374.
- Hobbs, W. H. 1911. Repeating patterns in the relief and structure of the land. Geological Society of America Bulletin 22: 123-176.
- Hodgson, R. A. 1961a. Regional study of jointing in Comb Ridge-Navajo Mountain area, Arizona and Utah. American Association of Petroleum Geologists Bulletin 45: 1-38.
- Hodgson, R. A. 1961b. Classification of structures of joint surfaces. American Journal of Science 259: 493-502.
- Hoek, E. & Bray, J. 1981. Rock slope engineering. The Institution of Mining and Metallurgy, London.
- Holmes, A. 1918. The Pre-Cambrian and associated rocks of the district of Mozambique. Geological Society of London Quarterly Journal 74: 31-97.
- Holmes, A. 1965. Principles of physical geology. Second Edition. Nelson, London.
- Holmes, A. & Wray, D. A. 1912. Outlines of the geology of Mozambique. Geological Magazine 9: 412-417.
- Holmes, A. & Wray, D. A. 1913. Mozambique - a geographical study. Geographical Journal 42: 143-152.
- Holmgren, D. A. 1976. Major fracture patterns in the British Isles. In Hodgson, R. A., Gay, S. P. & Benjamins, J. Y. (eds). First International Conference on the New Basement Tectonics, Salt Lake City, Utah 1974, Proceedings. Utah Geological Association Publication 5: 263-278.
- Horwitz, R. C. & Daily, B. 1958. Yorke Peninsula. In Glaessner, M. F. & Parkin, L. W. (eds). Geology of South Australia. pp. 46-60. Melbourne University Press, Melbourne.
- Hsui, A. T. 1982. Crystallization, double diffusive fingering and the formation of columnar joints. EOS (American Geophysical Union Transactions) 63: 1131.
- Hunt, C. B. 1938. A suggested explanation of the curvature of columnar joints in volcanic necks. American Journal of Science (Series 5) 36: 142-149.
- Hurault, J. 1963. Recherches sur les inselbergs granitiques nus en Guyane Française. Revue de Géomorphologie Dynamique 14:49-61.
- Hutton, J. T., Twidale, C. R. & Milnes, A. R. 1978. Characteristics and origin of some Australian silcretes. In Langford-Smith, T. (ed.). Silcrete in Australia. pp. 19-39. University of New England Press. Armidale.
- Iddings, J. P. 1886. The columnar structure of the igneous rock in Orange Mountain, New Jersey. American Journal of Science 31: 321-331.
- Iddings, J. P. 1909. Igneous rocks. Wiley, New York.
- Isaacson, E. de St Q. 1957. Research into the rockburst problem on the Kolar Goldfield. Mine and Quarry Engineering 23: 520-526.
- Isphording, W. C. 1977. Geomorphic evolution of tropical karst terranes. In Tolson, J. S. & Doyle, F. L. (eds). Karst hydrogeology. pp. 115-129. Twelfth Congress of the International Association of Hydrogeologists Memoirs, University of Alabama at Huntsville Press, Huntsville.
- Jack, R. L. 1912. The geology of portions of the counties of Le Hunte, Robinson and Dufferin, with special reference to underground water supplies. Geological Survey of South Australia Bulletin 1.

- Jaeger, J. C. 1961. The cooling of irregularly shaped igneous bodies. American Journal of Science 259: 721-734.
- Jahns, R. H. 1943. Sheet structure in granites: its origin and use as a measure of glacial erosion in New England. Journal of Geology 51: 71-98.
- James, A. V. G. 1920. Factors producing columnar structure in lavas and its occurrence near Melbourne, Australia. Journal of Geology 28: 458-469.
- Jennings, J. N. 1985. Karst geomorphology. Basil Blackwell, Oxford.
- Jennings, J. N. & Twidale, C. R. 1971. Origins and implications of the A-tent, a minor granite landform. Australian Geographical Studies 9: 41-53.
- Jessen, O. 1936. Reisen und Forschungen in Angola. Reimer, Berlin.
- Johns, R. K. 1968. Investigation of lakes Torrens and Gairdner. South Australian Geological Survey Report of Investigations 31.
- Johns, R. K., Hiern, M. N. & Nixon, L. G. 1966. Andamooka map sheet, 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Johns, R. K., Hiern, M. N., Nixon, L. G., Forbes, B. G. & Olliver, J. G. 1981. Torrens map sheet, 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Johnson, D. W. 1932. Rock planes of arid regions. Geographical Review 22:656-665.
- Johnson, M. R. W. & Frost, R. T. C. 1977. Fault and lineament patterns in the southern Highlands of Scotland. Geologie en Mijnbouw 56: 287-294.
- Judson, S. & Andrews, G. W. 1955. Pattern and form of some valleys in the Duftless area, Wisconsin. Journal of Geology 63: 328-336.
- Judson, S. & Ritter, D. F. 1964. Rates of regional denudation. Journal of Geophysical Research 69: 3395-3401.
- Jukes, J. B. 1862. Manual of geology. Black, Edinburgh.
- Jutson, J. T. 1914. An outline of the physiographical geology (physiography) of Western Australia. Western Australia Geological Survey Bulletin 61.
- Kaitanen, V. 1985. Problems concerning the origin of inselbergs in Finnish Lapland. Fennia 163: 359-364.
- Kantha, L. H. 1981. 'Basalt fingers' - Origin of columnar joints. Geological Magazine 118: 251-264.
- Katz, M. B. 1976. Lineament tectonics of the Willyama Block and its relationship to the Adelaide aulacogene. Geological Society of Australia Journal 23: 275-285.
- Kemp, E. M. 1978. Tertiary climatic evolution and vegetation history in the southeast Indian Ocean. Palaeogeography, Palaeoclimatology, Palaeoecology 24: 169-208.
- Kennedy, W. Q. 1962. Some theoretical factors in geomorphological analysis. Geological Magazine 99: 304-312.
- Keyes, C. R. 1912. Deflative systems of the geographic cycle in an arid climate. Geological Society of America Bulletin 23: 537-562.
- Kieslinger, A. 1960. Residual stress and relaxation in rocks. Twentyfirst International Geological Congress (Copenhagen) Report 18: 270-276.
- King, L. C. 1942. South African scenery: a textbook of geomorphology. Oliver & Boyd, Edinburgh.
- King, L. C. 1949a. A theory of bornhardts. Geographical Journal 112: 83-87.
- King, L. C. 1949b. The pediment landform: some current problems. Geological Magazine 86: 245-250.
- King, L. C. 1950. The cyclic land surfaces of Australia. Royal Society of Victoria Proceedings 62: 79-95.
- King, L. C. 1953. Canons of landscape evolution. Geological Society of America Bulletin 64 : 721-752.
- King, L. C. 1957. The uniformitarian nature of hillslopes. Geological Society of Edinburgh Transactions 106: 101-131.
- King, L. C. 1962. Morphology of the Earth. Oliver & Boyd, Edinburgh.
- King, L. C. 1966. The origin of bornhardts. Zeitschrift für Geomorphologie 10: 97-98.
- Kisvarsanyi, G. & Kisvarsanyi, E. B. 1976. Ortho-polygonal tectonic patterns in the exposed and buried Precambrian basement of southeast Missouri. In Hodgson, R. A., Gay, S. P. & Benjamins J. Y. First International Conference on the New Basement Tectonics, Salt Lake City, Utah, Proceedings. Utah Geological Association Publication 5: 169-182.
- Kranck, E. H. 1957. On folding movements in the zone of the basement. Geologische Rundschau 46: 261-282.
- Lafeber, D. 1956. Columnar jointing and intracolumnar differentiation in basaltic rocks. Verhandelingen van het Koninklijk Nederlandsch Geologisch- Mijnbouwkundig Genootschap 16: 241-251.

- Lamego, A. R., 1938. Escarpas do Rio de Janeiro. Ministerio da Agricultura, Departamento Nacional da Producao Mineral Servico Geologico e Mineralogico Boletim 93.
- Laut, P., Heyligers, P. C., Kieg, G., Loffler, E., Margules, C., Scott, R. M. & Sullivan, M. E. 1977. Environments of South Australia. Province 7. Western Pastoral. Australia, Commonwealth Scientific and Industrial Research Organisation, Division of Land Use Research, Canberra.
- Lawson, A. C. 1915. The epigene profiles of the desert. University of California, Berkeley, Publications in Geology 9: 23-40.
- Layshon, P. R. 1973. Two granite-gneiss domes in the Copper Queen area, Rhodesia. Geological Society of South Africa Special Publication 3: 97-109.
- Le Conte, J. N. 1873. On some of the ancient glaciers of the Sierras. American Journal of Science and Arts 5: 325-342.
- Leeman, E. F. 1962. Rock bursts in South African gold mines. New Scientist 16: 79-82.
- Lees, G. M. 1955. Recent Earth movements in the Middle East. Geologische Rundschau 42: 221-226.
- Lehmann, O. 1933. Morphologische Theorie der Verwitterung von Steinschlagwänden. Vierteljahrsschrift Naturforschende Gesellschaft in Zurich 87: 83-126.
- Lehmann, V. H. 1954. Der Tropische Kegelkarst auf der Grossen Antillen. Erdkunde 8: 130-139.
- Leigh, C. H. 1967. Some aspects of the geomorphology of granitic landforms and landscapes on parts of the New England Tableland, New South Wales. Ph. D. Thesis. University of New England, Armidale. (Unpublished).
- Lester, J. G. 1938. Geology of the region round Stone Mountain, Georgia. University of Colorado Studies, Series A 26: 88-91.
- Lewis, W. V. 1954. Pressure release and glacial erosion. Journal of Glaciology 2: 417-422.
- Linton, D. L. 1952. The significance of tors in glaciated lands. Seventeenth International Congress International Geographical Union Proceedings, Lisbon 8: 354-357.
- Linton, D. L. 1955. The problem of tors. Geological Journal 121: 470-487.
- Linton, D. L. 1957. The everlasting hills. Advancement of Science 14: 58-67.
- Lipman, P. W. & Christiansen R. L. 1964. Zonal features of an ashflow sheet in the Piapi Canyon Formation, southern Nevada. United States Geological Survey Professional Paper 501B; 74-78.
- Ljunger, E. 1930. Spaltentektonik und Morphologie der Schwedischen Skagerrak-Kuste. Geological Institution of the University of Uppsala Bulletin 21: 1-478.
- Löffler, E. & Ruxton, B. P. 1969. Relief and landform map of Australia. 1:5,000,000. Australia, Commonwealth Scientific and Industrial Research Organisation, Land Research, Canberra.
- Logan, J. R. 1849. The rocks of Palo Ubin. Genootschap Kunsten Wetenschappen (Batavia) 22: 3-43.
- Long, P. E. & Wood, B. J. 1986. Structures, textures and cooling histories of Columbia River basalt flows. Geological Society of America Bulletin 97: 1144-1155.
- Longchambon, M. 1913. Considerations sur la formation des colonnes prismatiques dans les coulees de roches eruptives. Societe Géologique de France Bulletin, Series 4, 13: 33.
- Loughnan, F. C. 1969. Chemical weathering of the silicate minerals. Elsevier, New York.
- Mabbutt, J. A. 1961. A stripped land surface in Western Australia. Institute of British Geographers Transactions and 29: 101-114.
- Mabbutt, J. A. 1966. Landforms of the Western Macdonnell Ranges. In Dury, G. H. (ed.) Essays in Geomorphology. pp. 83-119. Heinemann, London.
- Mabbutt, J. A. 1973. Landforms. Atlas of Australian Resources. Australia Department of Minerals and Energy, Geographic Section, Canberra.
- MacCulloch, J. 1814. On the granite tors of Cornwall. Geological Society Transactions 2: 66-78.
- Macdonald, G. A. 1968. Extrusive basaltic rocks. In Hess, H. H. & Poldervaart, A. Basalts, Poldevaart Treatise on rocks of basaltic composition. pp. 40-45. John Wiley & Sons, New York.
- Mackin, J. H. 1960. Structural significance of Tertiary volcanic rocks in southwestern Utah. American Journal of Science 258: 81-131.
- MacMahon, C. A. 1893. Notes on Dartmoor. Geological Society of London Quarterly Journal 49: 385-397.
- Mainguet, M. 1968. Le Borku. Aspects d'un modelé éolien. Annales de Géographie 77: 296-322.
- Mainguet, M. 1972. Le modelé des gres. Institut Geographique National, Paris.
- Mallet, R. 1875. On the origin and mechanism of production of the prismatic structure of basalt. Philosophical Magazine, Series 4, 50: 122-135 & 201-226.
- Mandelbrot, B. B. 1983. The fractal geometry of Nature. Freeman and Company, New York.

- Marshall, P. 1935. Acid rocks of the Taupo-Rotorua Volcanic District. Royal Society of New Zealand Transactions and Proceedings 64: 323-366.
- Martin, D. 1989. A stirring of crystals and currents. New Scientist 25 November: 35-41.
- Matthes, F. E. 1930. Geologic history of the Yosemite Valley. United States Geological Survey Professional Paper 160.
- Maughan, E. K. & Perry, W. J. 1986. Lineaments and their tectonic implications in the Rocky Mountains and adjacent plains region. In Peterson, J. A. (ed.). Paleotectonics and sedimentation in the Rocky Mountain Region, United States. pp. 41-53. American Association of Petroleum Geologists Memoir 41.
- McCall, G. J. H. 1977. Meteorite craters. Benchmark Papers in Geology 36. Dowden, Hutchison & Ross, Stroudsburg, Pennsylvania.
- McFarlane, M. J. & Heydemann, M. T. 1984. Some aspects of kaolinite dissolution by a laterite-indigenous micro-organism. Geographie et Ecologie Tropicale 8: 73-91.
- McKinstry, H. E. 1953. Shears of the second order. American Journal of Science 251: 401-414.
- Mead, W. J. 1920. Notes on the mechanics of geologic structures. Journal of Geology 28: 505-523.
- Mennell, F. P. 1904. Some aspects of the Matapos. Rhodesian Scientific Association Proceedings 4: 72-77.
- Merrill, G. P. 1898. Treatise on rocks, weathering and soils. Macmillan, London.
- Meunier, A. R. 1961. Contribution a l'étude géomorphologique du Nord-est du Brésil. Société Géologique de France Bulletin, Series 7, 3: 492-500.
- Michel, P. 1978. Cuirassés bauxitiques et ferrugineuses d'Afrique occidentale. Aperçu chronologique. (In Géomorphologie des reliefs cuirassés dans les pays tropicaux et humides). Travaux et Documents de Géographie Tropicale 33: 11-32.
- Milnes, A. R., Bourman, R. P. & Fitzpatrick, R. W. Petrology and mineralogy of 'laterites' in southern and eastern Australia and southern Africa. Chemical Geology 60:237-250.
- Moody, J. D. & Hill, M. J. 1956. Wrench-fault tectonics. Geological Society of America Bulletin 67: 1207-1246.
- Moore, R. F. & Simpson, C. T. 1982. Computer manipulation of a digital terrain model (DTM) of Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 7: 63-67.
- Morin, S. 1982. Types d'évolution des versants dans l'ouest Cameroun. Laboratoire de Géographie Physique Appliquée, Université de Bordeaux, Travaux 6: 39-95.
- Mount, T. J. 1982. Geology of the Dullingari Murta oilfield. In Moore, P. S. & Mount, T. J. (eds). Eromanga Basin symposium, summary papers. pp. 356-374. Geological Society of Australia and Petroleum Exploration Society Australia, Adelaide.
- Moye, D. G. 1958. Rock mechanics in the investigation and construction of T.1 underground power station, Snowy Mountains, Australia. Geological Society of America Engineering Geology Case Histories 3.
- Mueller, J. E. & Twidale C. R. 1988. Geomorphic development of City of Rocks, Grant County, New Mexico. New Mexico Geology 10: 74-79.
- Nature Conservation Society of South Australia. 1972. The Gawler Ranges - report on a survey 29 September- 9 October. Nature Conservation Society, Adelaide.
- Nesbitt, H. M. 1979. Mobility and fractionation of rare earth elements during weathering of a granodiorite. Nature (London) 279: 206-210.
- Nesbitt, H. W., Markovics, G. & Price, R. C. 1980. Chemical processes affecting alkalis and alkaline earths during continental weathering. Geochimica et Cosmochimica Acta 44: 1659-1666.
- Nickelsen R. P. & Hough, V. D. 1967. Jointing in the Appalachian Plateau of Pennsylvania. Geological Society of America Bulletin 78: 609-630.
- Obst, E. 1923. Das abflusslose Rumpfschollenland in nordöstlichen Deutsch-Ostafrika. Mitteilungen der Geographischen Gesellschaft in Hamburg 35.
- O'Driscoll, E. S. T. 1980. The double helix in global tectonics. Tectonophysics 63: 397-417.
- O'Driscoll, E. S. T. 1981. Structural corridors in Landsat lineament interpretation. Mineralium Deposita 16: 85-101.
- O'Driscoll, E. S. T. 1982. Patterns of discovery - the challenge for innovative thinking. Petroleum Exploration Society of Australia Journal 1: 11-31.
- O'Driscoll, E. S. T. 1983. Deep tectonic foundations of the Eromanga Basin. Petroleum Exploration Society of Australia Journal 23: 5-17.
- O'Driscoll, E. S. T. 1985. The application of lineament tectonics in the discovery of the Olympic Dam Cu-Au-U deposit at Roxby Downs, South Australia. Global Tectonics and Metallogeny 3: 43-57.
- O'Driscoll, E. S. T. 1986. Observations of the lineament ore relation. Royal Society of London Philosophical Transactions, Series A 317: 195-219.



- Oen, I. S. 1965. Sheeting and exfoliation in the granites of Sermersôq, South Greenland. Meddelelser om Grønland 179: 1-40.
- O'Leary, D. W., Friedman, J. D. & Pohn, H. A. 1976. Lineament and linear, a terminological reappraisal. In Podwysoki, M. H. & Earle, J. L. (eds). Second International Conference on Basement Tectonics, Denver Proceedings. pp. 571-577.
- Ollier, C. D. 1964. Dirt cracking - a type of insolation weathering. Australian Journal of Science 27 : 263-267.
- Ollier, C. D. 1969. Weathering. Oliver & Boyd, Edinburgh.
- Ollier, C. D. 1971. Causes of spheroidal weathering. Earth Science Review 7: 127-141.
- Ollier, C. D. & Tuddenham, W. G. 1962. Inselbergs of central Australia. Zeitschrift für Geomorphologie 5: 257-276.
- O'Reilly, J. P. 1879. Explanatory notes and discussion on the nature of the prismatic forms of a group of columnar basalts, Giants' Causeway. Royal Irish Academy Transactions 26: 641-728.
- Parker, A. J. 1983. Whyalla map sheet, 1:250,000 Geological Series. South Australia Department of Mines and Energy.
- Parker, A. J., Fanning, C. M. & Flint, R. B. 1985. Geology. In Twidale, C. R., Tyler, M. J. & Davies, M. (eds). Natural History of Eyre Peninsula. pp.21-45. Royal Society of South Australia, Adelaide.
- Parkin, L. W. 1969. Handbook of South Australian Geology. Geological Survey of South Australia, Adelaide.
- Partridge, T. C. & Maud, R. R. 1987. Geomorphic evolution of southern Africa since the Mesozoic. South African Journal of Geology 90: 179-208.
- Passarge, A. 1895. Adamaua. Reimer, Berlin.
- Passarge, S. 1904. Die inselberglandschaft im tropischen Afrika. Naturwissenschaftliche Wochenschrift 42.
- Pavich, M. J. 1986. Processes and rates of saprolite production and erosion on a foliated granitic rock of the Virginian Piedmont. In Colman, S. M. & Dethier, D. P. (eds). Rates of chemical weathering of rocks and minerals. pp. 551-590. Academic Press, Orlando.
- Peck, D. L. & Minakimi, T. 1968. The formation of columnar joints in the upper part of Kilauean lava lakes. Geological Society of America Bulletin 79: 1151-1166.
- Peel, R. F. 1960. Some aspects of desert geomorphology. Geography 45: 241-262.
- Playford, P. E., Cope, R. N., Cockbain, A. E., Low, G. H. & Lowry, D. C. 1975. Perth Basin: Collie and Wilga Basins: Superficial Phanerozoic deposits on the West Australian Shield. Geological Survey of Western Australia Memoir 2: 227-259, 420-431, 432-433.
- Pohn, H. A. 1983. The relationship of joints and stream drainage in flat-lying rocks of south-central New York and northern Pennsylvania. Zeitschrift für Geomorphologie 27: 375-384.
- Pollard, D. D. & Aydin, A. 1988. Progress in understanding jointing over the past century. Geological Society of America Bulletin 100: 1181-1204.
- Preiss, W. V. 1987. The Adelaide Geosyncline. Geological Survey of South Australia Bulletin 53.
- Preston, F. W. 1930. Ball and socket jointing in basalt prisms. Royal Society of London Proceedings, Series B 106: 87-93.
- Price, N. J. 1966. Fault and joint development in brittle and semi-brittle rock. Pergamon, New York.
- Pugh, J. C. 1956. Fringing pediments and marginal depressions in the inselberg landscape of Nigeria. Institute of British Geographers Transactions and Papers 22:15-31.
- Quilty, P. G. 1984. Phanerozoic climates and environments of Australia. In Veevers, J. J. (ed.). Phanerozoic earth history of Australia. pp. 48-57. Clarendon Press, Oxford.
- Ramsay, A. C. 1846. On the denudation of South Wales. Geological Survey of Great Britain Memoir 1: 297-335.
- Ramberg, I. B., Gabrielsen, R. H., Larsen, B. T. & Solli, A. 1977. Analysis of fracture pattern in southern Norway. Geologie en Mijnbouw 56: 295-310.
- Roberts, J. C. 1961. Feather fracture, and the mechanics of rock-jointing. American Journal of Science 259: 481-492.
- Rod, E. 1966. Clues to ancient Australian geosutures. Eclogae Geologicae Helvetiae 59: 849-883.
- Rognon, P. 1967. Le Massif de l'Atakor et ses bordures. (Sahara central). Editions du Centre National de la Recherche Scientifique, Paris.
- Ross, C. S. & Smith, R. L. 1961. Ash flows, their origin, geologic relations and identification. United States Geological Survey Professional Paper 366.
- Ruellan, F. 1931. La décomposition et la désagregation du granite à biotite au Japon et au Corse et les formes du modelé qui en resultent. Academie Sciences (Paris) Comptes Rendus 193: 67-69.
- Ryan, M. P. & Sammis, C. G. 1978. Cyclic fracture mechanisms in cooling basalt. Geological Society of America Bulletin 89: 1295-1308.

- Sander, L. M. 1987. Fractal growth. Scientific American 256: 82-88.
- Sarna-Wotcicki, A. M., Shipley, S., Waitt, R. B., Dzurisin, D. & Wood, S. H. 1981. Areal distribution, thickness, mass, volume and grain size of air-fall ash from the six major eruptions of 1980. United States Geological Survey Professional Paper 1250: 577-600.
- Scheffer, F., Meyer, B. & Kalk, E. 1963. Biologische Ursachen der Wüstenlackbildung. Zeitschrift für Geomorphologie 7: 112-119.
- Schrepfer, H. 1933. Inselberge in Lappland und Neufundland. Geologische Rundschau 24: 137-143.
- Schumm, S. A. 1963. Disparity between present rates of denudation and orogeny. United States Geological Survey Professional Paper 454.
- Selby, M. J. 1977. Bornhardts of the Namib Desert. Zeitschrift für Geomorphologie 21:1-13.
- Selby, M. J. 1985. Earth's Changing Surface. Clarendon Press, Oxford.
- Shaler, N. S. 1869. Notes on the concentric structure of granitic rocks. Boston Society of Natural History Proceedings 12: 289-293.
- Sheldon, P. G. 1912. Some observations and experiments on joint planes. Journal of Geology 20: 53-79.
- Shepherd, R. G. 1968. Regional hydrological survey of Counties Buxton and Jervois. Geological Survey of South Australia Report Book 67/113. (Unpublished).
- Simpson, H. 1948. Discussion (of Hewes 1948). American Journal of Science 246: 591-592.
- Skinner, B. J. & Porter, S. C. 1987. Physical Geology. John Wiley & Sons, New York.
- Smalley, I. J. 1966. Contraction network in basalt flows. Geological Magazine 103: 110-114.
- Smedes, H. W. & Lang, A. J. 1955. Basalt column rinds caused by deuteric alteration. American Journal of Science 253: 173-181.
- Smith, D. M. 1976. The denudation chronology of the southern Gawler Ranges and adjacent areas. M.A. Thesis. Department of Geography, University of Adelaide, Adelaide. (unpublished).
- Sosman, R. B. 1916. Types of prismatic structure in igneous rocks. Journal of Geology 24: 215-234.
- South Australia, Department of Mines and Energy. 1982a. Bouguer gravity anomaly map of South Australia 1:2,000,000. South Australia, Department of Mines and Energy, Adelaide.
- South Australia, Department of Mines and Energy. 1982b. Total magnetic intensity map of South Australia 1:2,000,000. South Australia, Department of Mines and Energy, Adelaide.
- Sparks, B. W. 1974. Geomorphology (Second Edition). Longman, London.
- Spencer, E. W. 1977. Introduction to the Structure of the Earth. (Second Edition). McGraw-Hill Kogakusha, Tokyo.
- Spry, A. H. 1962. The origin of columnar jointing, particularly in basalt flows. Geological Society of Australia Journal 8: 191-21.
- Spry, A. H. & Solomon, M. 1964. Columnar buchites at Apsley, Tasmania. Geological Society of London Quarterly Journal 120: 519-545.
- Stapledon, D. H. 1966. Geological investigations at the site for Kangaroo Creek Dam, South Australia. Institution of Engineers Site Investigation Symposium, Sydney 1966.
- Stauffer, M. R. & Gendzwill, D. J. 1987. Fractures in the northern plains, stream patterns, and the midcontinent stress field. Canadian Journal of Earth Sciences 24: 1086-1097.
- Sternberg, H. O. & Russell, R. J. 1952. Fracture patterns in the Amazon and Mississippi valleys. Eighth General Assembly and Seventeenth International Congress of the International Geographical Union, Washington, Proceedings pp. 380-385.
- Stewart, I. C. F., Slade, A. & Sutton, D. J. 1973. South Australian seismicity 1967-1971. Geological Society of Australia Journal 19: 441-452.
- Sussmilch, C. A. 1922. Geology of New South Wales. (Third edition). Angus & Robertson. Sydney.
- Sutton, D. J. & White. 1968. The seismicity of South Australia. Geological Society of Australia Journal 15: 25-32.
- Sweeting, M. M. 1972. Karst landforms. Macmillan, London.
- Tator, B. A. 1952. Pediment characteristics and terminology. Part I Objectives. Association of American Geographers Annals 42: 295-317.
- Tator, B. A. 1953. Pediment characteristics and terminology. Part II Terminology. Association of American Geographers Annals 43: 47-53.
- Thomas, G. E. 1974. Lineament-block tectonics: Williston-Blood Creek basin. American Association of Petroleum Geologists 58: 1305-1322.
- Thomas, G. E. 1976. The crustal fracture system of North America and its possible origin. In Hodgson, R. A., Gay, S. P. & Benjamins, J. Y. (eds). First International Conference on the New Basement Tectonics, Salt Lake City, Utah 1974. Utah Geological Association Publication 5: 537-549.
- Thomas, M. F. 1965. Some aspects of the geomorphology of domes and tors in Nigeria. Zeitschrift für Geomorphologie 9: 63-81.

- Thomas, M. F. 1966. Some geomorphological implications of deep weathering patterns in crystalline rocks in Nigeria. Institute of British Geographers Transactions 40: 173-193.
- Thomson, B. P. 1969. Precambrian crystalline basement. In Parkin, L. W. (ed.). Handbook of South Australian Geology. pp.21-48. Geological Survey of South Australia, Adelaide.
- Thomson, B. P. 1970. A review of the Precambrian and Lower Proterozoic tectonics of South Australia. Royal Society of South Australia Transactions 94: 193-221.
- Thomson, J. 1864. On the origin of the jointed prismatic structure in basalts and other igneous rocks. British Association for the Advancement of Science Transactions of the Thirty-third Meeting, Newcastle. p. 89.
- Thomson, J. 1879. Jointed prismatic structures in basaltic rocks. Geological Society of Glasgow Transactions 6: 95-110.
- Tolman, C. F. & Robertson, F. 1969. Exposed Precambrian rocks in southeast Missouri. Contribution to Precambrian Geology 1. Missouri Geological Survey and Water Resources Report of Investigations 44.
- Tompkeieff, S. I. 1940. The basalt lavas of the Giants' Causeway District of northern Ireland. Bulletin Volcanologique 6: 89-143.
- Trudinger, P. A. & Swaine, D. J. 1979. Biogeochemical cycling of mineral-forming elements. Elsevier Scientific Publishing Co., Amsterdam.
- Tucker, D. H., Boyd, D. M. & Anfiloff, V. 1986. Magnetic dykes of Australia. 1:5,000,000. Australia Bureau of Mineral Resources, Canberra.
- Turner, A. R. 1975. The petrology of the eastern Gawler Ranges Volcanic Complex. Geological Survey of South Australia Bulletin 45.
- Turner, F. J. & Verhoogen, J. 1960. Igneous and metamorphic petrology. McGraw-Hill, New York.
- Twidale, C. R. 1962. Steepened margins of inselbergs from northwestern Eyre Peninsula, South Australia. Zeitschrift für Geomorphologie 6: 51-69.
- Twidale, C. R. 1964. A contribution to the general theory of domed inselbergs. Conclusions derived from observations in South Australia. Institute of British Geographers Transactions and Papers 34: 91-113.
- Twidale, C. R. 1966. Geomorphology of the Leichhardt-Gilbert area of northwest Queensland. Australia Commonwealth Scientific and Industrial Research Organization, Land Research Series 16.
- Twidale, C. R. 1967. Origin of the piedmont angle, as evidenced in South Australia. Journal of Geology 75: 393-411.
- Twidale, C. R. 1971. Structural landforms. Australian National University Press, Canberra.
- Twidale, C. R. 1972. The neglected third dimension. Zeitschrift für Geomorphologie 16: 283-300.
- Twidale, C. R. 1973. On the origin of sheet jointing. Rock Mechanics 5: 163-187.
- Twidale, C. R. 1976a. On the survival of palaeoforms. American Journal of Science 276: 77-94.
- Twidale, C. R. 1976b. Geomorphological Evolution. In Twidale, C. R., Tyler, M. J. & Webb, B. P. (eds). Natural History of the Adelaide Region. pp. 43-59. Royal Society of South Australia, Adelaide.
- Twidale, C. R. 1976c. Analysis of landforms. John Wiley & Sons, Sydney.
- Twidale, C. R. 1978. On the origin of Ayers Rock, central Australia. Zeitschrift für Geomorphologie Supplement-band 31: 177-306.
- Twidale, C. R. 1980a. Landforms. In Corbett, D. W. P. (ed.). A field guide to the Flinders Ranges. pp.13-41. Rigby, Adelaide.
- Twidale, C. R. 1980b. The origin of bornhardts. Geological Society of Australia Journal 27: 195-208.
- Twidale, C. R. 1981a. Granite inselbergs; domed, block-strewn and castellated. Geographical Journal 147: 54-71.
- Twidale, C. R. 1981b. Origins and environments of pediments. Geological Society of Australia Journal 28: 423-434.
- Twidale, C. R. 1982a. Granite landforms. Elsevier, Amsterdam.
- Twidale, C. R. 1982b. The evolution of bornhardts. American Scientist 70: 268-276.
- Twidale, C. R. 1983. Pediments, peneplains and ultiplains. Revue de Géomorphologie Dynamique 32: 1-35.
- Twidale, C. R. 1986a. Granite landform evolution: factors and implications. Geologische Rundschau 75: 769-779.
- Twidale, C. R. 1986b. A recently formed A-tent on Mt Wudinna, Eyre Peninsula, South Australia. Revue de Géomorphologie Dynamique 35: 21-24.
- Twidale, C. R. 1987. Review of J. L. Blès 'Fracturation profonde des massifs rocheuses granitiques. Progress in Physical Geography 11: 464.

- Twidale, C. R. 1990. The origin and implications of some erosional landforms. Journal of Geology. (In press).
- Twidale, C. R. & Bourne, J. A. 1975. Episodic exposure of inselbergs. Geological Society of America Bulletin 86: 1473-1481.
- Twidale, C. R. & Bourne, J. A. 1976a. Origin and significance of pitting on granite rocks. Zeitschrift für Geomorphologie 20: 405-416.
- Twidale, C. R. & Bourne, J. A. 1976b. The shaping and interpretation of large residual granite boulders. Geological Society of Australia Journal 23: 371-381.
- Twidale, C. R. & Bourne, J. A. 1978a. Bornhardts developed in sedimentary rocks, central Australia. South African Geographer 60: 34-50.
- Twidale, C. R. & Bourne, J. A. 1978b. Bornhardts. Zeitschrift für Geomorphologie Supplement-Band 31: 111-137.
- Twidale, C. R., Bourne, J. A. & Smith, D. M. 1974. Reinforcement and stabilisation mechanisms in landform development. Revue de Géomorphologie Dynamique 23: 115-125.
- Twidale, C. R., Bourne, J. A. & Smith, D. M. 1976. Age and origin of surfaces on Eyre Peninsula and the southern Gawler Ranges, South Australia. Zeitschrift für Geomorphologie 20: 28-55.
- Twidale, C. R. & Campbell, E. M. 1985. The form of the land surface. In Twidale, C. R., Tyler, M. J. & Davies, M. Natural History of Eyre Peninsula. pp. 57-76. Royal Society of South Australia, Adelaide.
- Twidale, C. R. & Campbell, E. M. 1988. Ancient Australia. Geo Journal 16: 339-354.
- Twidale, C. R., Campbell, E. M. & Foale, M. 1986. Landforms. In Griffin, T. L. C. & McCaskill, M. (eds). Atlas of South Australia. pp. 48-49. Government Printer, Adelaide.
- Twidale, C. R. & Harris, W. K. 1977. On the age of Ayers Rock and the Olgas, central Australia. Royal Society of South Australia Transactions 101: 45-50.
- Twidale, C. R., Shepherd, J. A. & Thomson, R. M. 1970. Geomorphology of the southern part of the Arcoona Plateau and of the Tent Hill region west and north of Port Augusta, South Australia. Royal Society of South Australia Transactions 94: 55-67.
- Twidale, C. R. & Sved, G. 1978. Minor granite landforms associated with the release of compressive stress. Australian Geographical Studies 16: 161-174.
- Veevers, J. J. (ed.). 1984. Phanerozoic Earth History of Australia. Clarendon Press, London.
- Velbel, M. A. 1985. Geochemical mass balances and weathering rates in forested watersheds of the southern Blue Ridge. American Journal of Science 285: 904-930.
- Vening Meinesz, F. A. 1947. Shear patterns of the Earth's crust. American Geophysical Union Transactions 28: 1-61.
- Verstappen, H. T. 1960. Some observations on karst development in the Malay Archipelago. Journal of Tropical Geography 14: 1-10.
- Warburton, P. E. 1858. Report of tour of inspection by Major Warburton. South Australian Parliamentary Paper 25: 38-42.
- Waters, A. C. 1960. Determining direction of flow in basalts. American Journal of Science 258A: 350-366.
- Waters, R. S. 1954. Pseudo-bedding in the Dartmoor Granite. Geological Society of Cornwall Transactions 18:456-462.
- Watt, G. 1804. Observations on basalt, and on the transition from the vitreous to the stony texture which occurs in the gradual refrigeration of melted basalt: with some geological remarks. Royal Society of London Philosophical Transactions 94: 279-314.
- Wellman, P. 1976. Gravity trends and the growth of Australia - a tentative correlation. Geological Society of Australia Journal 23: 11-14.
- Whitaker, C. R. 1973. Pediments, a bibliography. Geo Abstracts, Norwich.
- Whitaker, C. R. 1979. The use of the term 'pediment' and related terminology. Zeitschrift für Geomorphologie 23: 427-439.
- White, W. A. 1945. Origin of granite domes in the southeastern Piedmont. Journal of Geology 53: 276-282.
- White, W. S. 1946. Rock bursts in the granite quarries at Barre, Vermont. United States Geological Survey Circular 13.
- Whitehouse, I. E., McSaveney, M. J., Knuepfer, P. L. K. & Chinn, T. J. H. 1986. Growth of weathering rinds on Torlesse Sandstone, Southern Alps, New Zealand. In Colman S. M. & Dethier, D. P. (eds). Rates of chemical weathering of rocks and minerals. pp. 419-435. Academic Press, Orlando.
- Wilhelmy, H. 1958. Klimamorphologie der Massengesteine. Westermann, Brunswick.
- Williams, G. E. 1986. The Acraman Impact Structure: Source of ejecta in Late Precambrian shales, South Australia. Science 233: 200-203.

- Williams, G. E. 1987. The Acraman Structure - Australia's largest impact scar. Search 18: 143-145.
- Williams, H. & McBirney, A. R. 1979. Volcanology. Freeman & Cooper, San Francisco.
- Willis, B. 1923. Geologic structures. McGraw-Hill, New York.
- Willis, B. 1934. Inselbergs. Association of American Geographers Annals 24: 123-129.
- Winkler, E. M. 1987. Weathering and weathering rates of natural stone. Environmental Geology and Water Sciences 9: 85-92.
- Wood, A. 1940. The development of hillside slopes. Geologists' Association, London Proceedings 53: 28-138.
- Woodard, G. D. 1955. The stratigraphic succession in the vicinity of Mt Babbage Station, South Australia. Royal Society of South Australia Transactions 78: 8-17.
- Wopfner, H. 1969. Mesozoic era. In Parkin, L. W. (ed.). Handbook of South Australian Geology. pp. 133-171. Geological Survey of South Australia, Adelaide.
- Wopfner, H. 1978. Silcrete of northern South Australia and adjacent regions. In Langford-Smith, T. (ed.). Silcrete in Australia. pp. 93-141. Department of Geography, University of New England, Armidale.
- Wopfner, H. 1983. Kaolinisation and the formation of silicified wood on Late Jurassic Gondwana surfaces. In Wilson, R. L. C. (ed.). Residual deposits: surface related weathering processes and materials. pp. 27-31. Geological Society of London, Oxford.
- Wopfner, H. 1985. Some thoughts on the post-orogenic development of northeastern South Australia and adjoining regions. South Australian Department of Mines and Energy Special Publication 5: 365-372.
- Wopfner, H., Callen, R. & Harris, W. K. 1974. The lower Tertiary Eyre Formation of the southwestern Great Artesian Basin. Geological Society of Australia Journal 21: 17-51.
- Wopfner, H., Freytag, I. B. & Heath, G. R. 1970. Basal Jurassic-Cretaceous rocks of the western Great Artesian Basin, South Australia: stratigraphy and environment. American Association of Petroleum Geologists Bulletin 54: 383-416.
- Wopfner, H. & Twidale, C. R. 1967. Geomorphological history of Lake Eyre bBasin. In Jennings, J. N. & Mabbutt, J. A. (eds). Landform studies from Australia and New Guinea. pp. 118-143. Australian National University, Canberra.
- Young, R. W. 1988. Quartz etching and sandstone karst: examples from the east Kimberleys, northwestern Australia. Zeitschrift für Geomorphologie 32: 409-423.
- Zernitz, E. R. 1932. Drainage patterns and their significance. Journal of Geology 40: 498-521.

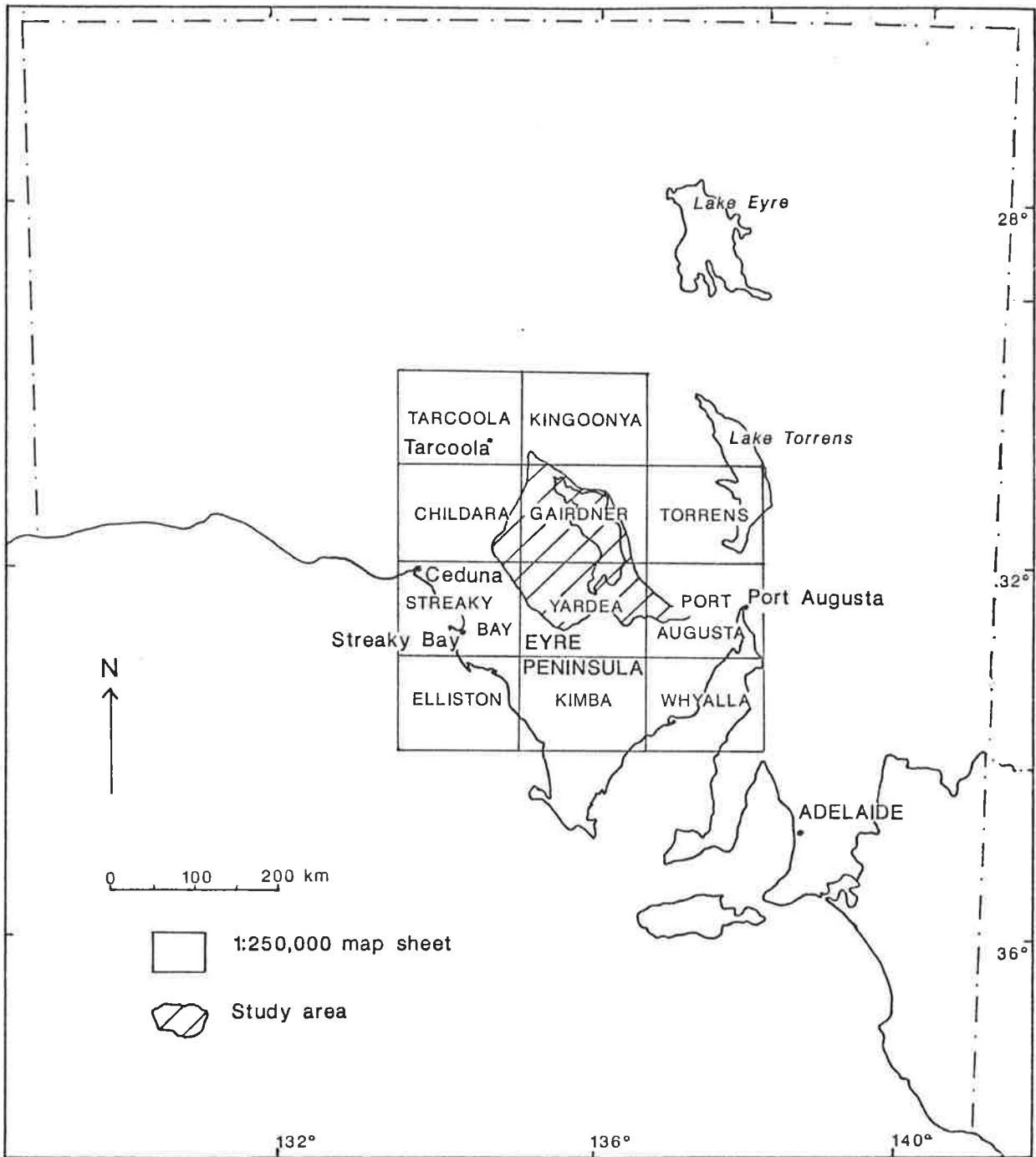


Figure 1.1A Location of study area.

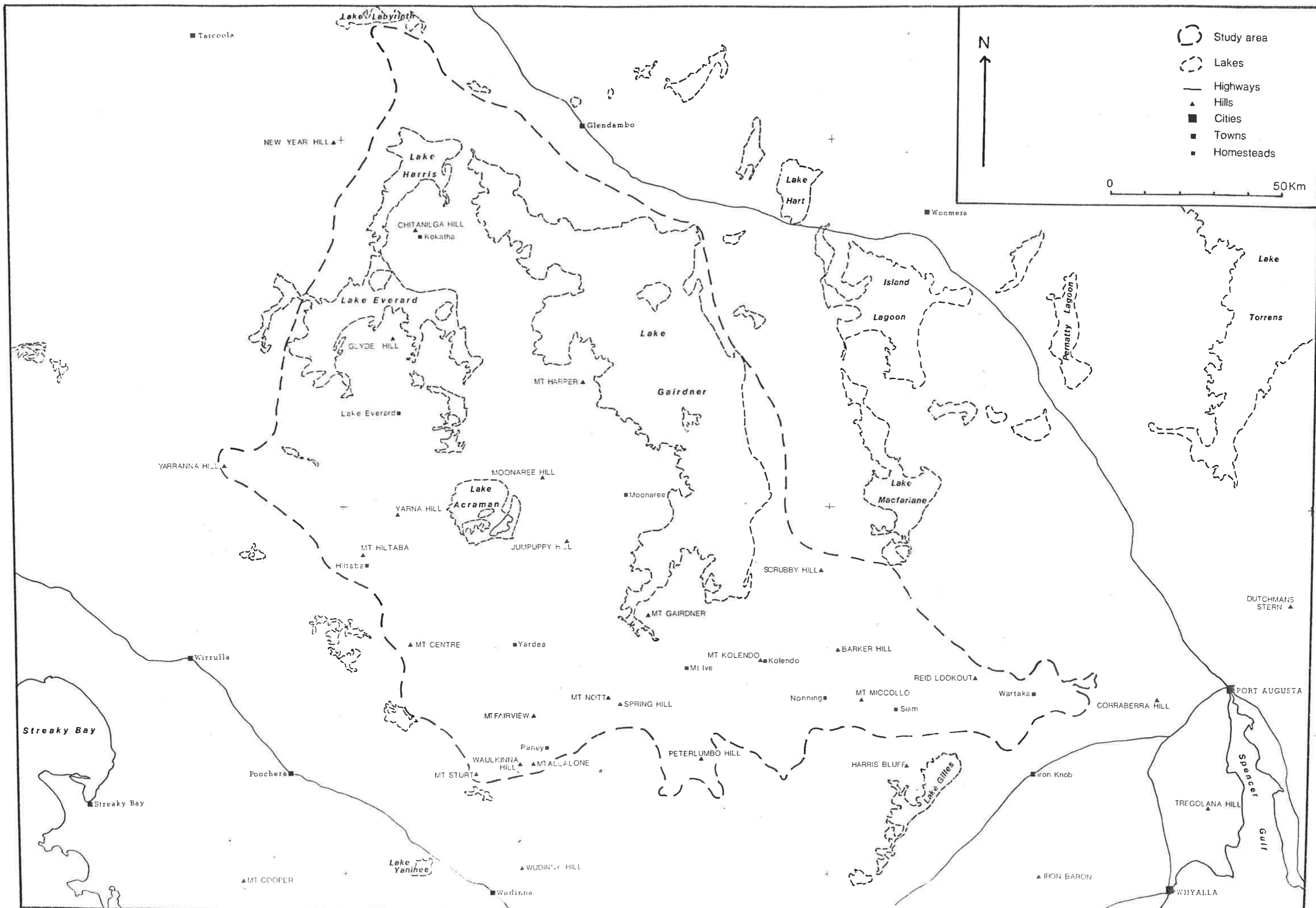
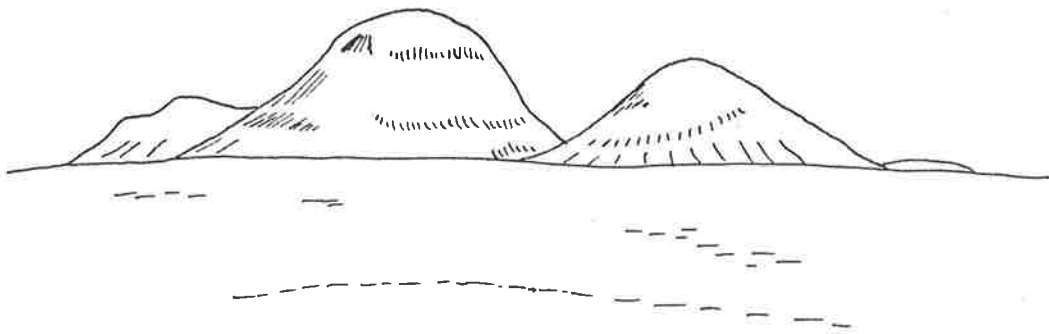
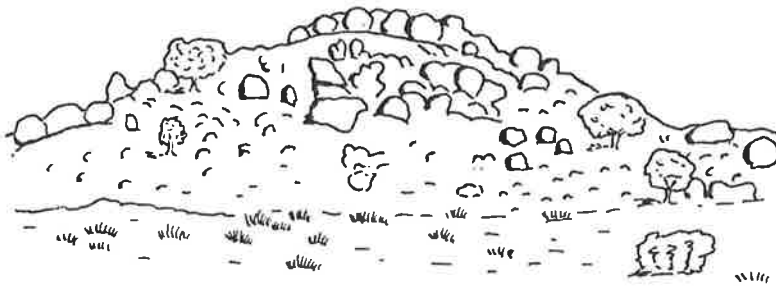


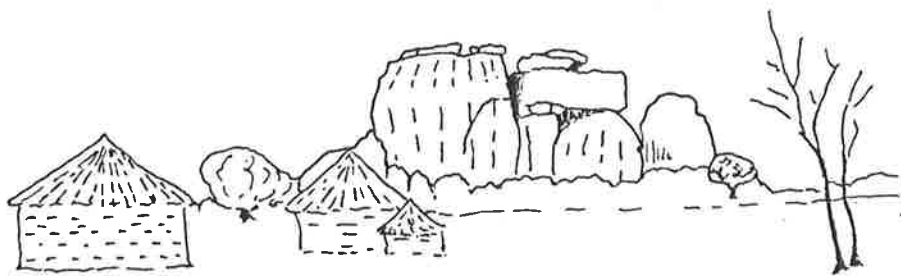
Figure 1.1B Location map of the Gawler Ranges and surrounding areas.



A



B



C

Figure 1.2 Three types of inselberg: (A) bornhardts, (B) nubbins, (C) castle koppies.

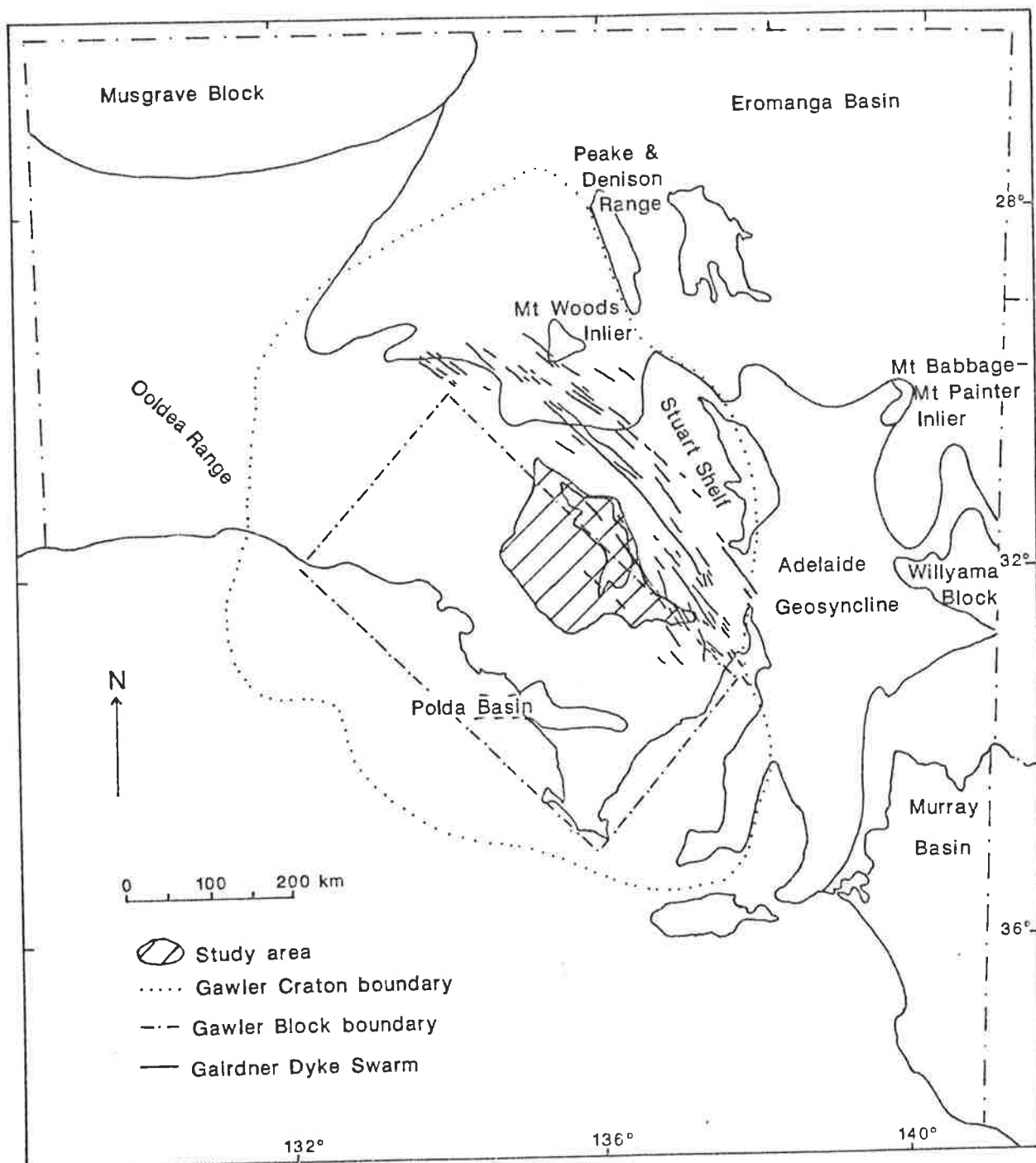
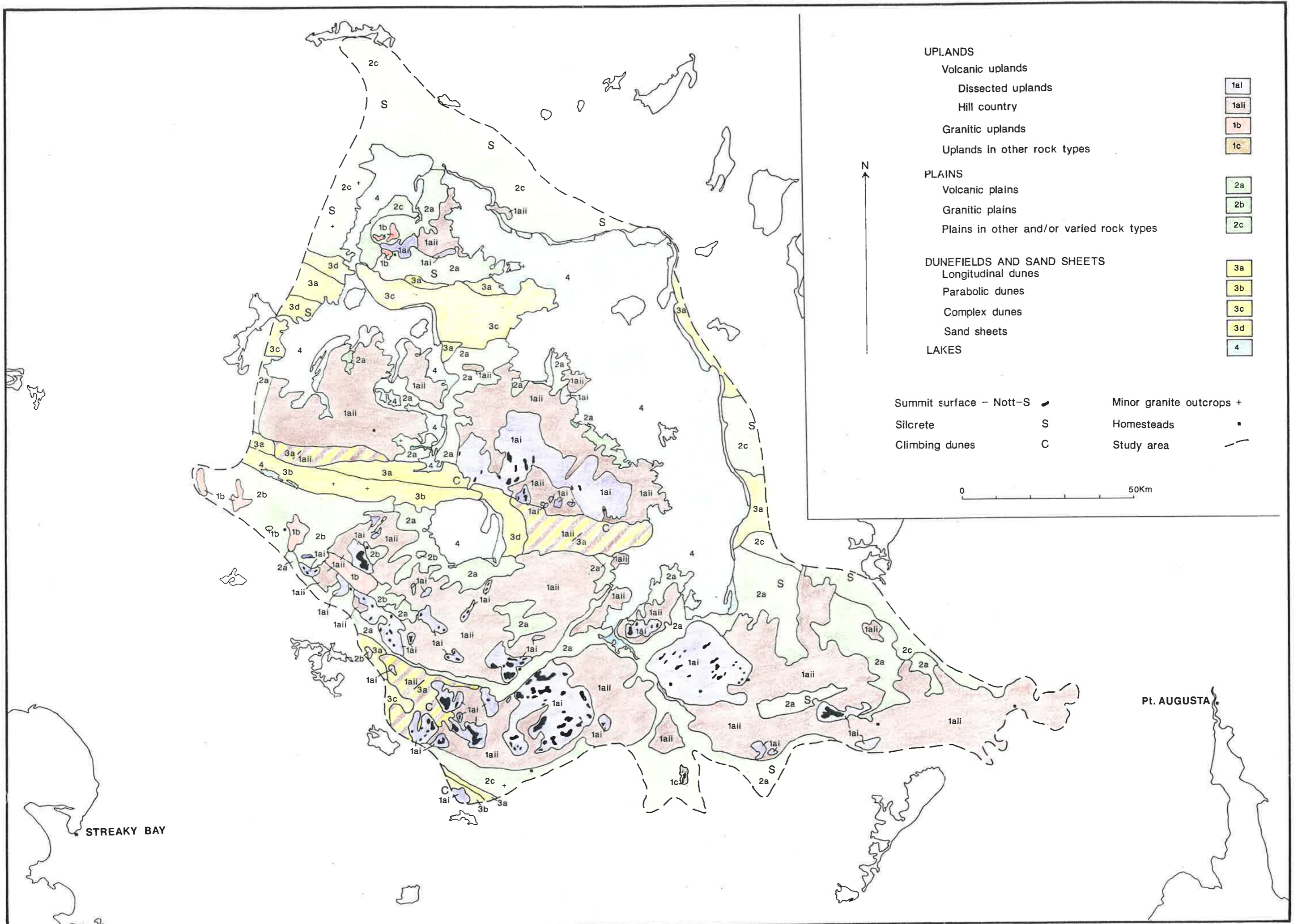


Figure 1.4 Geologic setting of the study area.

Figure 1.5 Geomorphologic regions

	Dominant features	Subdominant features
<u>EROSIONAL FORMS</u>		
<u>Uplands</u>		
Volcanic uplands Dissected uplands	High bornhardts rising to 180 m above narrow valleys. Relief amplitude >100 m/km ²	Nott-S summit surface; Spring Surface; pediments.
Hill country	Low bornhardts and broad valleys. Relief amplitude <100 m/km ² .	Pediments; longitudinal dunes; climbing and falling dunes.
Granitic uplands	Nubbins, whalebacks, low bouldery rises and platforms.	Mt Wallaby is a bornhardt; pediments; minor forms include boulders, flares, Rillen, tafoni, gnammas, A-tents, and polygonal weathering.
Uplands in other rock types	Inselberg	Pediments.
<u>Plains</u>		
Volcanic plains	Pediments and flat to undulating plains	Inselbergs; bornhardts; alluvial deposits; dunes; salinas.
Granitic plains	"	"
Plains cut in other and/or varied rock types	"	"
<u>DEPOSITIONAL FORMS</u>		
<u>Dunefields and sand sheets</u>		
Longitudinal dunes	ESE to SE trending longitudinal dunes rising 5-15 m above interdune corridors	Low bornhardts and platforms; salinas in interdune corridors
Parabolic dunes	In lowlying areas; parabolic dunes, U of dune opens to W	Low bornhardts and salinas
Complex dunes	Various dune types- longitudinal, parabolic circular, irregular	"
Sand sheets	Aeolian deposits with no dune forms	"
<u>Lakes</u>	Shallow, ephemeral, saline lakes	Islands of bedrock or quartzitic or gypsiferous sand; fans; deltas; bars; beaches; lunettes



UPLANDS

Volcanic uplands

Dissected uplands

Hill country

Granitic uplands

Uplands in other rock types

- 1ai
- 1a
- 1b
- 1c

PLAINS

Volcanic plains

Granitic plains

Plains in other and/or varied rock types

- 2a
- 2b
- 2c

DUNEFIELDS AND SAND SHEETS

Longitudinal dunes

Parabolic dunes

Complex dunes

Sand sheets

- 3a
- 3b
- 3c
- 3d
- 4

LAKES

Summit surface - Nott-S

Minor granite outcrops +

Silcrete S

Homesteads

Climbing dunes C

Study area

0 50Km

STREAKY BAY

Pt. AUGUSTA

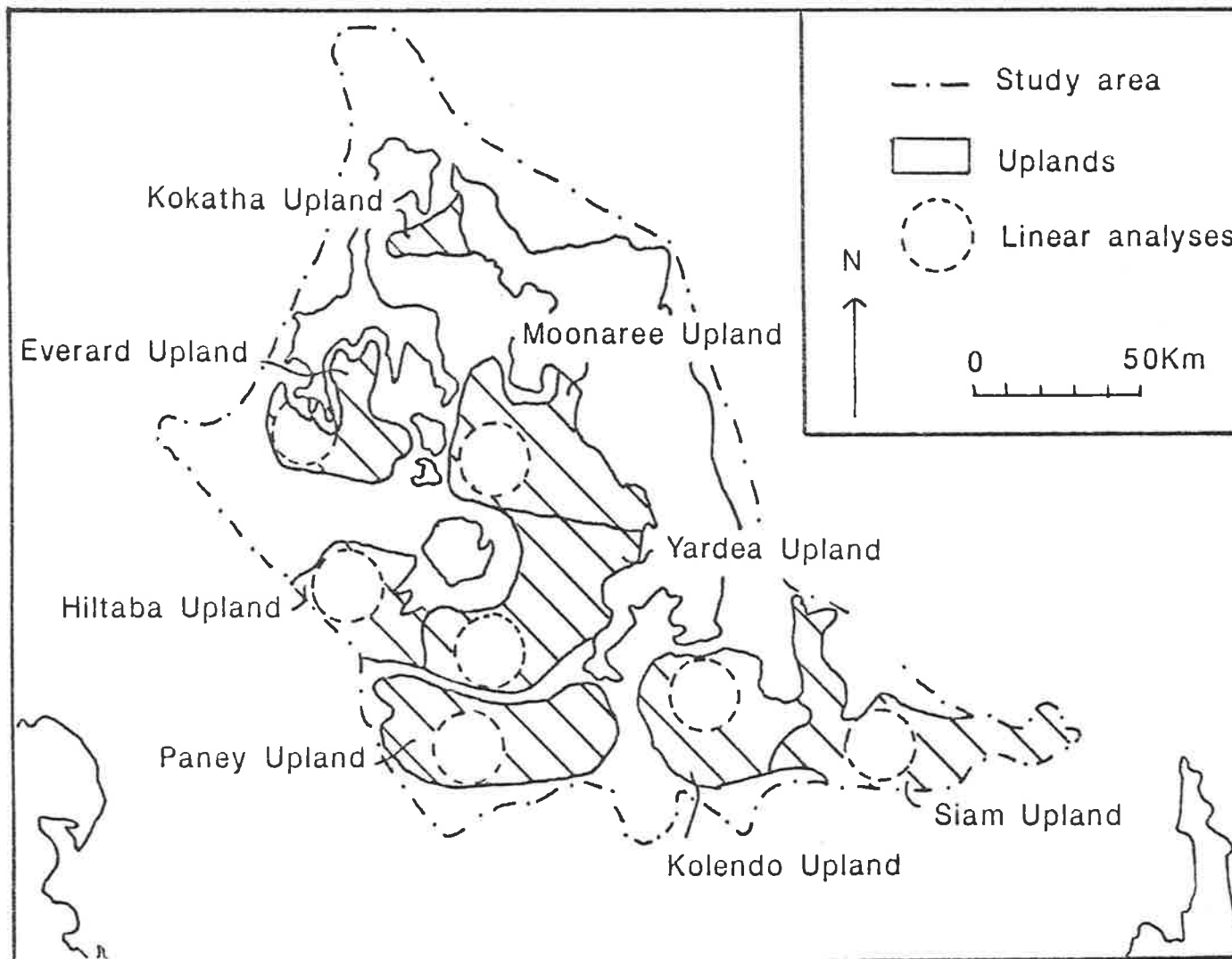


Figure 1.6 Uplands within the study area, showing also the areas used for linear analyses (see Sections 5.3 and A2.3).

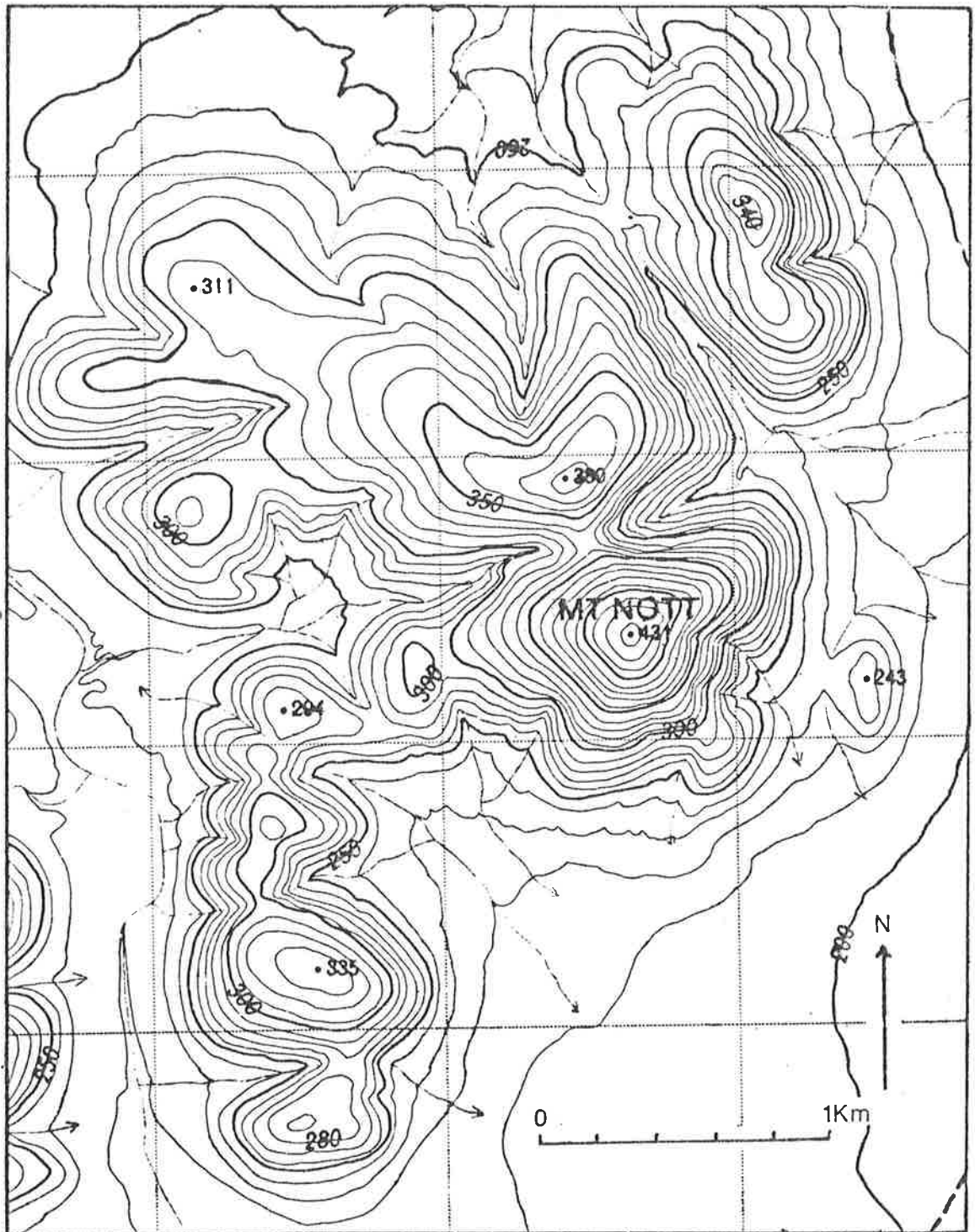


Figure 2.1 Contour plan of a complex of bornhardts around Mt Nott, southern Gawler Ranges, showing intricate plan forms due to linking of adjacent masses (from South Australia Department of Lands Topographic Series 1:50,000, Nott Sheet).

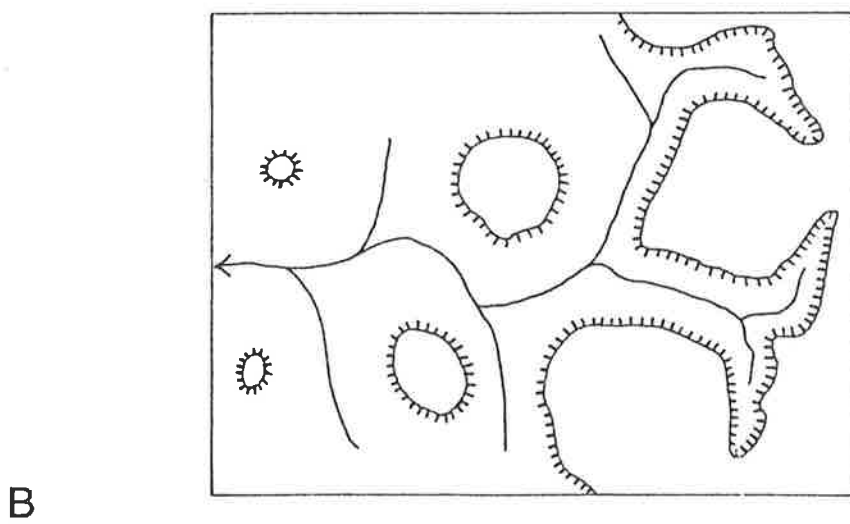
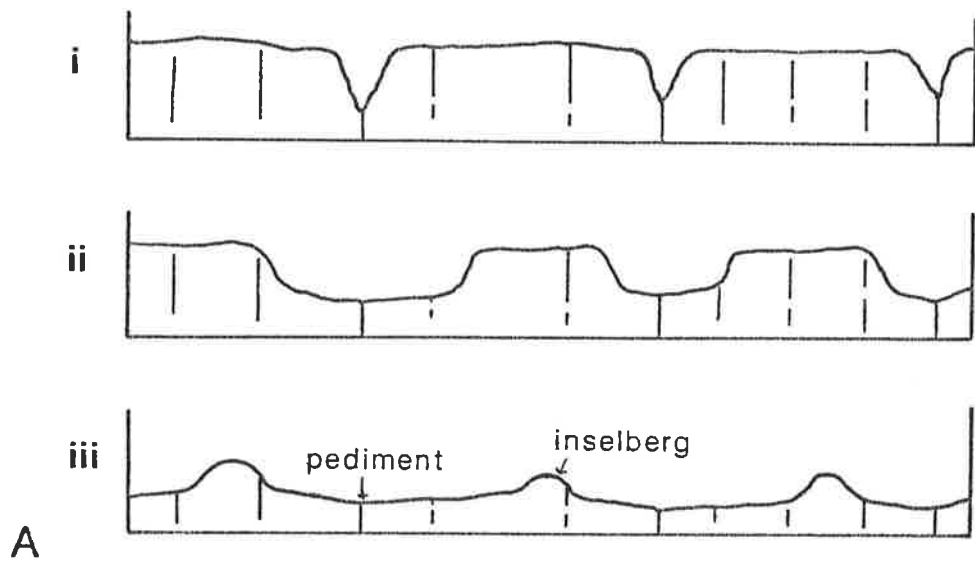


Figure 2.2 Scarp retreat: (A) profile (after Sparks 1974), (B) plan.

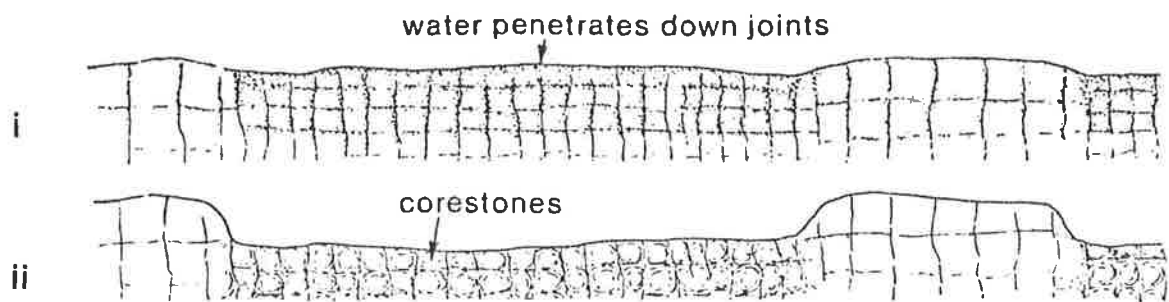


Figure 2.3 Two-stage development of bornhardts (from Twidale 1976c).

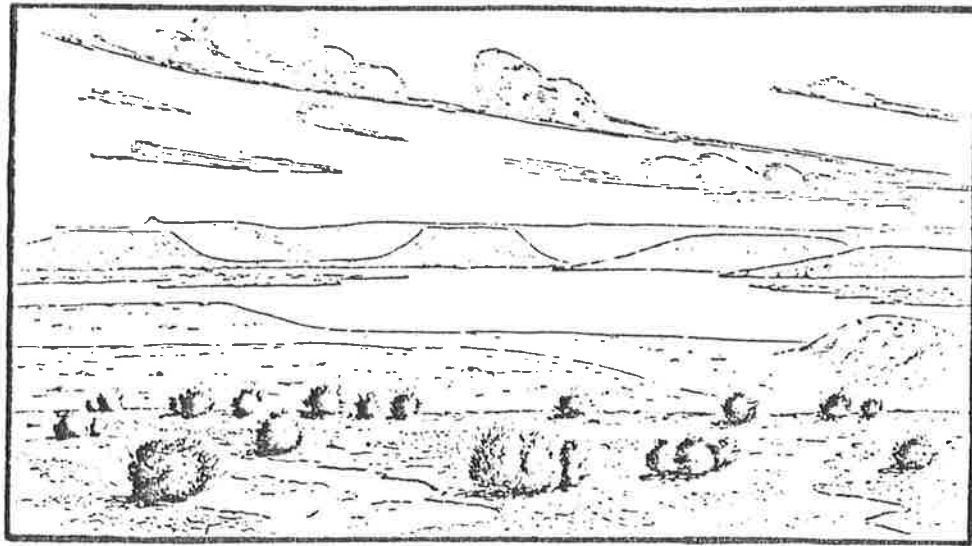
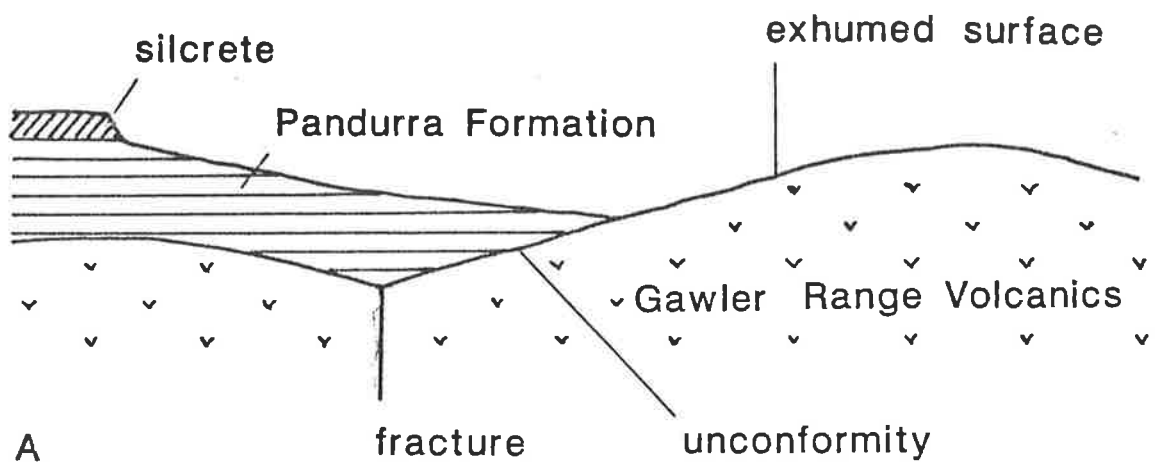
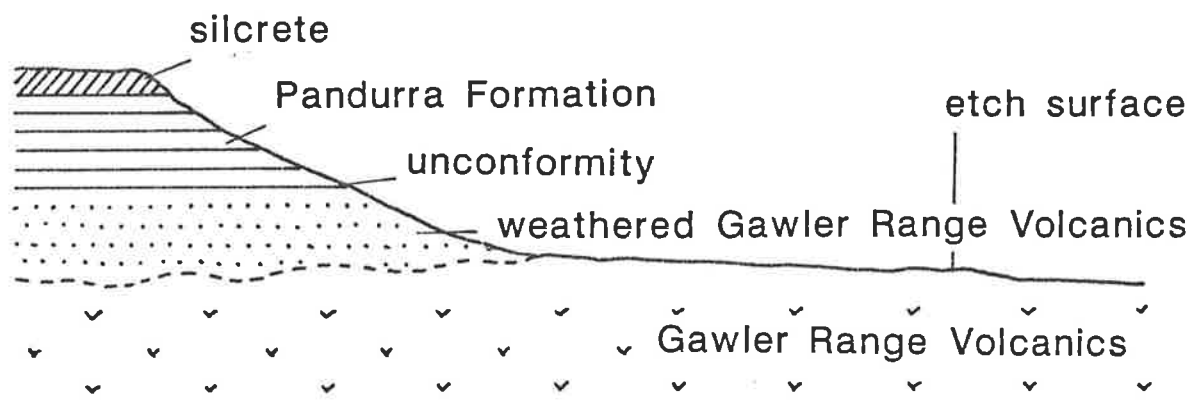


Figure 3.1 Dickinson's (1942) sketch of bevelled summits near Lake Gairdner.



A



B

Figure 3.2 Scrubby Surface: (A) with no pre-Pandurra regolith preserved, (B) with regolith preserved

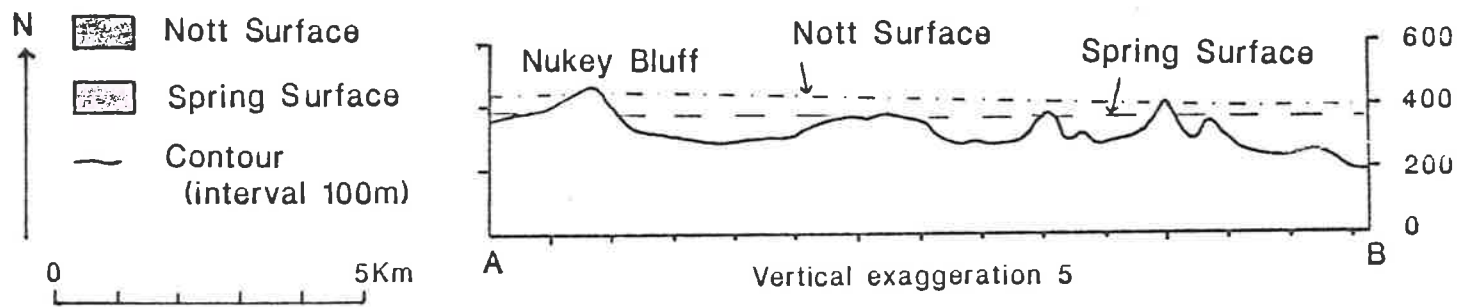
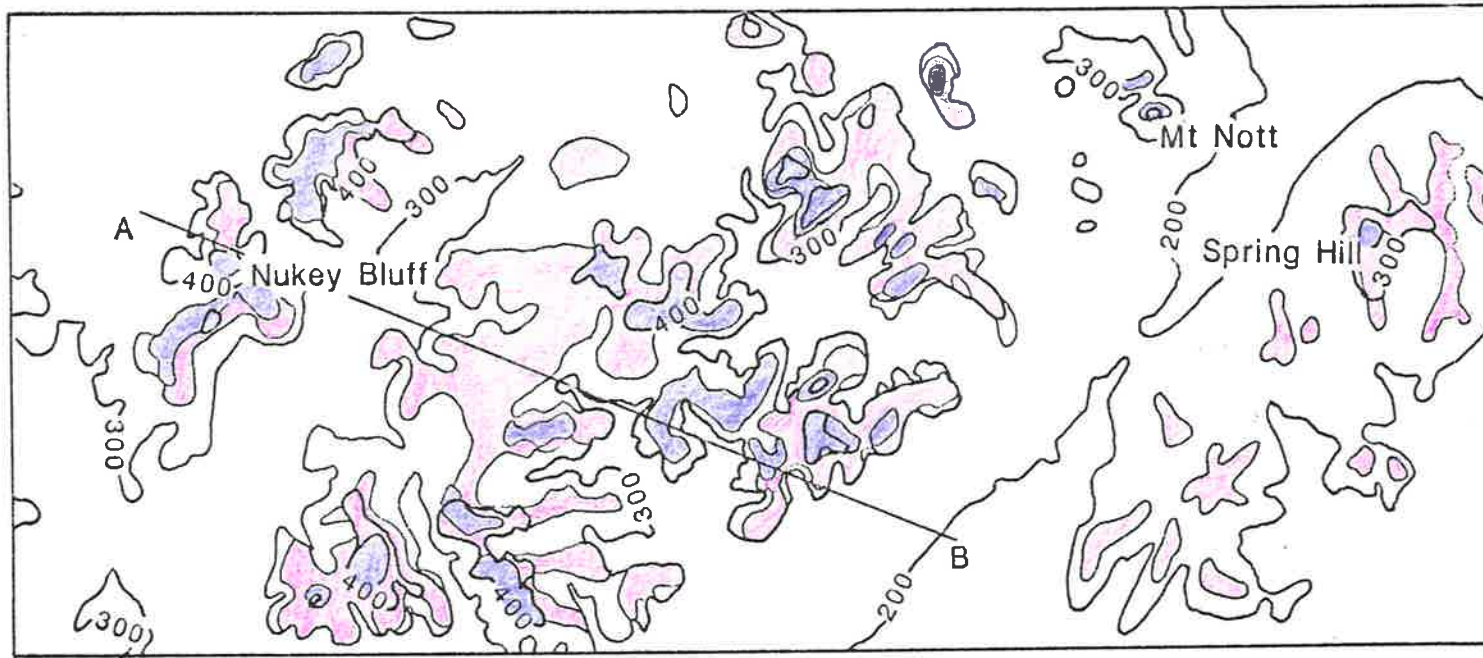


Figure 3.3 The Spring Surface in part of the Paney Upland, southern Gawler Ranges (drawn from National Topographic Series 1:100,000 Cacuppa Sheet).

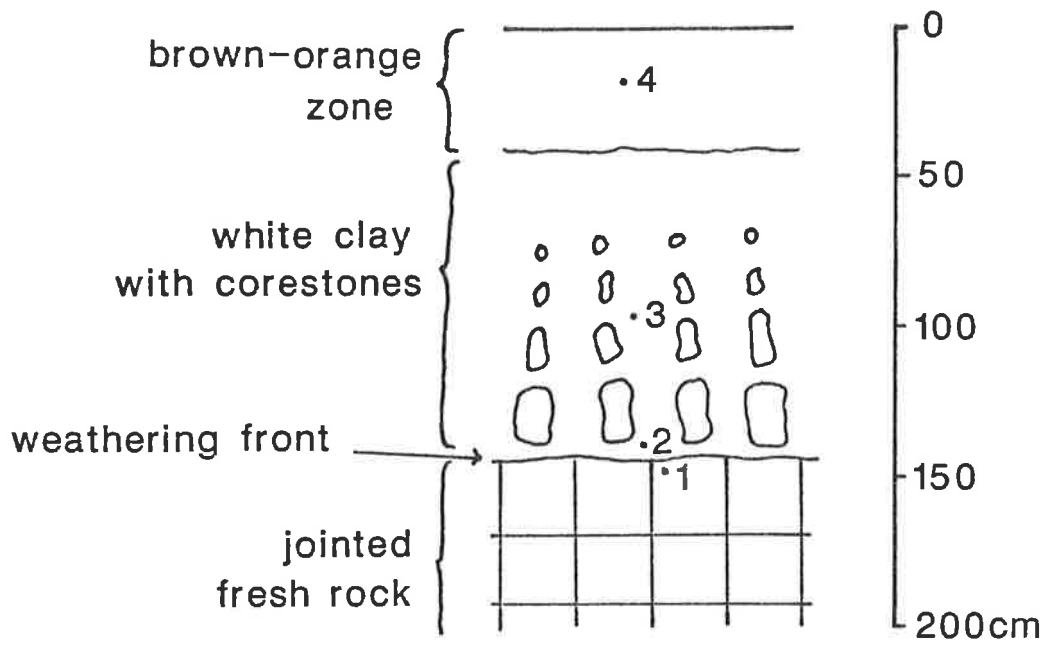
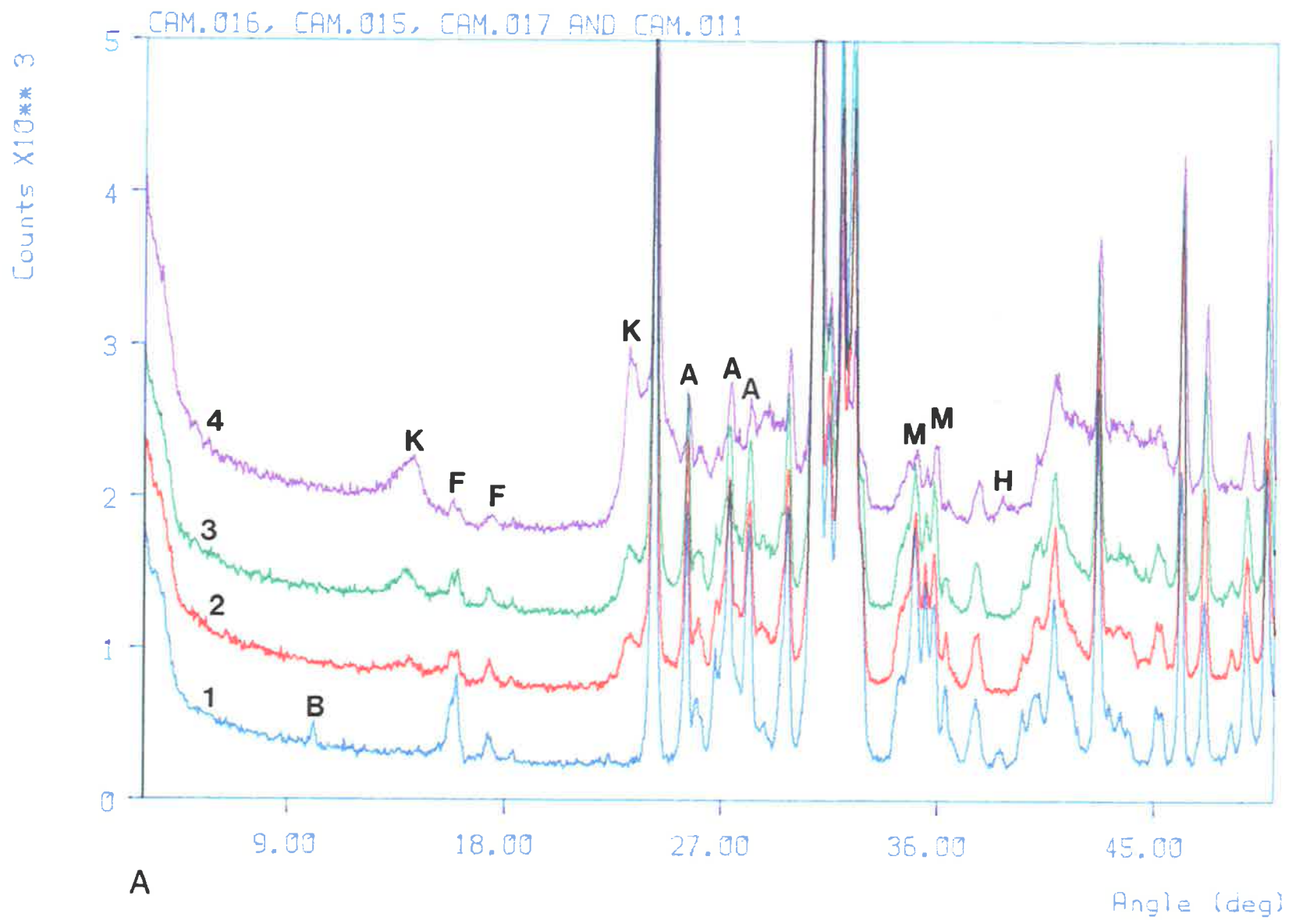


Figure 3.4A Sketch of weathering profile at Mt Cooper, showing location of samples.

Figure 3.4B X-ray diffraction analysis of four samples (1-4) from a weathering profile in rhyolite at Mt Cooper (from 0-50°, offset by 500 counts): (1) blue (016) below weathering front, depth 145 cm; (2) red (015) above the weathering front, depth 135cm; (3) green (017) depth 90 cm; (4) purple (011) from the surface zone. B = biotite, K = kaolinite, F = feldspars, A = albite, M = microcline, H = hematite.



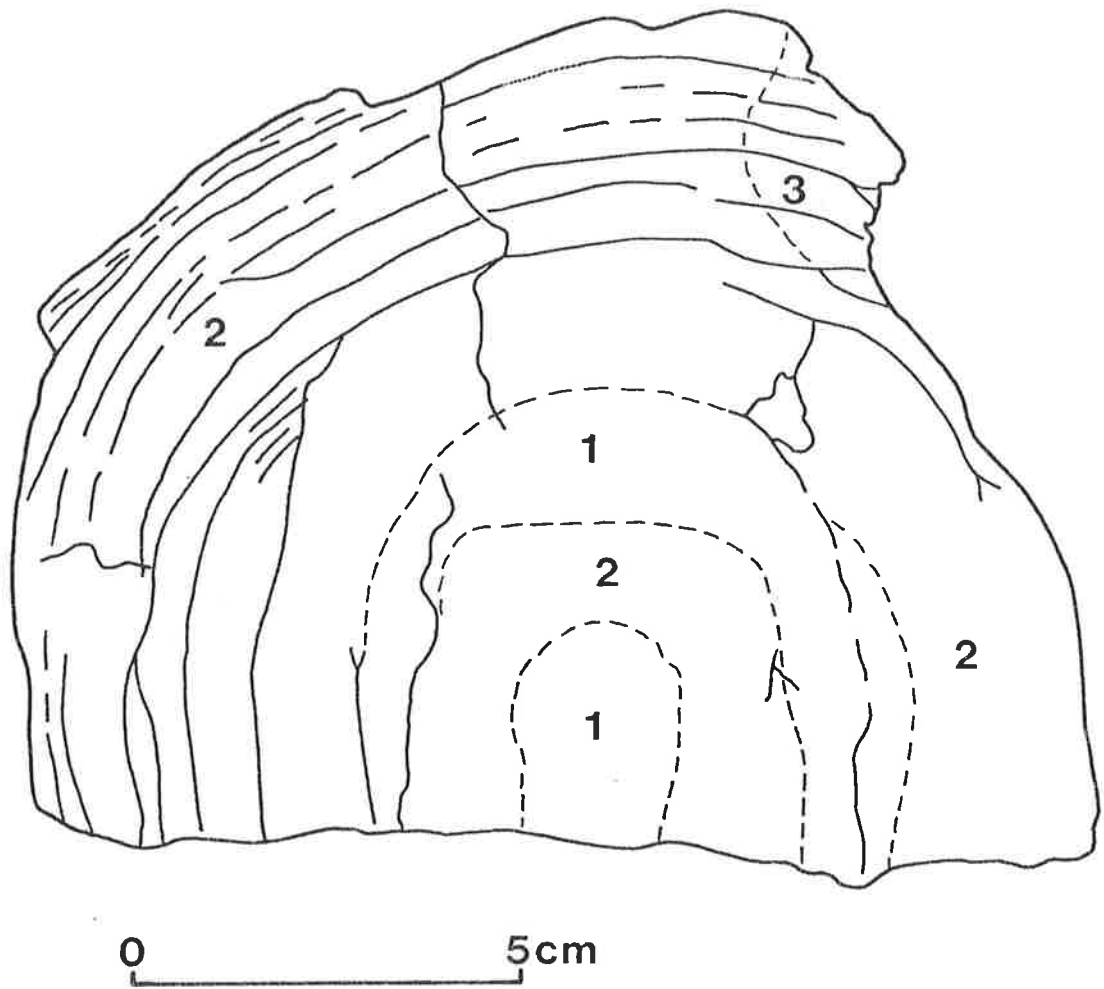


Figure 3.5 Cross-section of a corestone of Yardea Dacite from north of Paney H.S., showing fractures (solid lines) and zones of weathering (dashed lines): (1) 10 R 5/4 Pale reddish brown, (2) 5 YR 5/6 - 10 YR 6/6 Light brown - dark yellowish orange, (3) 10 YR 7/4 Grayish orange (Rock-color chart, Geological Society of America 1984).

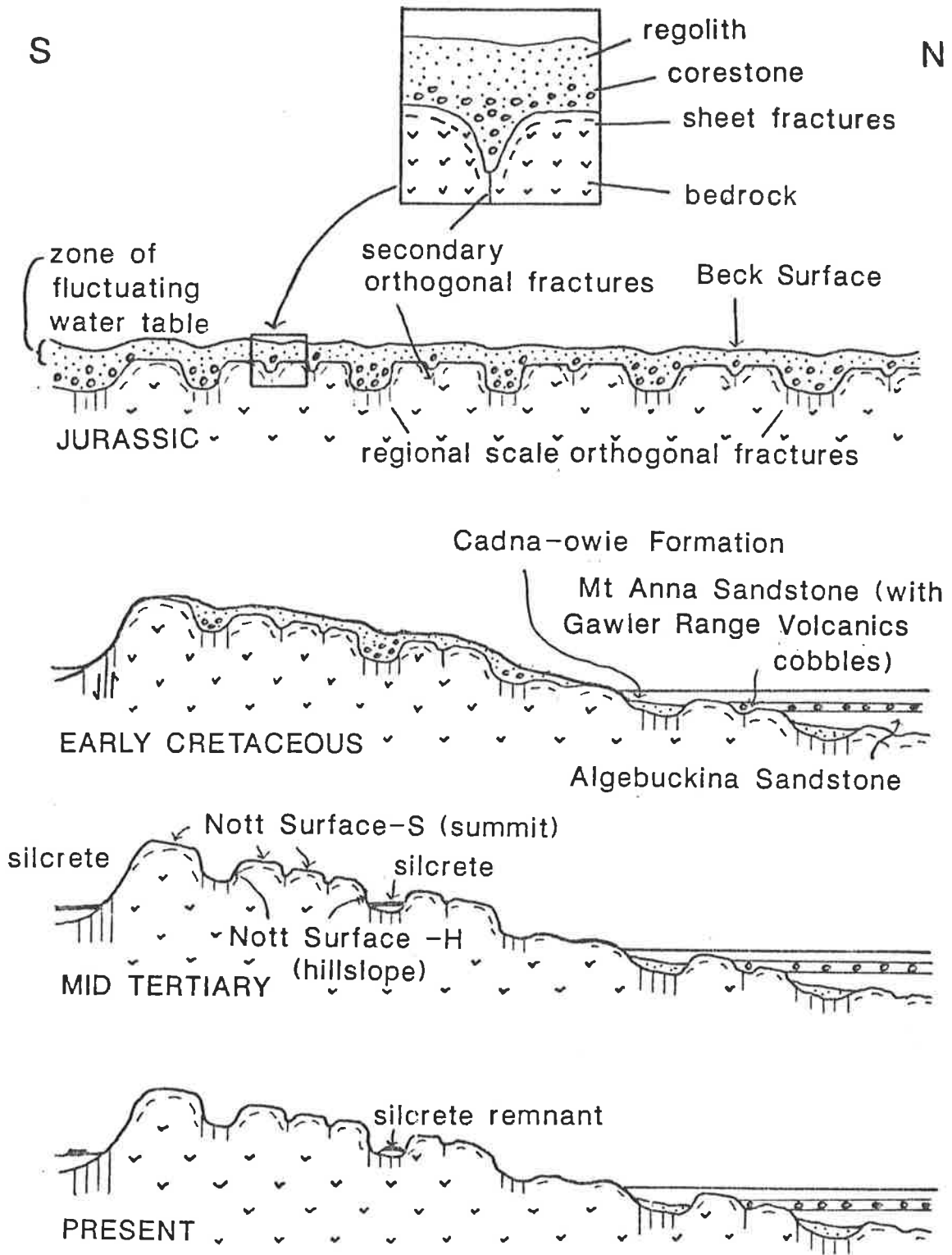


Figure 3.6 Suggested stages in the evolution of the Gawler Ranges (not to scale).

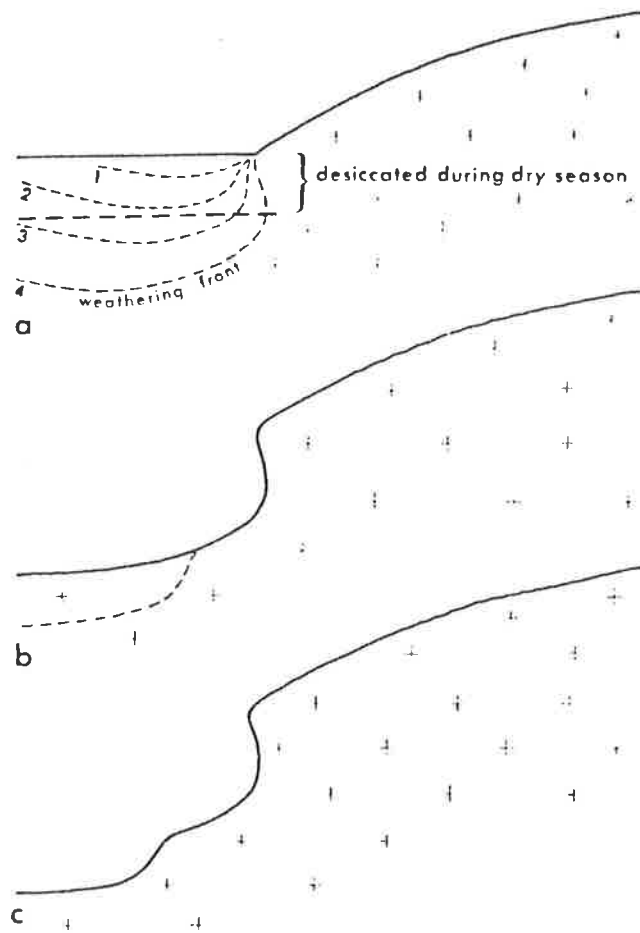


Figure 3.7 Stages in the development of flared slopes (after Twidale 1962).

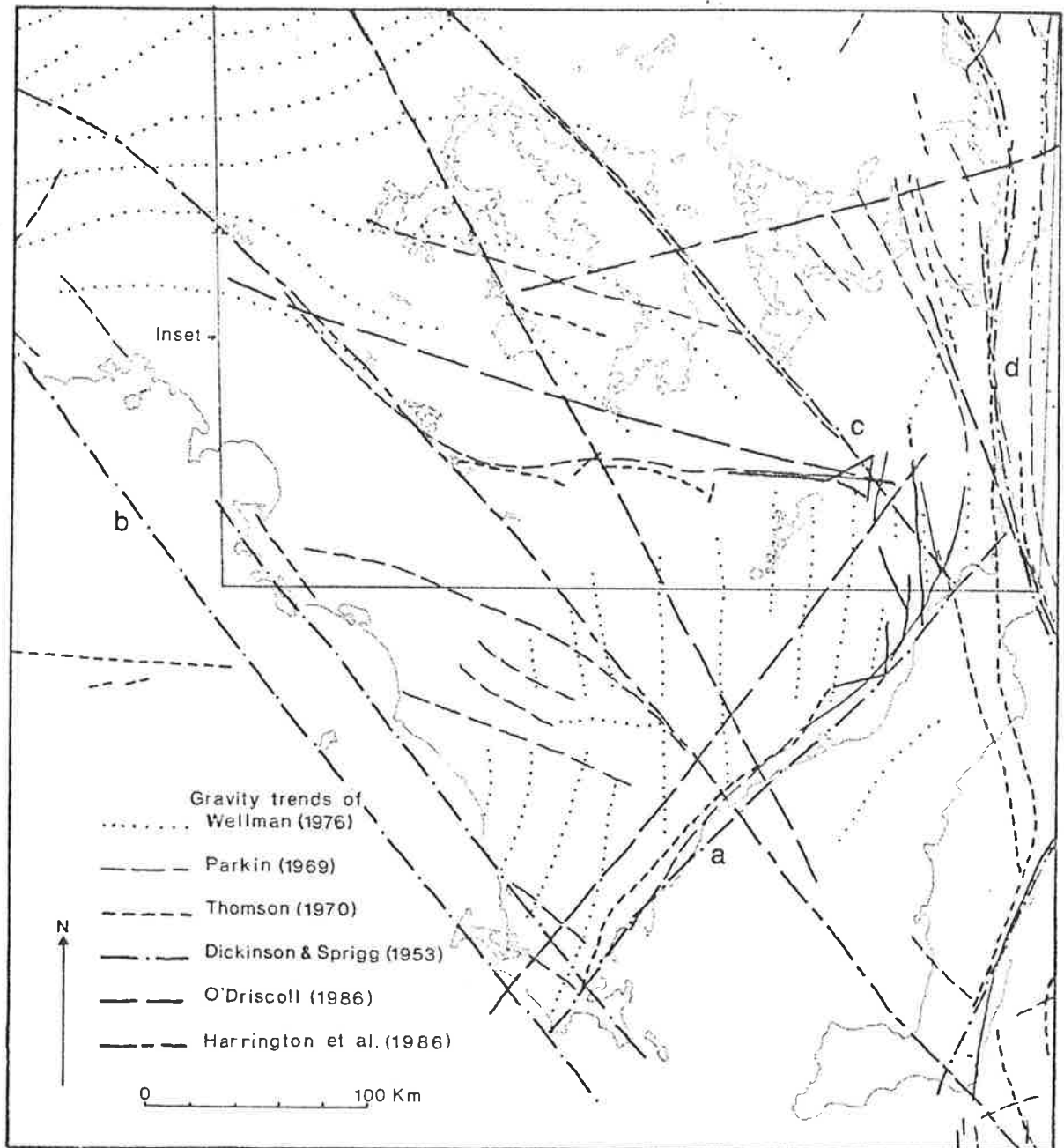


Figure 4.1 Lineament plots due to various authors and gravity trends of Wellman (1976) for the Gawler Craton. For inset see Figure 4.5A.

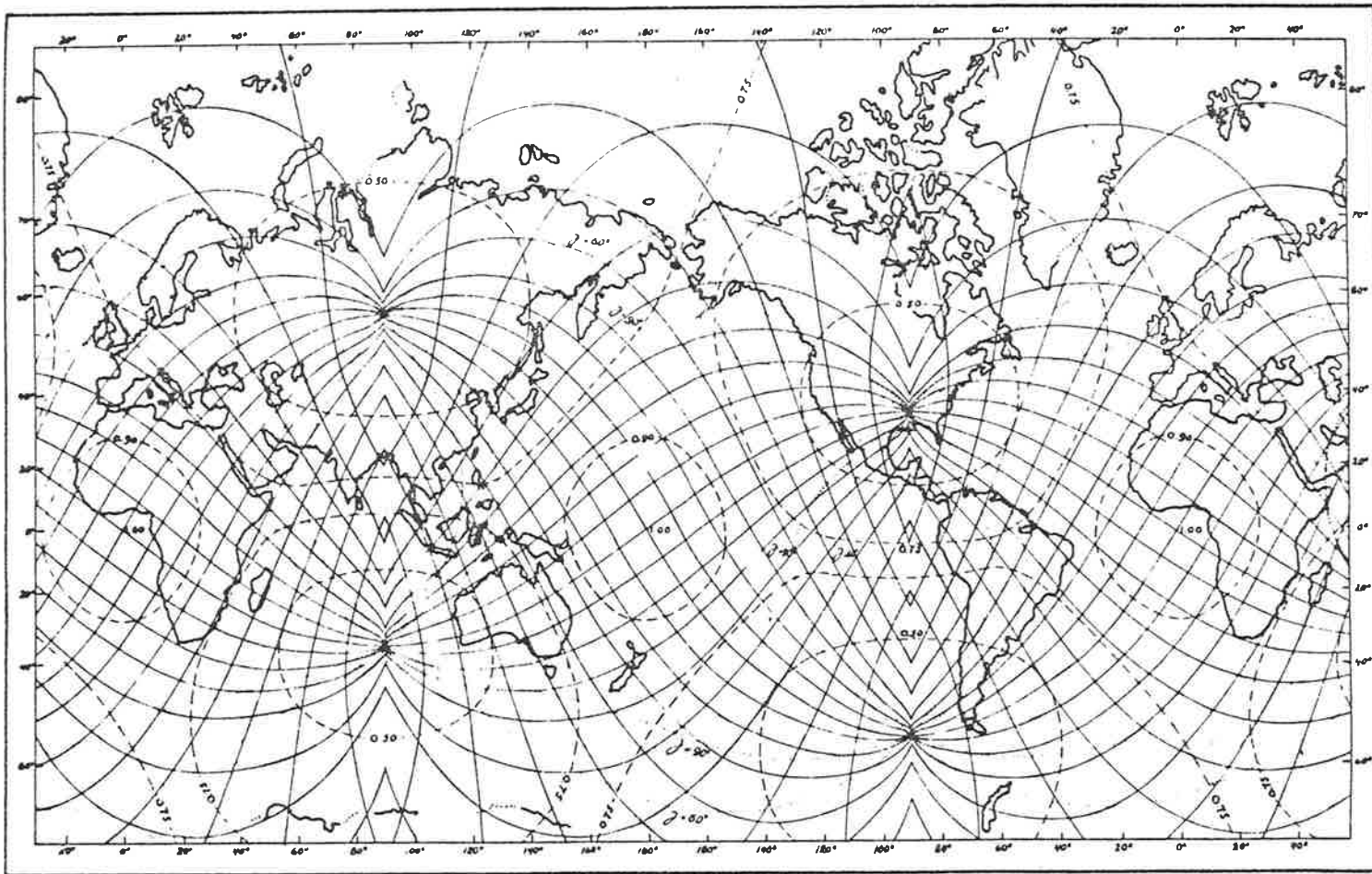


Figure 4.3 Vening Meinesz's (1947) global network of shears.



Figure 4.4 Australian lineaments (broken lines) recognised by Hills (1956) and compared with Vening Meinesz's global pattern.



Figure 4.5B Crawford's (1963) lineaments.

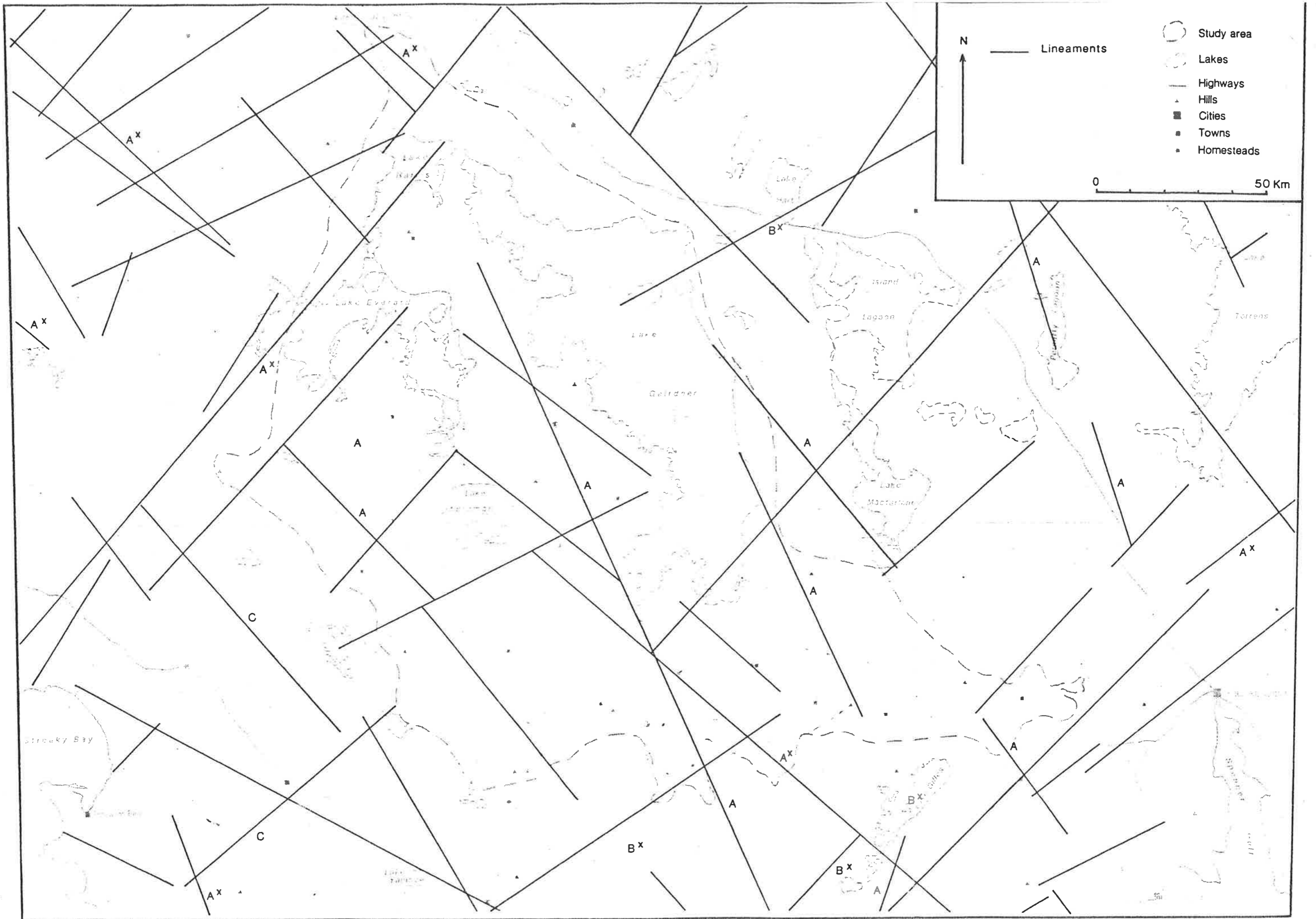


Figure 4.5C Firman's (1974) lineaments.

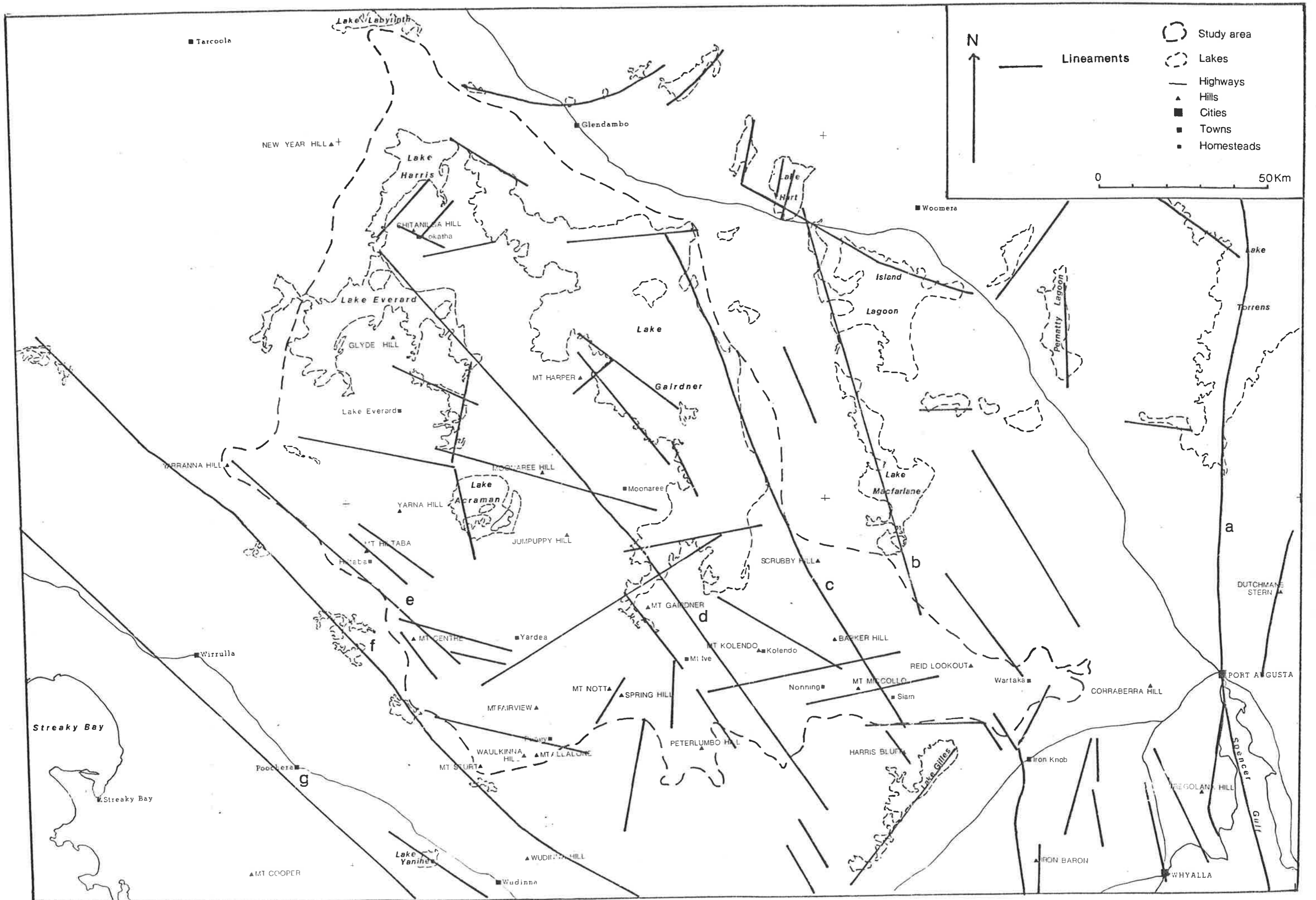
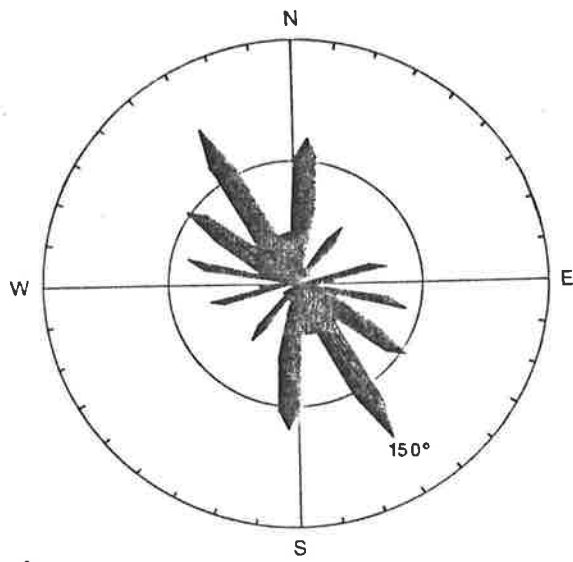
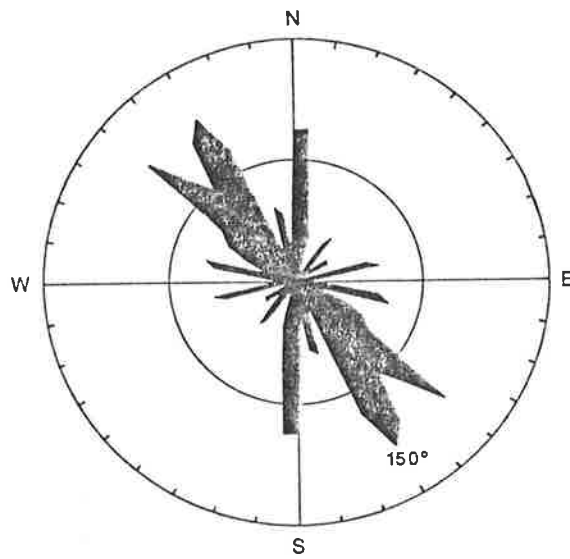


Figure 4.6 Lineaments of the Gawler Ranges and surrounding areas. The north, NNW and NW trending lineaments (a-g) are dominant.

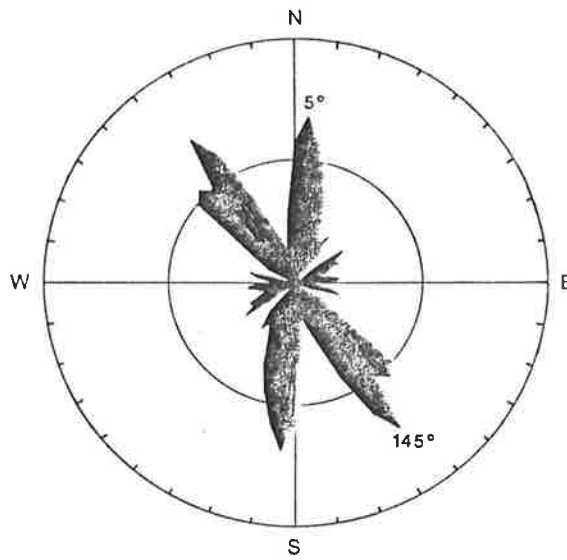


A

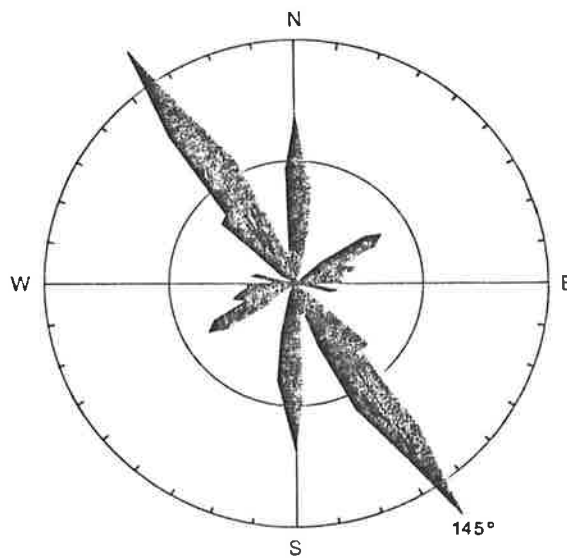


B

Figure 4.7 Lineaments of the Gawler Ranges and surrounding areas rose diagrams. (A) by number of lineaments, (B) by length of lineaments.



A



B

Figure 4.8 Faults of the Gawler Ranges and surrounding areas rose diagrams. (A) by number of faults, (B) by length of faults.

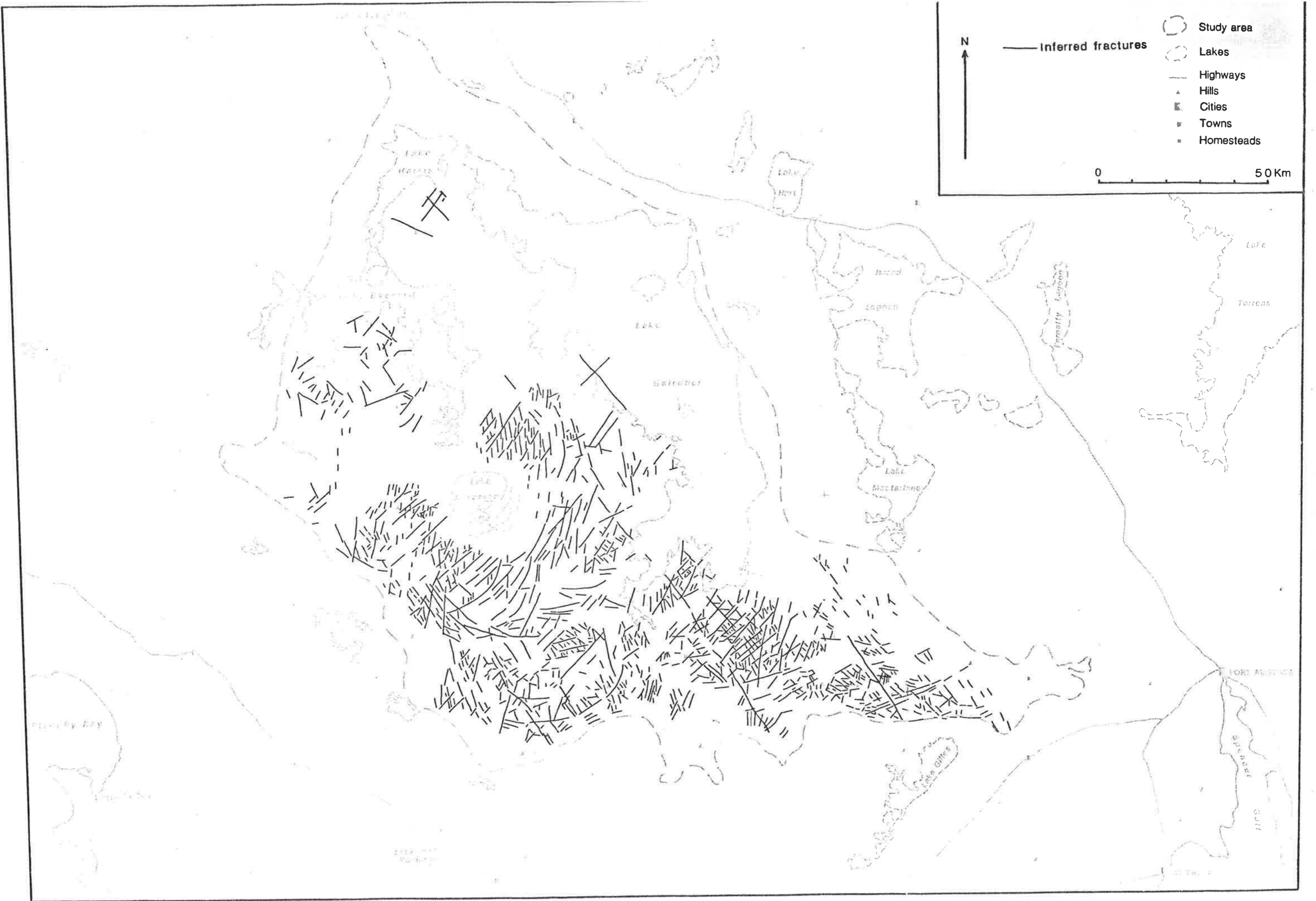
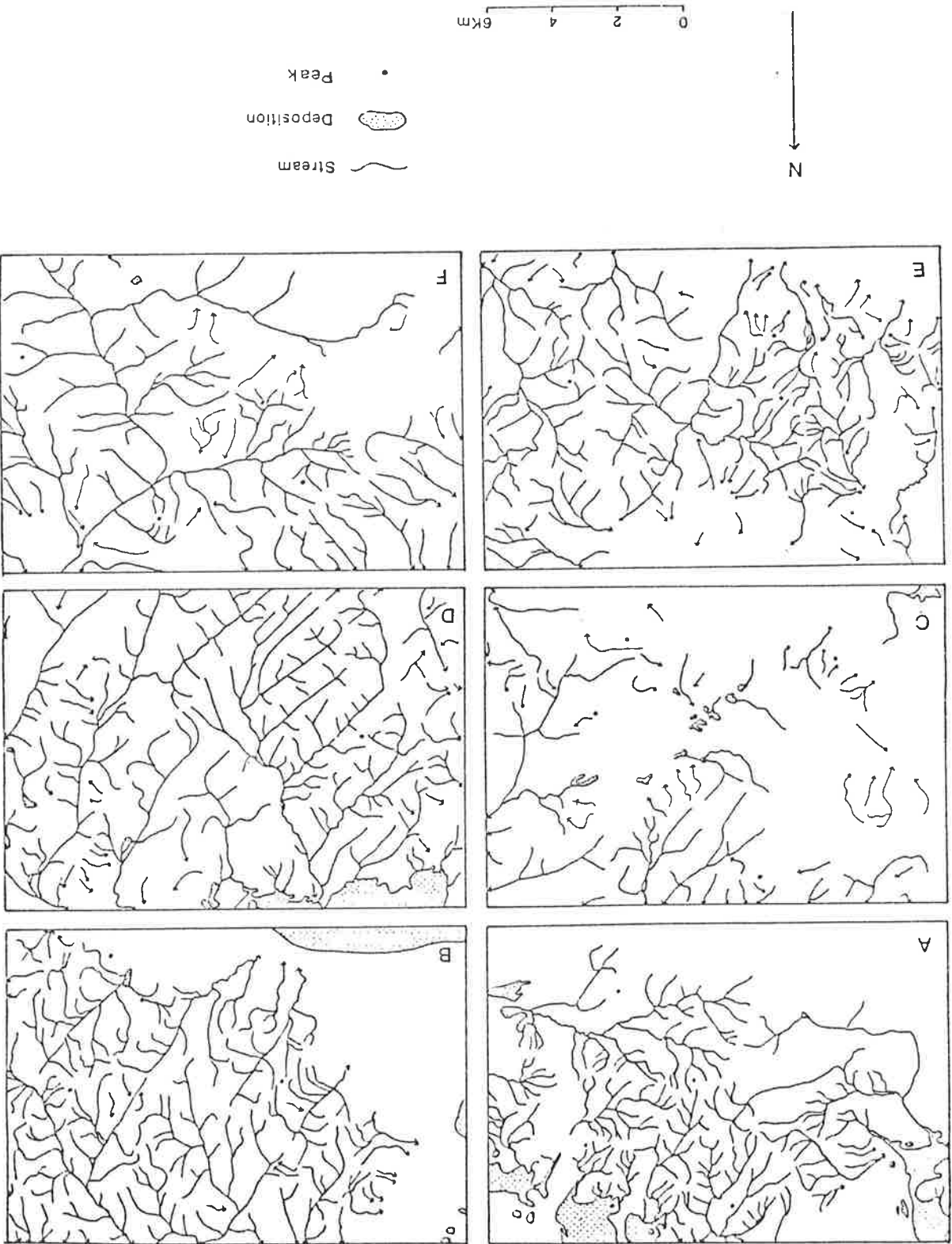


Figure 5.1 Regional scale orthogonal fracture systems of the Gawler Ranges.

Figure 5.2 Drainage patterns in selected areas within the Gawler Ranges. Part of (A) Everard



Upland, (B) Moonaree Upland, (C) Yardea Upland, (D) Kolendo Upland, (E) Paney Upland, (F) Siam

Upland (drawn from National Topographic Series 1:100,000 maps Everard, Moonaree, Yardea,

Kolendo, Cacuppa and Uno sheets).

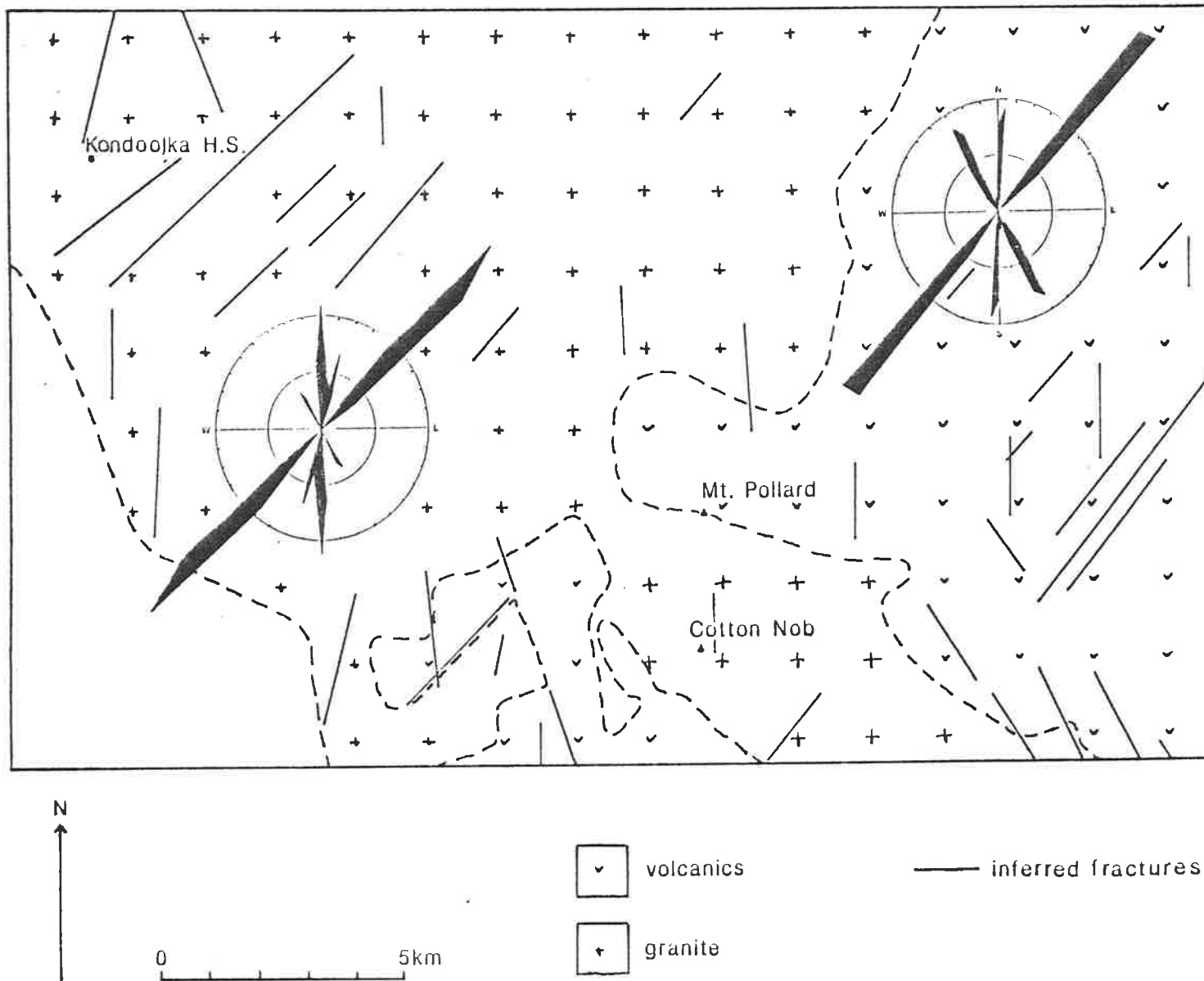


Figure 5.3 The fracture system which subdivides the volcanic rocks extends also to the granitic areas (illustrated by fracture rose diagrams, analysis by length - see Appendix 2. Drawn from National Topographic Series 1:100,000 Childara, Everard, Wirrulla and Yartoo sheets).

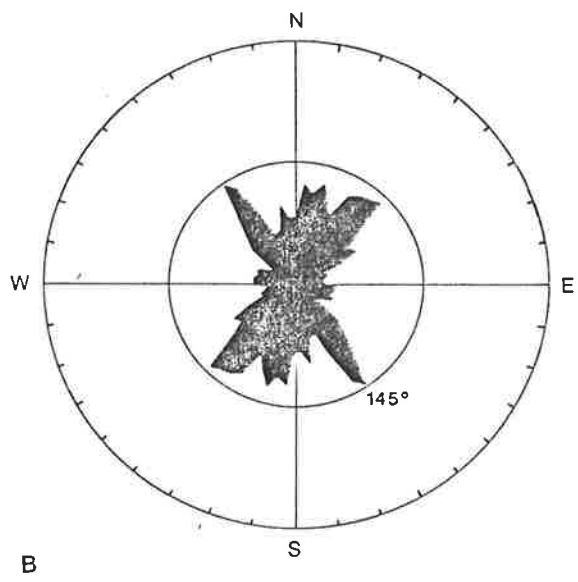
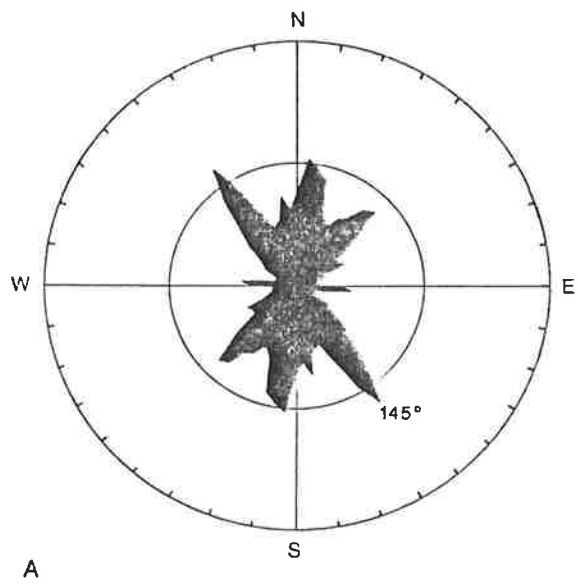


Figure 5.4 Regional scale orthogonal fracture rose diagrams:
(A) by number, (B) by length.

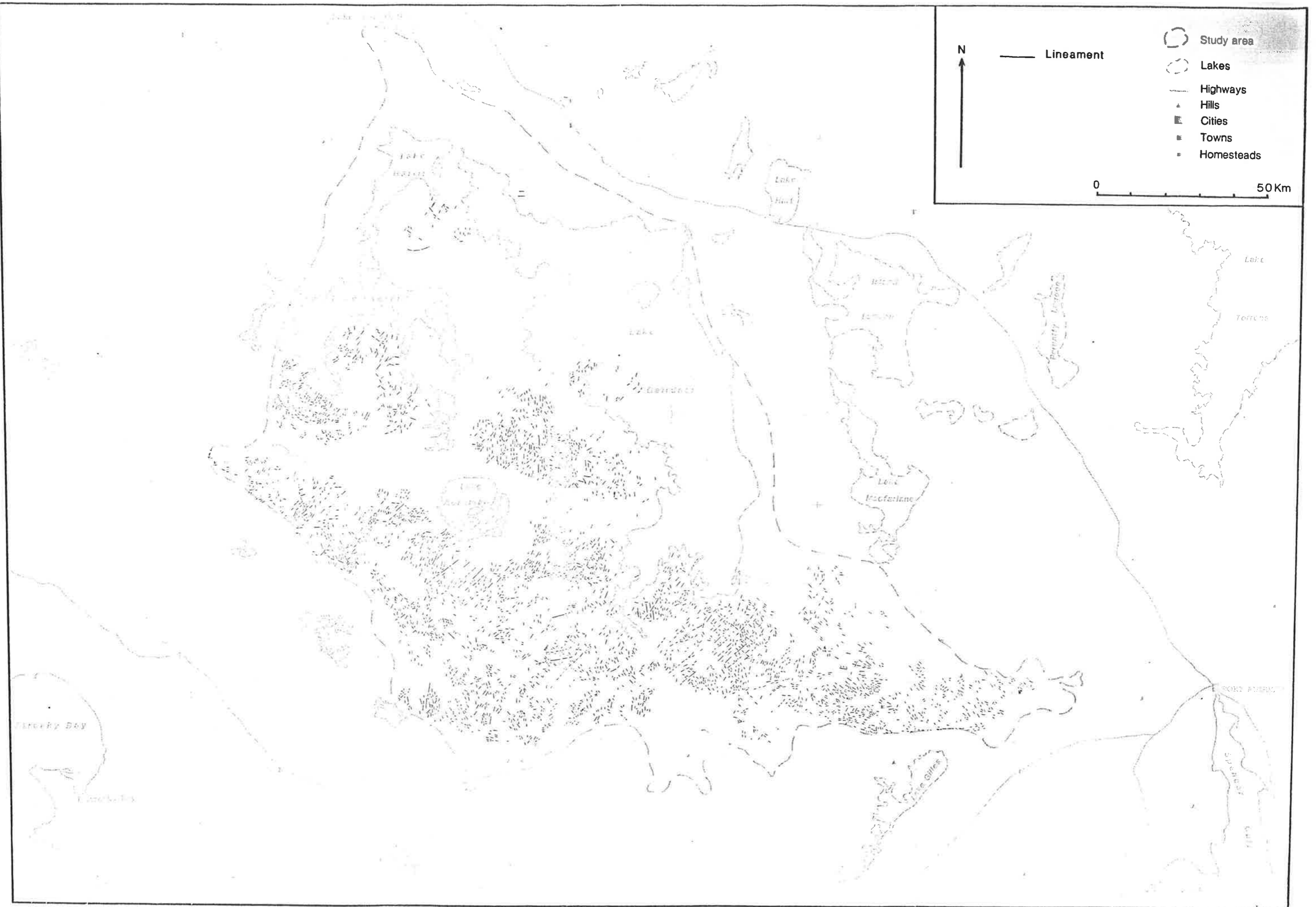


Figure 5.5 Linears of the Gawler Ranges.

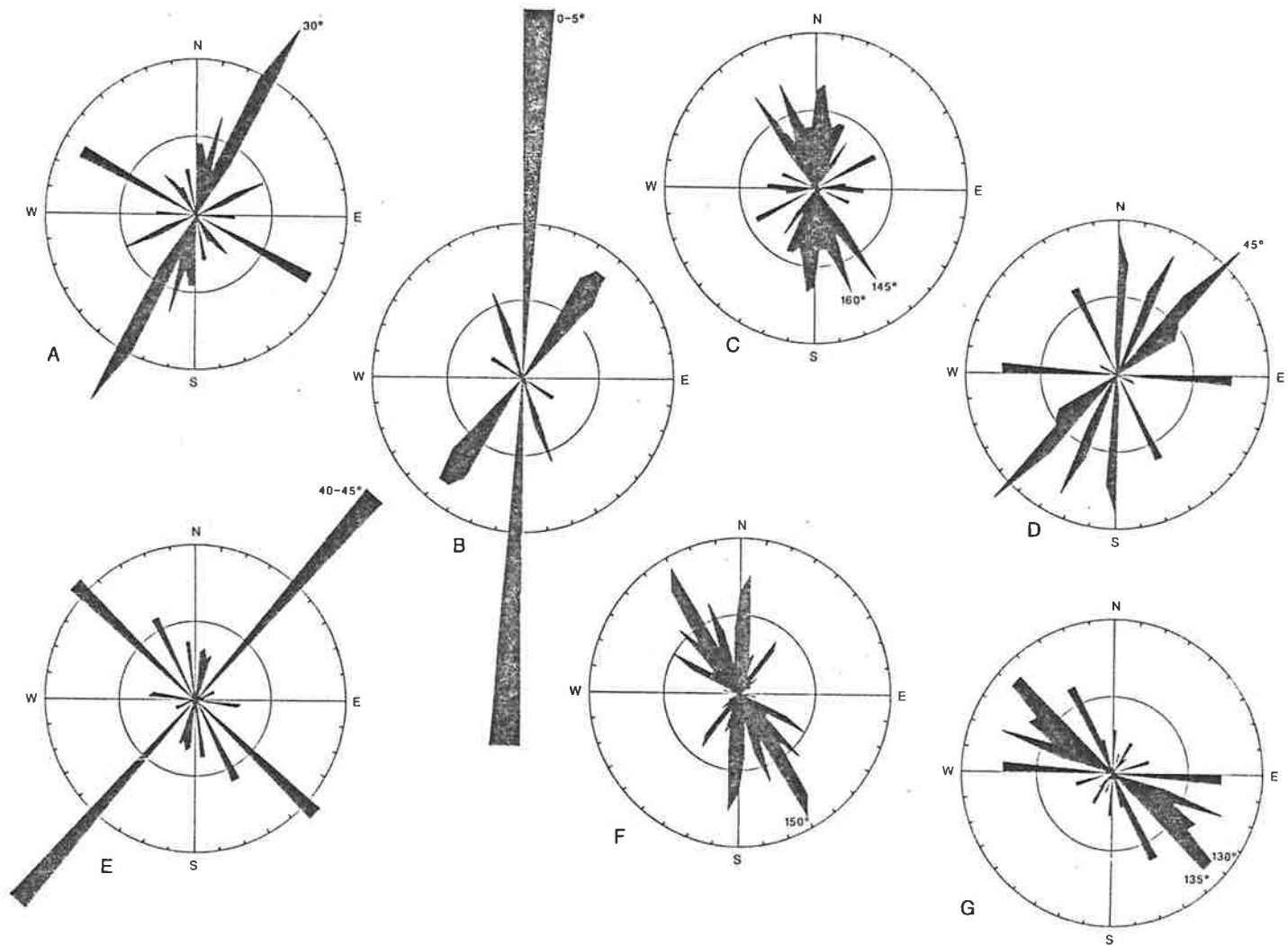


Figure 5.6 Linear rose diagrams: (A) Everard Upland, (B) Moonaree Upland, (C) Yardea Upland, (D) Kolendo Upland, (E) Paney Upland (F) Siam Upland (G) Hiltaba Upland.

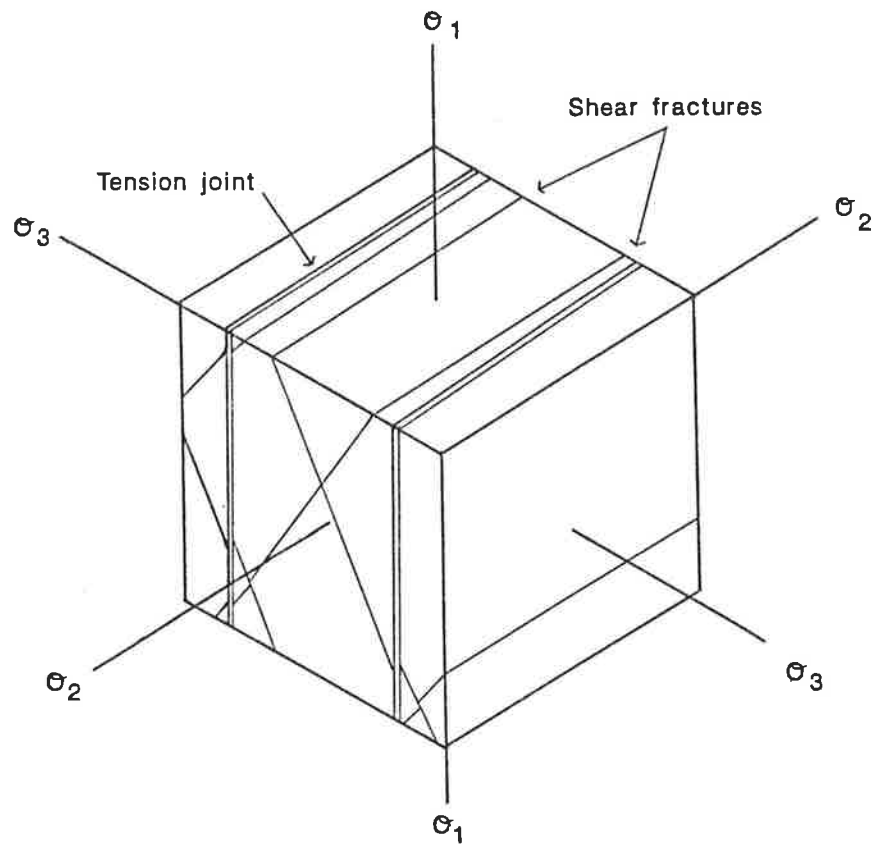


Figure 5.7 Stress-strain relationships, showing conjugate shear fractures and tension fractures (from Davis 1984).

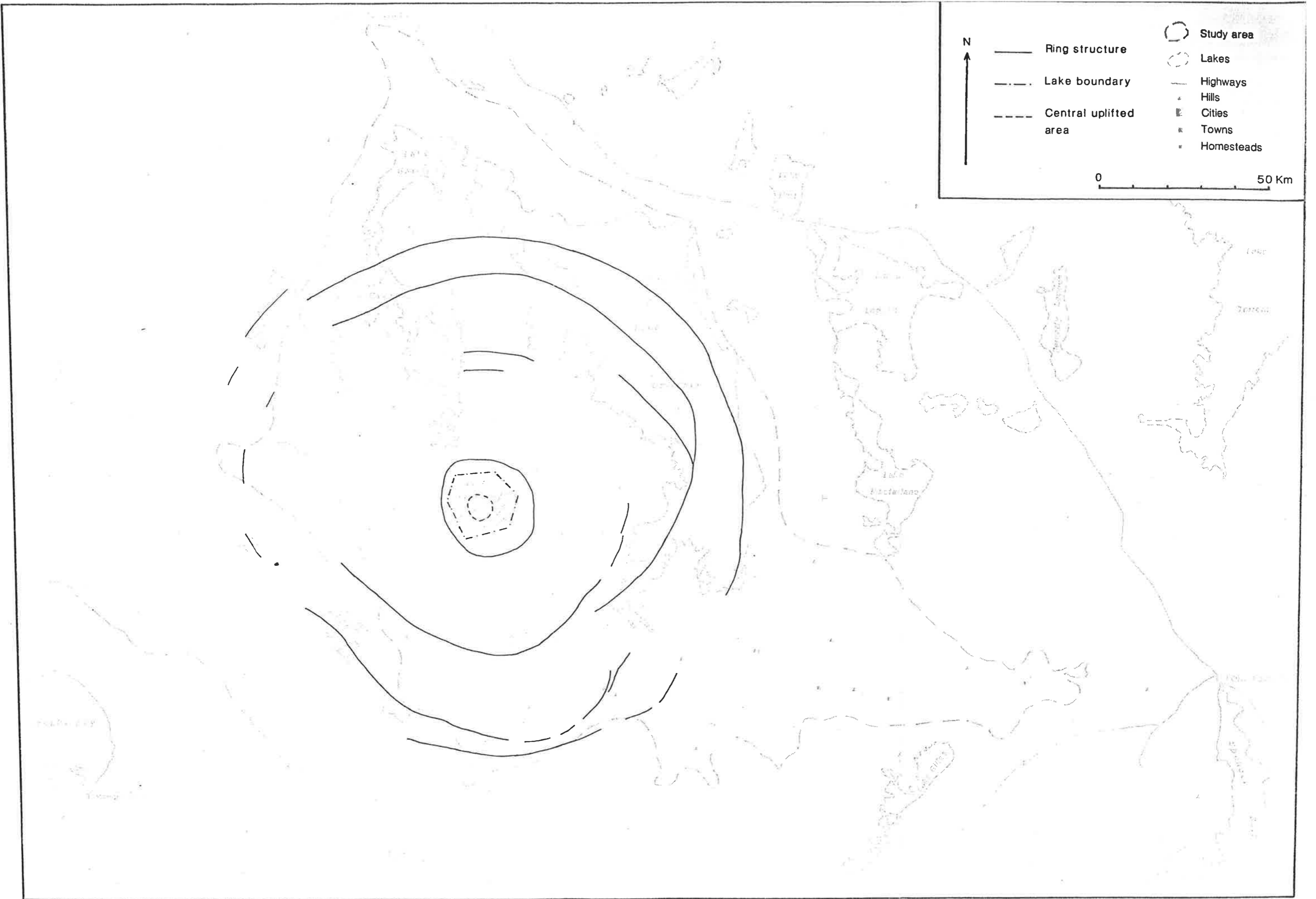


Figure 5.8 Possible circular fractures related to the Acraman meteorite impact (see Williams 1986, 1987).

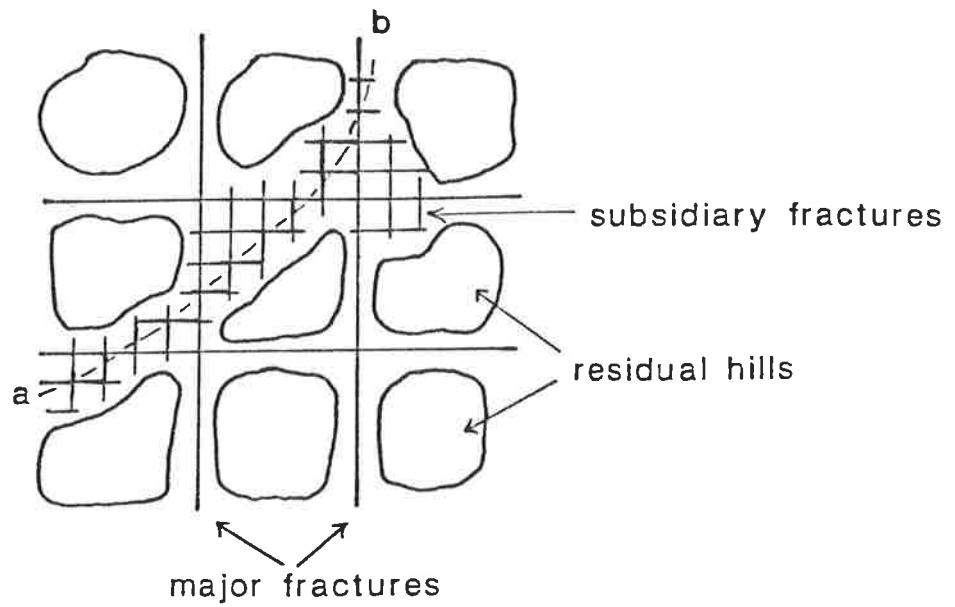


Figure 5.9 Arcuate fracture (a-b), or linked linear sectors of an orthogonal system of fractures.

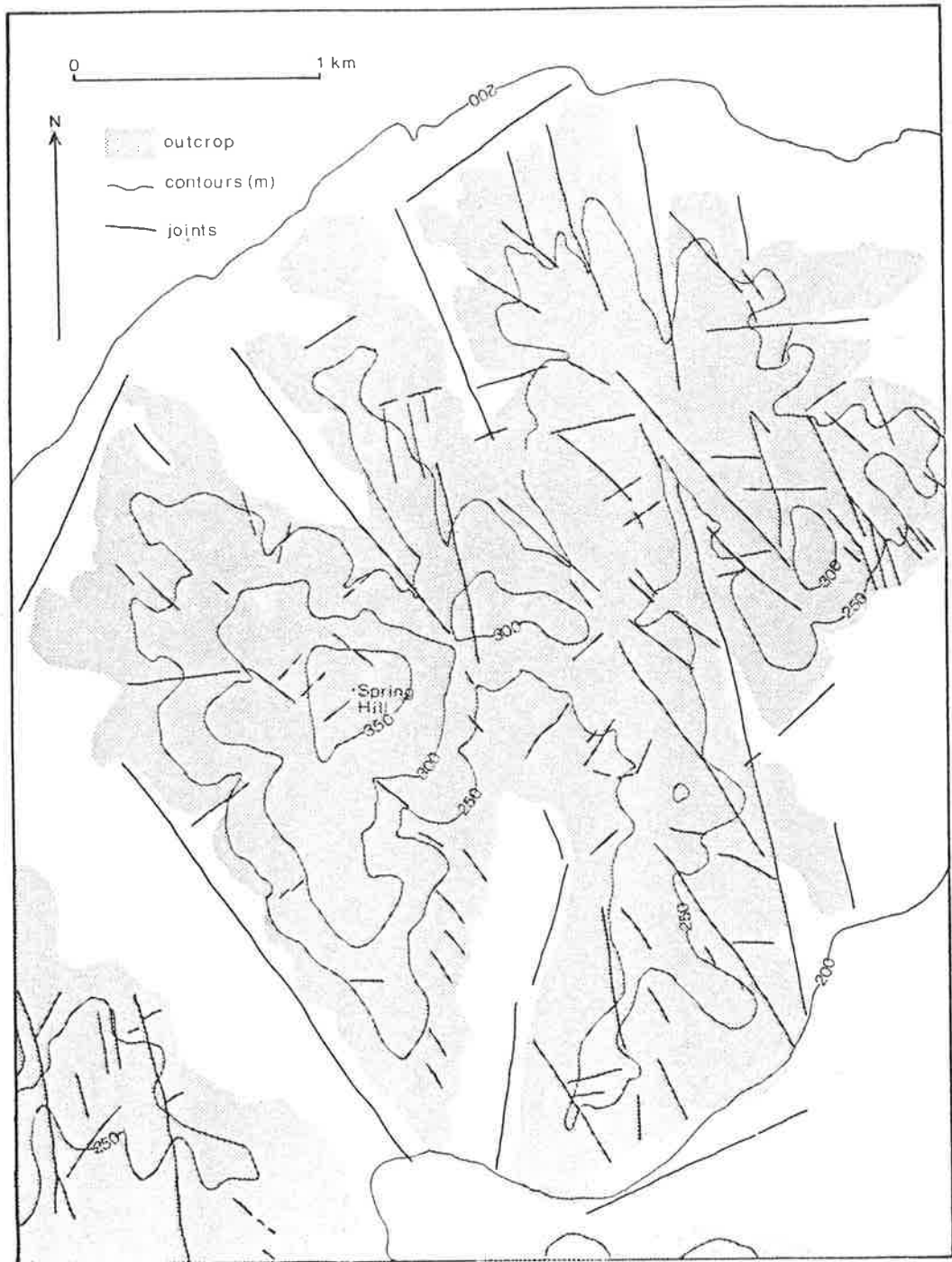





Figure 5.10 A Inferred local scale orthogonal fracture systems: Spring Hill.
 Drawn from aerial photographs, scale 1:86,000, South Australia Lands Department,
 and National Topographic Series 1:100,000 Kolendo and Yardea sheets.



-  outcrop
-  contours (50m interval)
-  inferred fracture

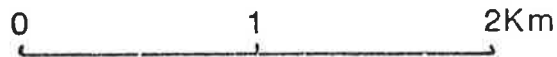


Figure 5.10B Inferred local scale orthogonal fracture systems: Kolendo. Drawn from aerial photographs, scale 1:86,000, South Australia Lands Department, and National Topographic Series 1:100,000 Kolendo and Yardea sheets.

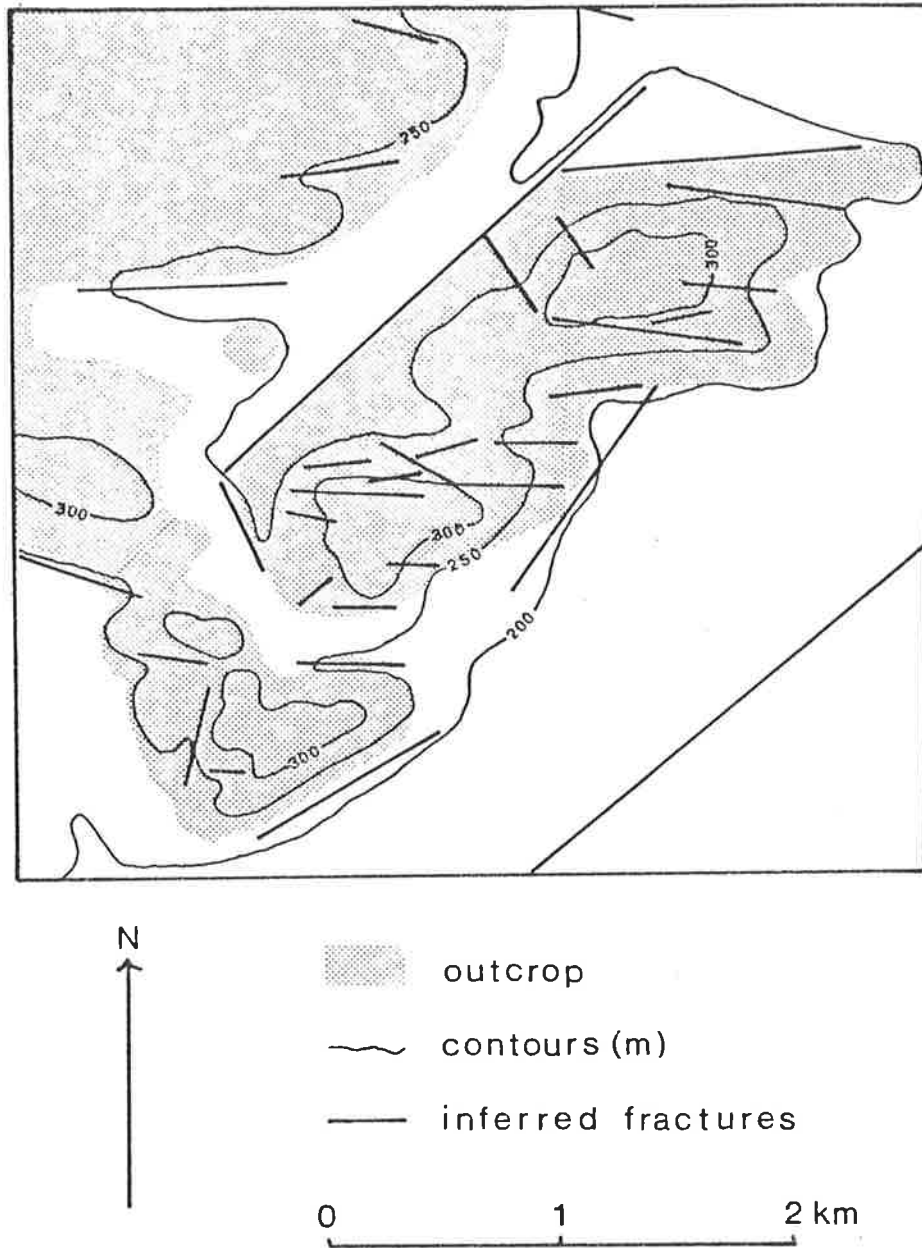


Figure 5.10C Inferred local scale orthogonal fracture systems: Yardea East. Drawn from aerial photographs, scale 1:86,000, South Australia Lands Department, and National Topographic Series 1:100,000 Kolendo and Yardea sheets.

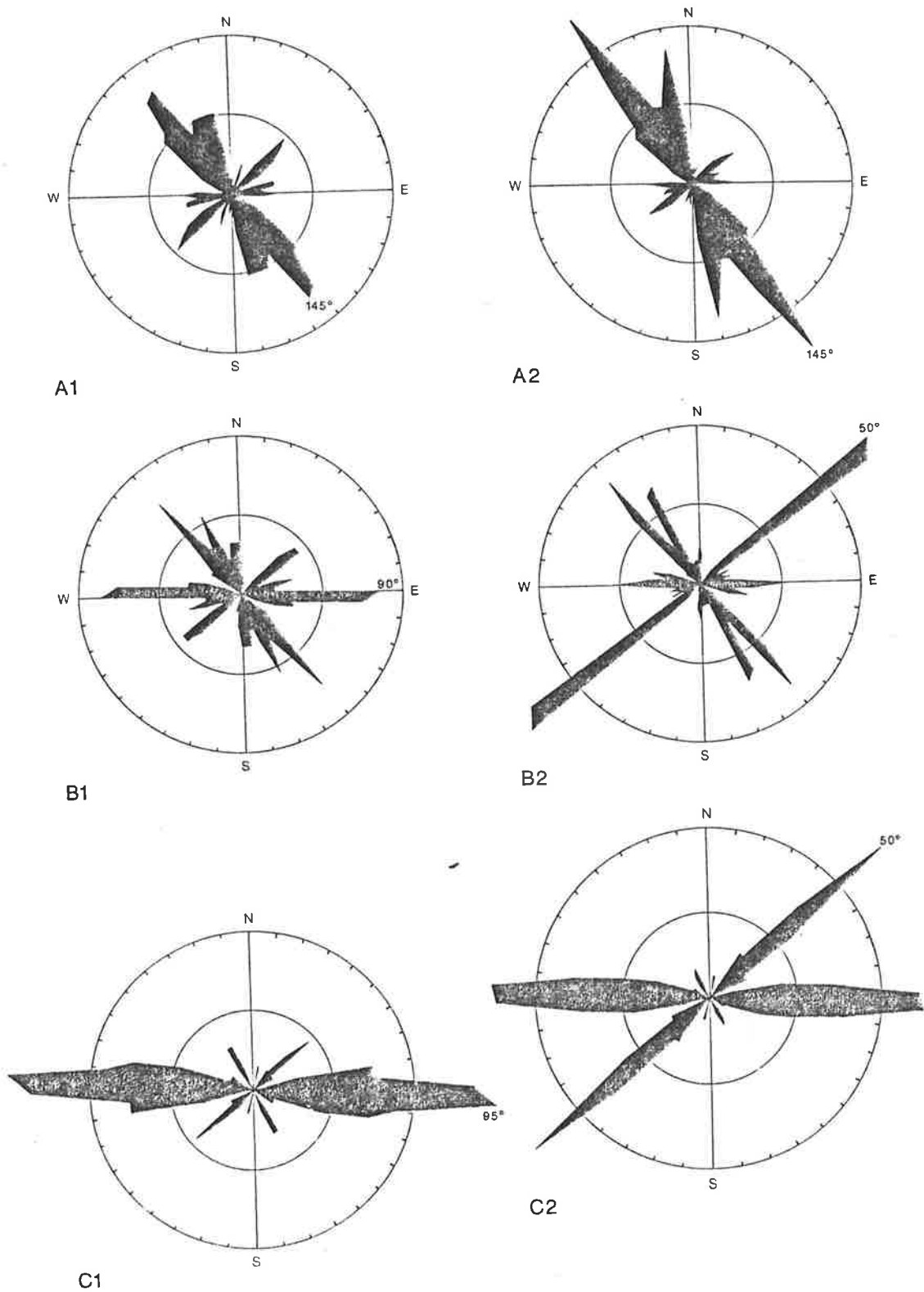


Figure 5.11 Rose diagrams for inferred local scale fractures: (A) Spring Hill, (B) Kolendo, (C) Yardea East: (1) by number, (2) by length.

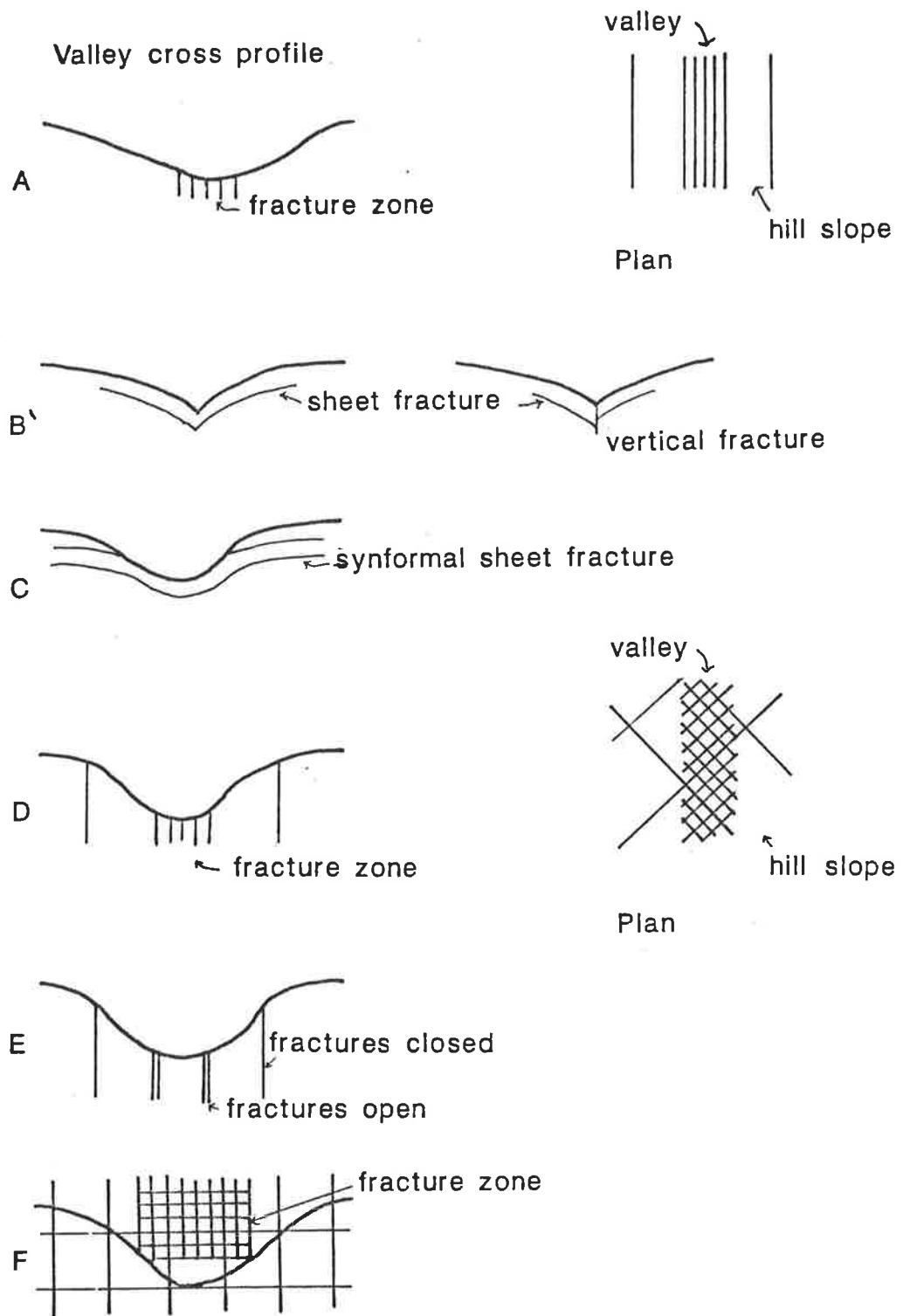
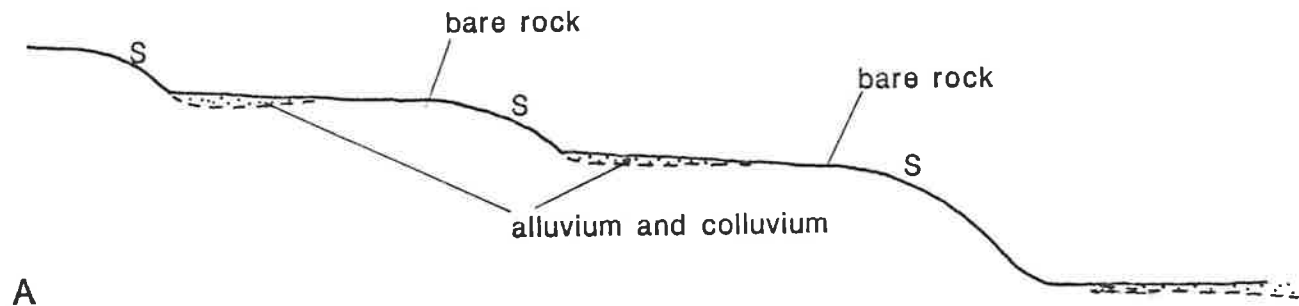
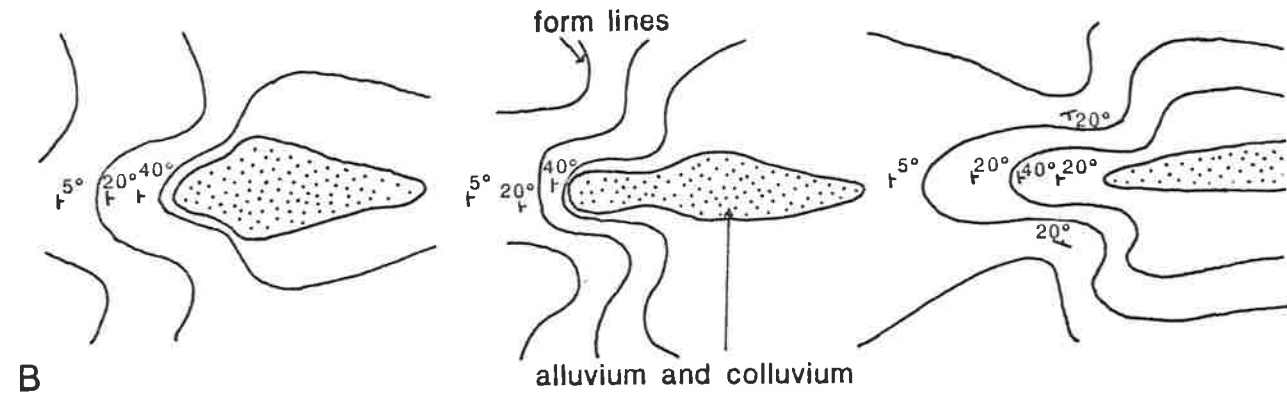


Figure 5.12 Suggested relationships of minor valleys to fractures

(see text for explanation).



A



B

r 20° Strike and dip of sheet fractures
 S Sheet fractures

Figure 5.13 Basin-like sheet fractures repeated along a valley in Spring Hill: (A) plan, (B) profile.

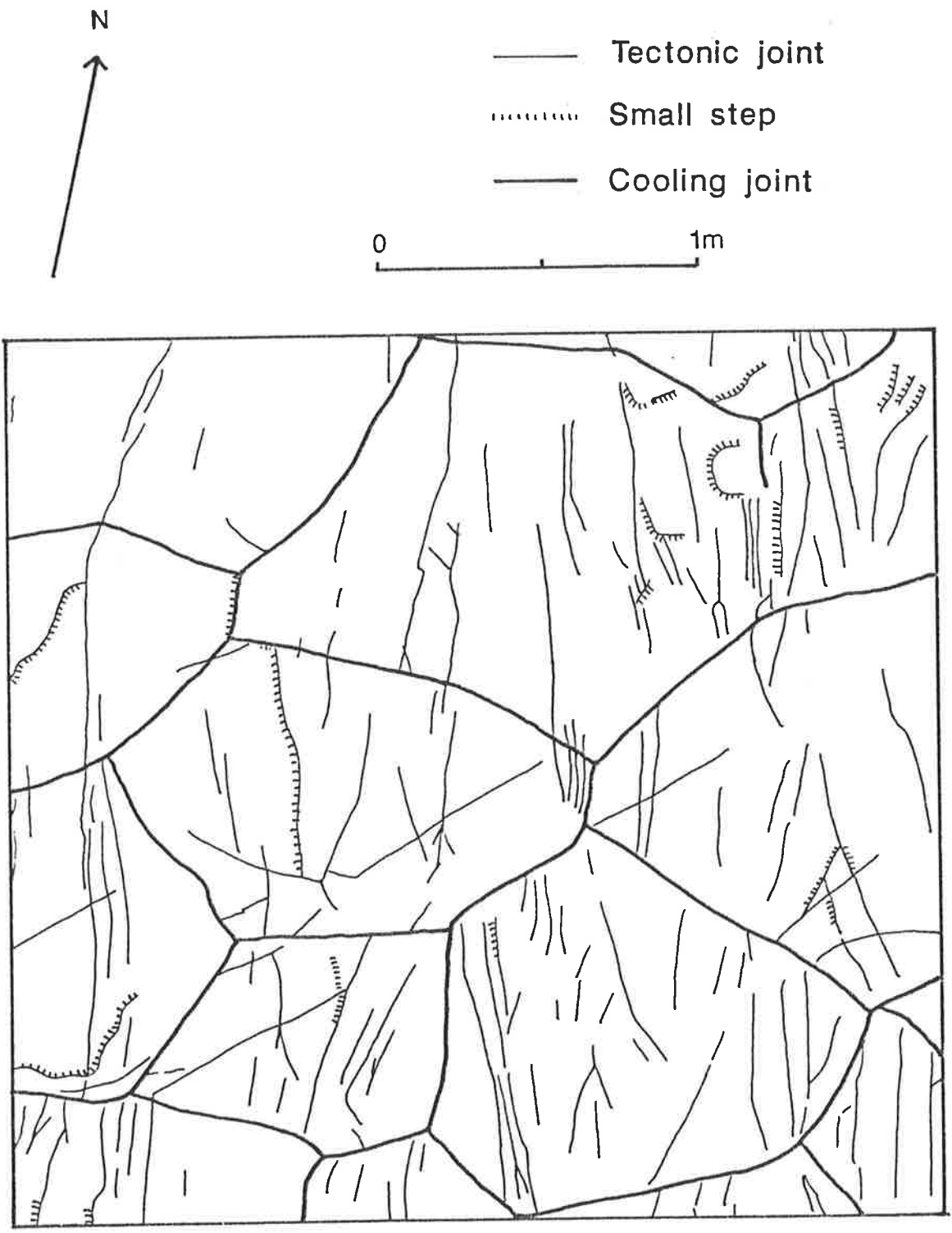





Figure 5.14 A The trace of fractures on a platform on Spring Hill, southern Gawler Ranges.



-  open fissure
-  joint
-  edge of platform


0  1m

Figure 5.14 B The trace of fractures on a platform on Yandinga Hill,
southern Gawler Ranges.

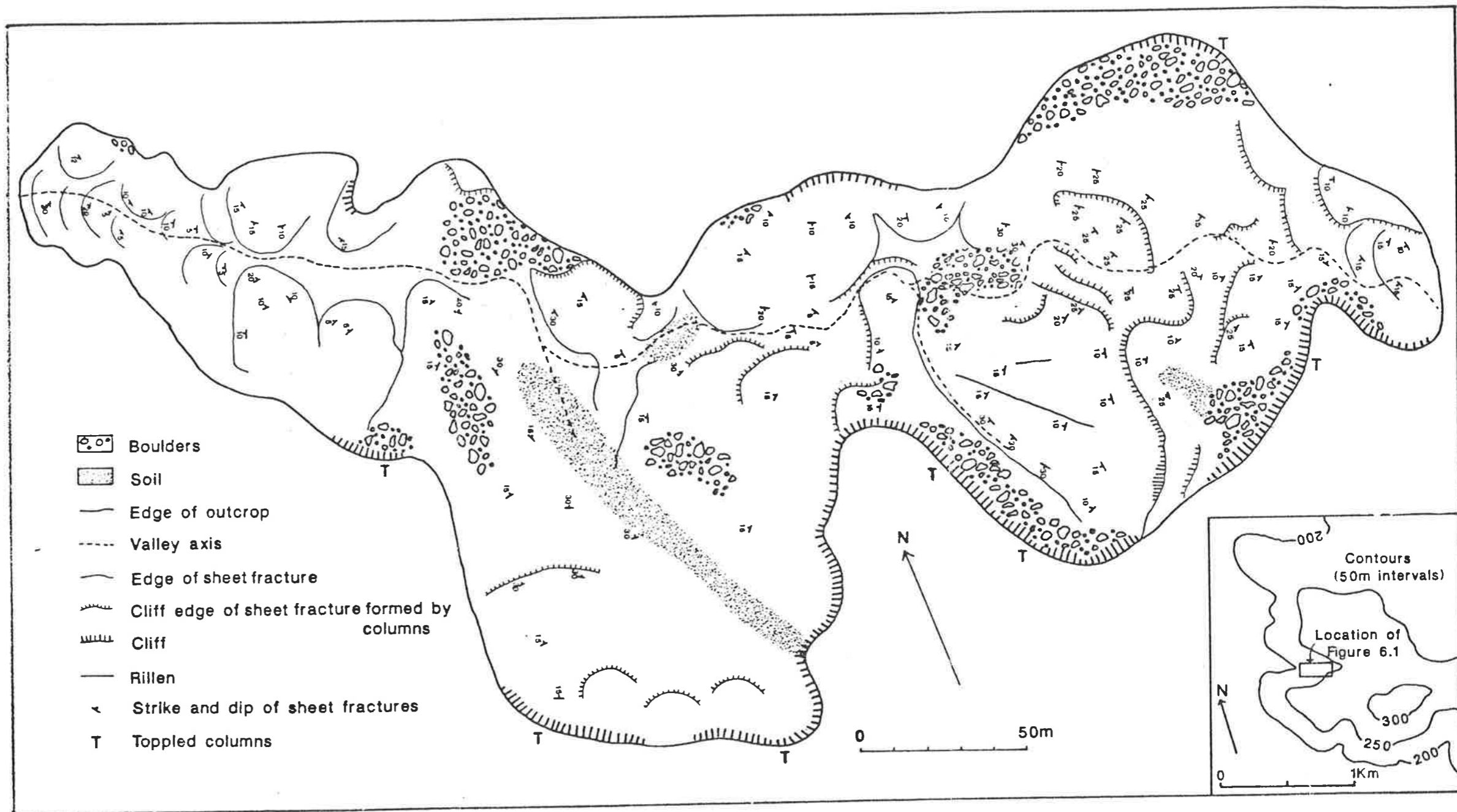


Figure 6.1 Features including sheet fractures and columnar joints exposed on a rock outcrop in a valley in Peterby Hill, southern Gawler Ranges.

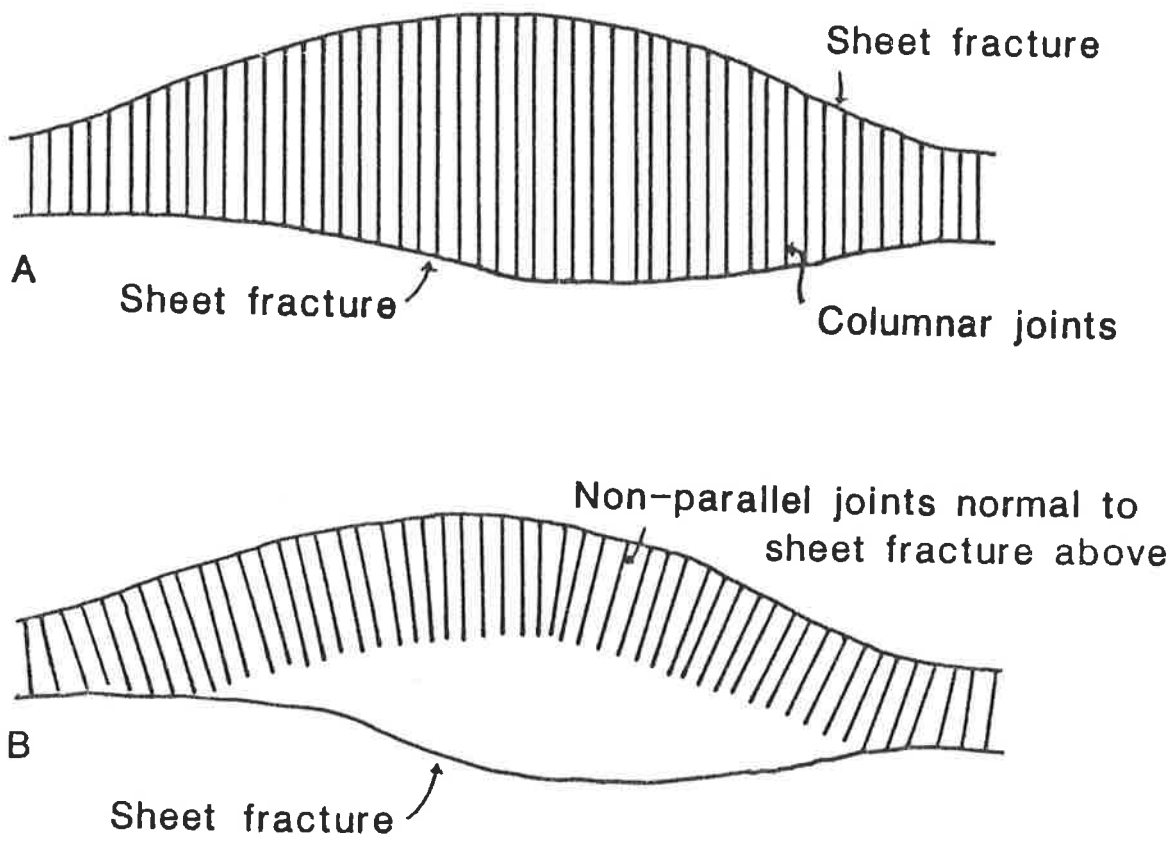
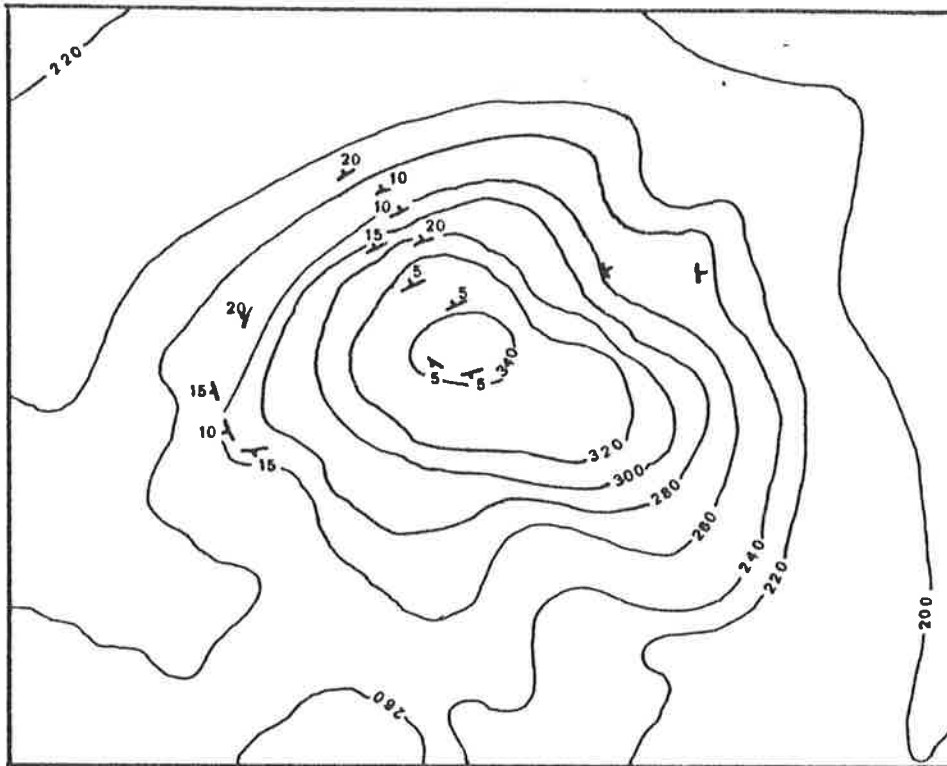


Figure 6.2 The relationship of sheet fractures and columnar joints: (A) in the Gawler Ranges, (B) as would be expected if the columnar joints postdated the sheet fractures.



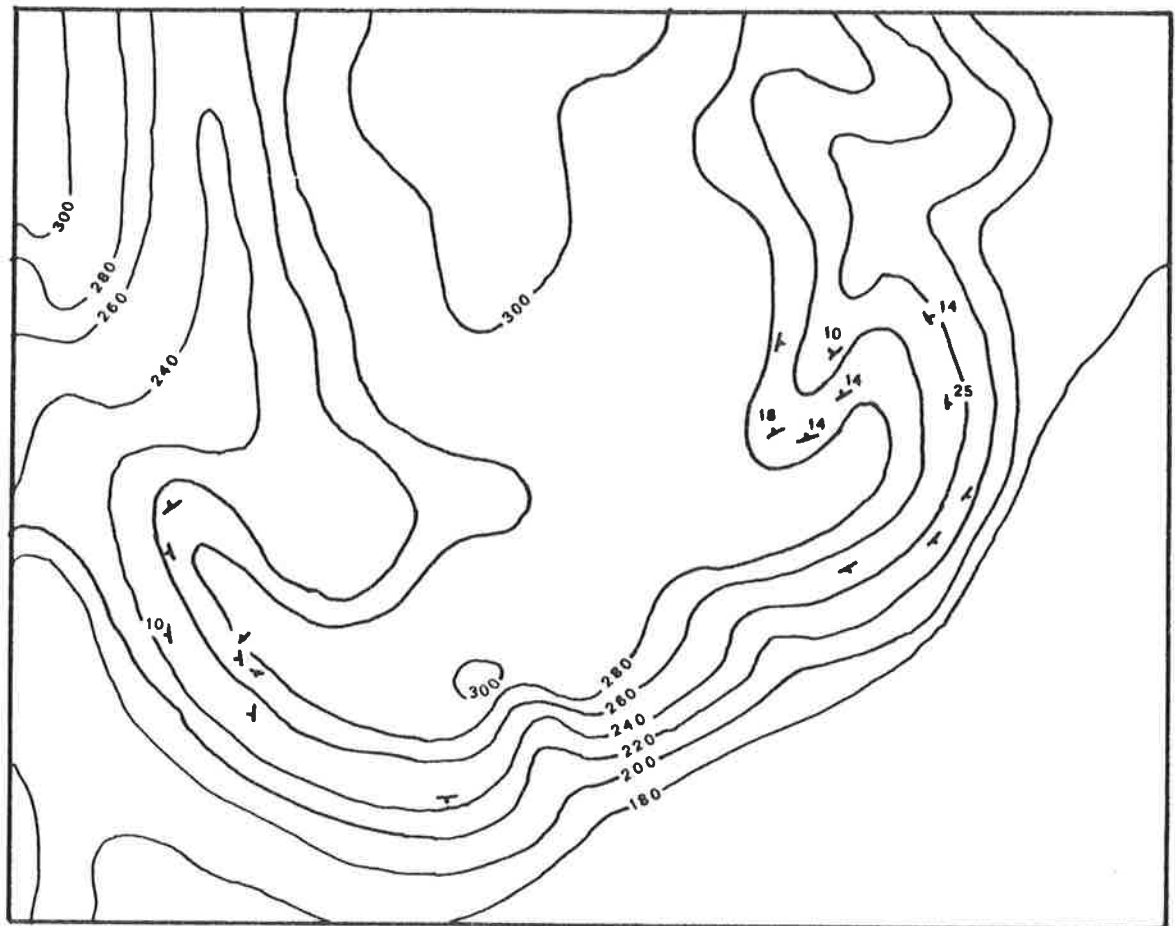
— Contours (20m interval)

\wedge_{15} Strike and dip of sheet fractures

0 1Km

Figure 6.3 A Contour plan of bornhardt's showing sheet fractures dipping quaquaversally:

Mt Kolendo, central Gawler Ranges



\swarrow_{20} Strike and dip of sheet fractures

— Contours (20m interval)

0 1Km

Figure 6.3B Contour plan of bornhardt showing sheet fractures dipping quaquaversally:

Yandinga Hill, southern Gawler Ranges.

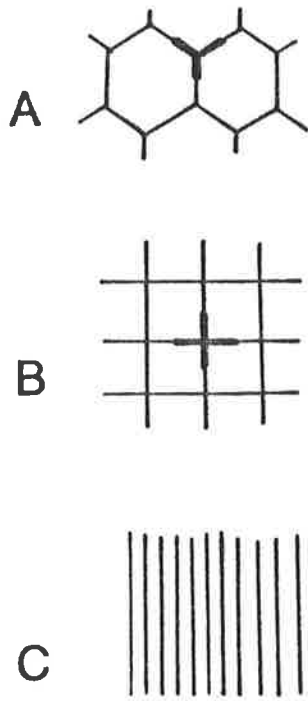


Figure 7.1

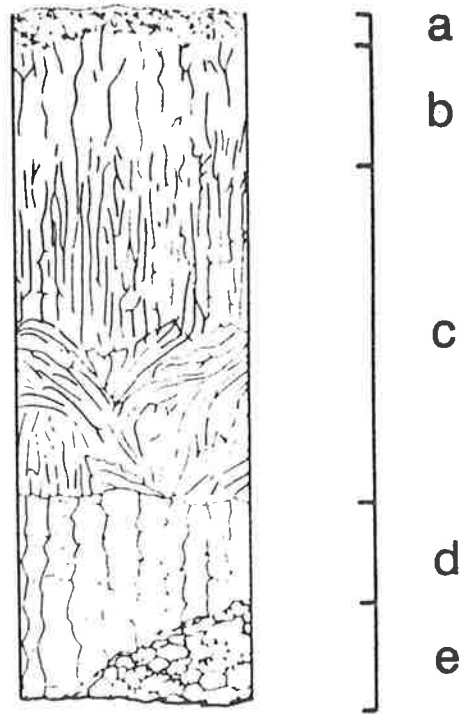


Figure 7.2

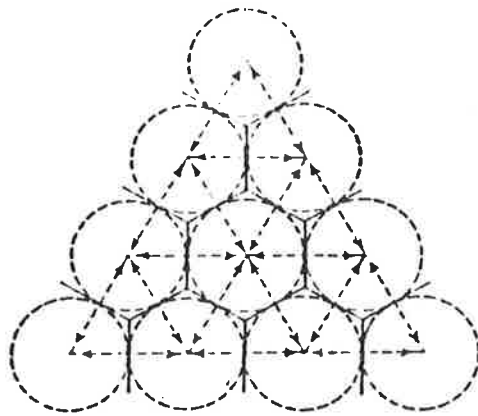


Figure 7.3

Figure 7.1 X and Y intersections of columnar joints (A and B) and slabs defined by sets of closely spaced fractures (C).

Figure 7.2 The differentiation of the Grande Ronde Basalt flow into zones according to Long & Wood (1986): (a) vesicular flow top, (b) upper colonnade, (c) entablature, (d) lower colonnade and (e) pillow zone.

Figure 7.3 The hexagonal pattern of columnar joints developed by contraction from equally spaced centres (from Iddings 1909).

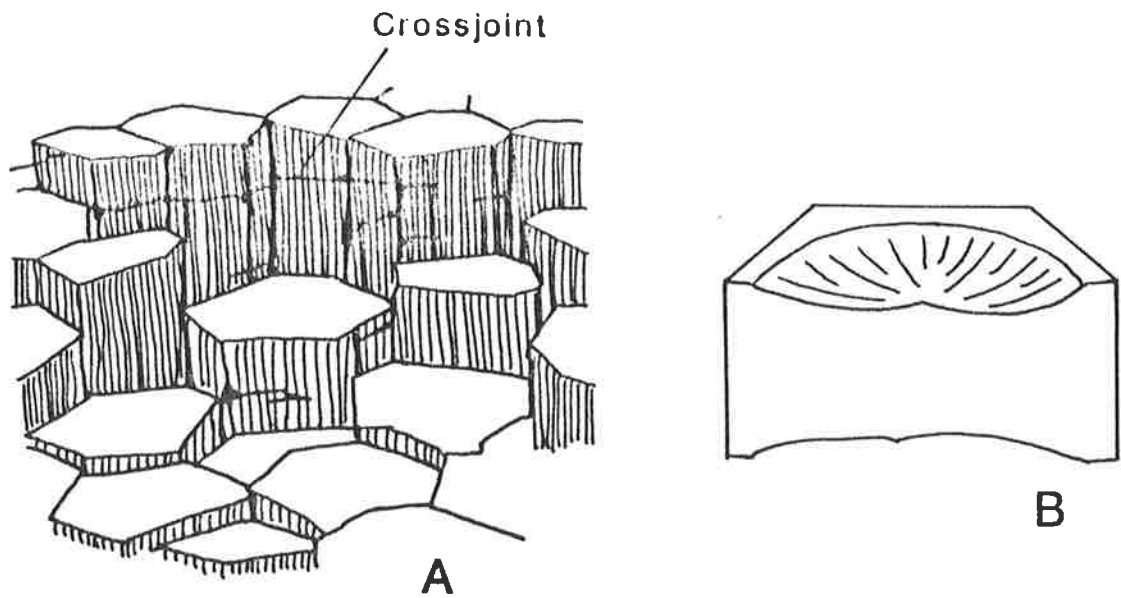


Figure 7.4

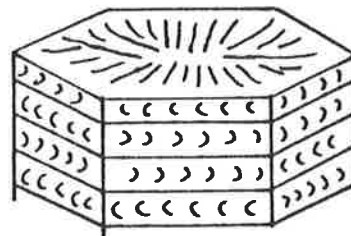


Figure 7.5

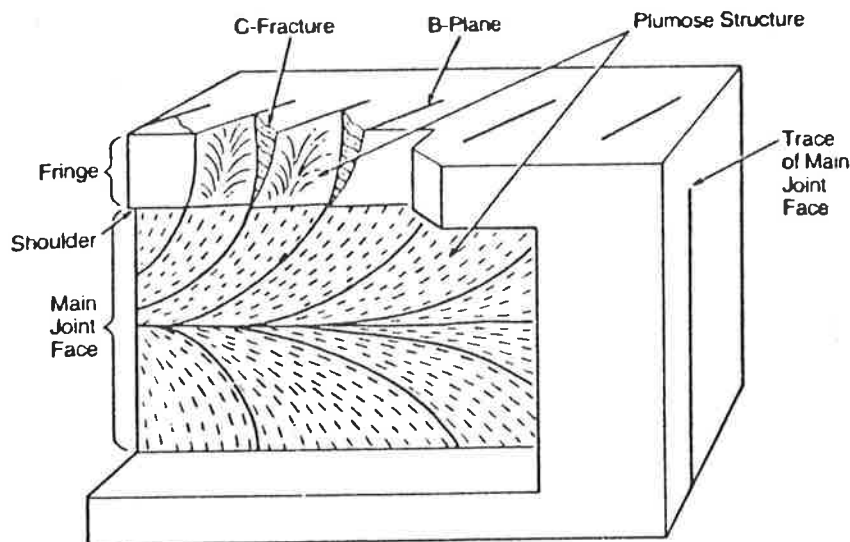


Figure 7.6

Figure 7.4 Well developed cross joints in columns: (A) planar joints (after Thomson 1879) and (B) ball and socket joints (after Tomkeieff 1940).

Figure 7.5 Chisel marks on columns (after Tomkeieff 1940).

Figure 7.6 Schematic diagram showing a major joint face with plumose structure, bordered by a fringe, some fractures of which also display plumose structure. Direction of main joint propagation from left to right (from Davis 1984, after Hodgson 1961).

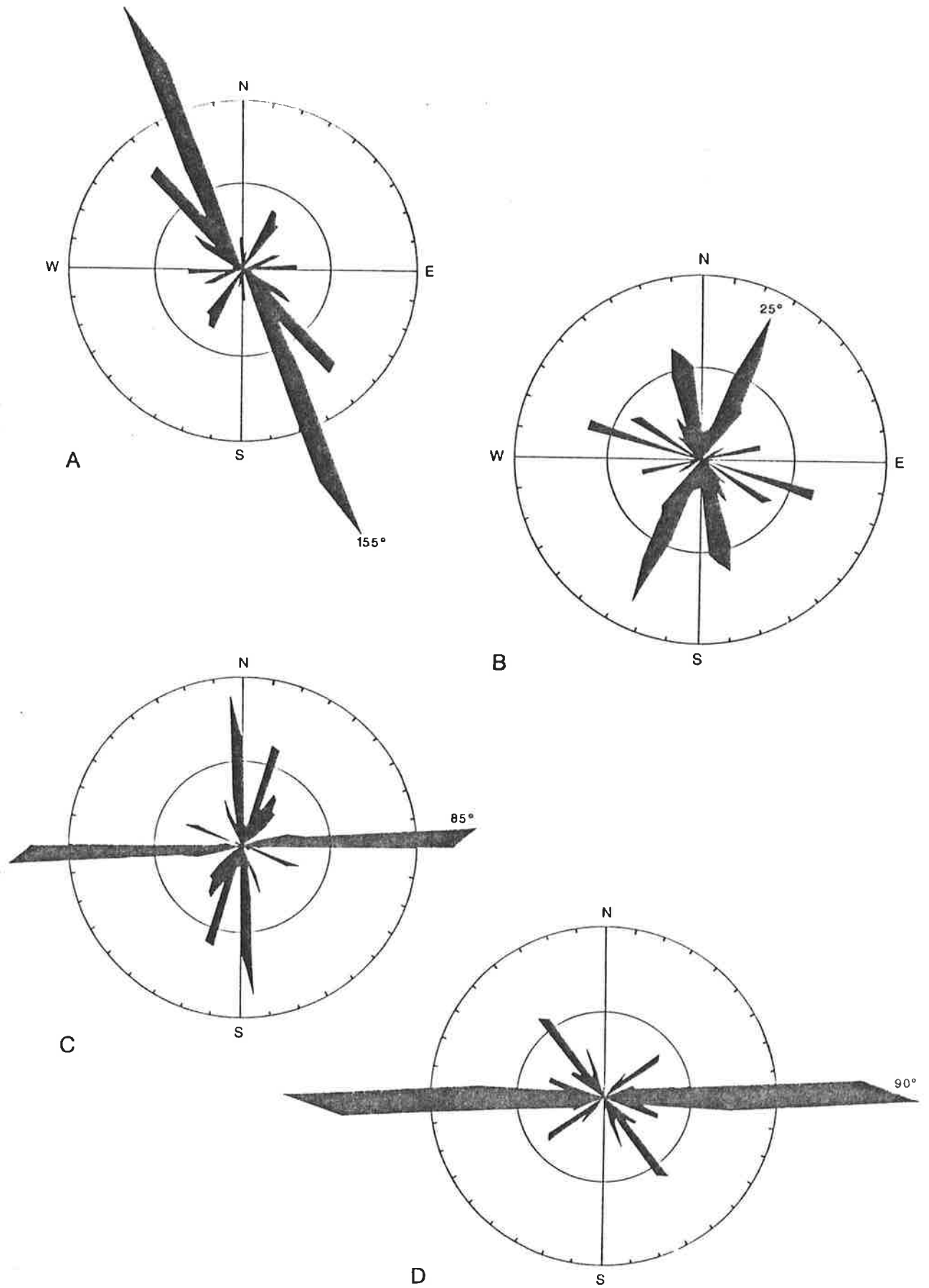


Figure 7.7 Joint rose diagrams: (A) Spring Hill, (B) Yandinga Hill, (C) Fossil Hill, (D) Yardea East, by length.

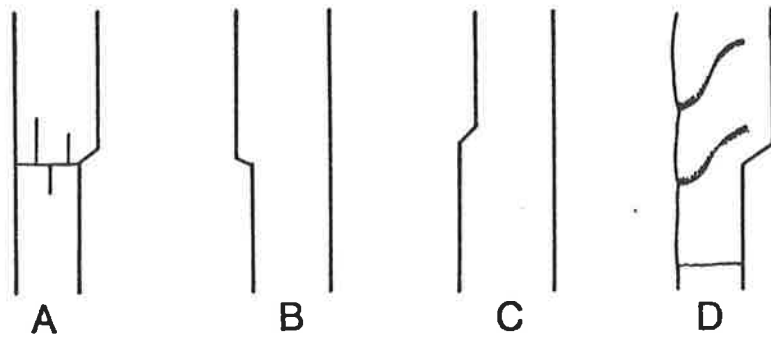


Figure 7.8

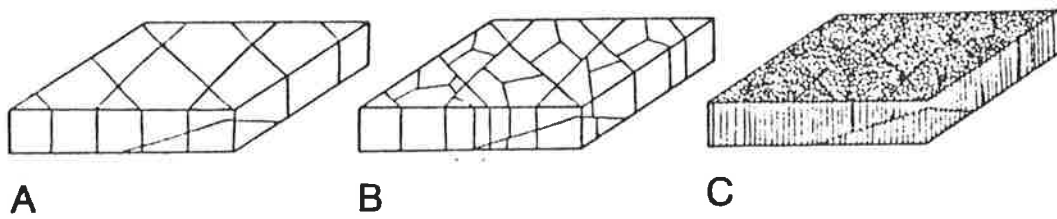


Figure 7.9

Figure 7.8 The faces of many of the columns in the Gawler Ranges are stepped. (A) decrease in diameter with depth associated with a cross joint, (B) increase in diameter with depth, (C) decrease in diameter with depth and (D) curved steps.

Figure 7.9 Stages in the continuous development of progressively smaller columns (after Spry 1962).

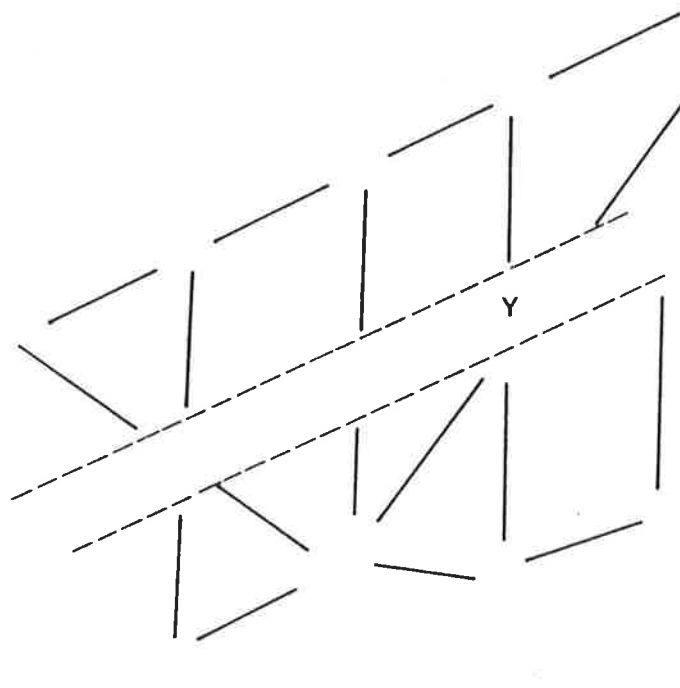
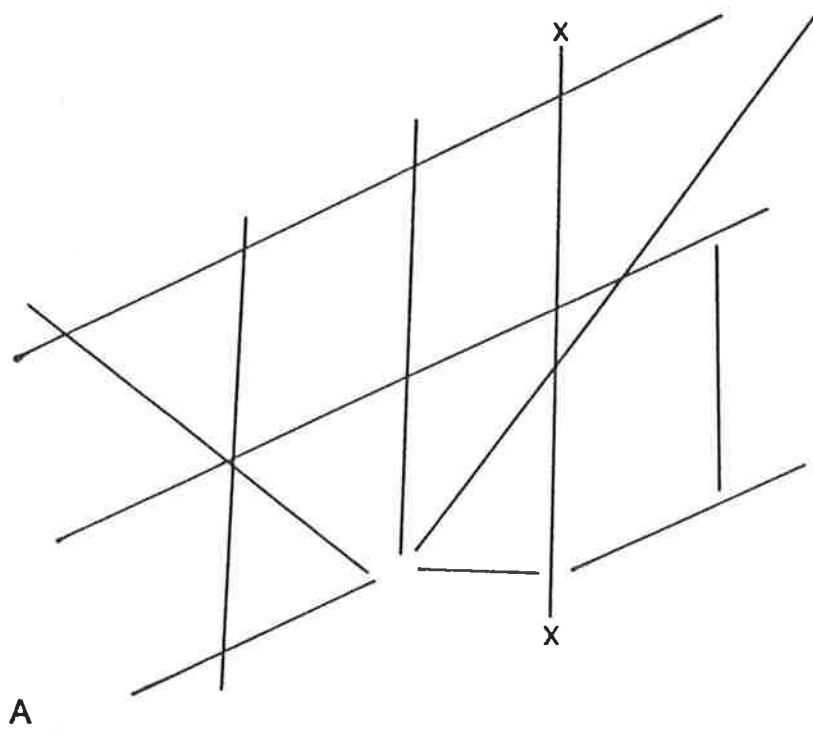


Figure A2.1 Gaps in alignment of linears, rather than indicating a continuous linear

X-X (A), may represent a zone of different intensity of deformation Y (B).

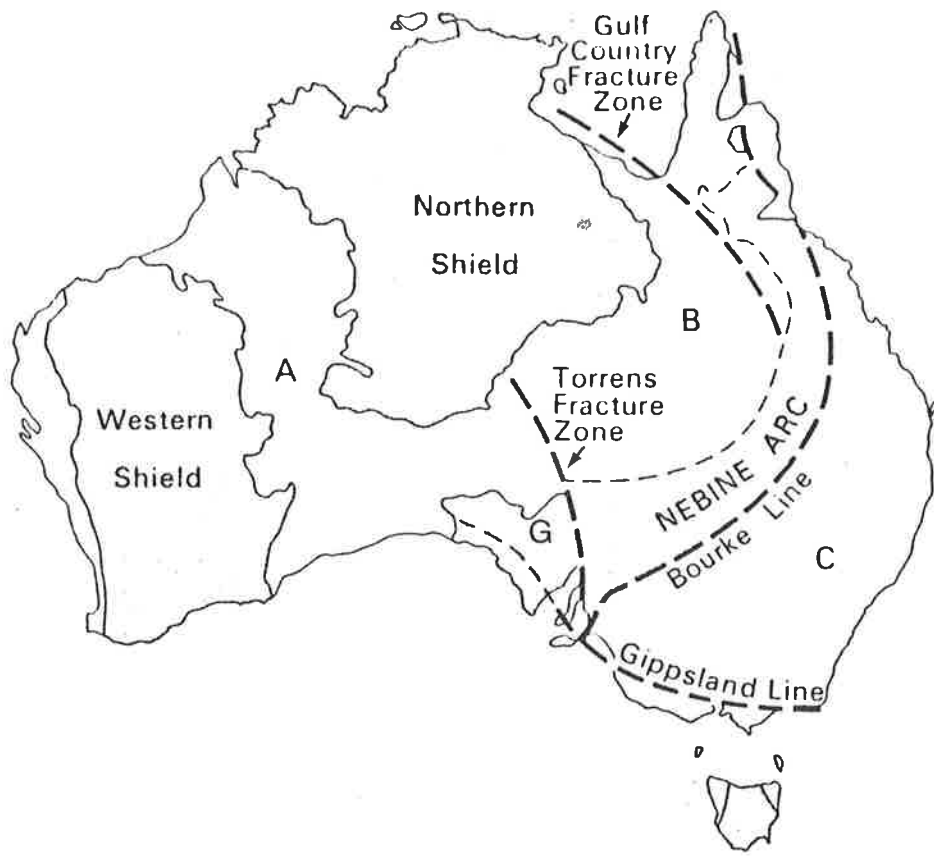


Figure A3.1 The Gippsland Line of Victoria is continued into South Australia along the Corrobinnie Depression, south of the Gawler Ranges (G) and to the Ooldea Range (see Harrington *et al.* 1982).

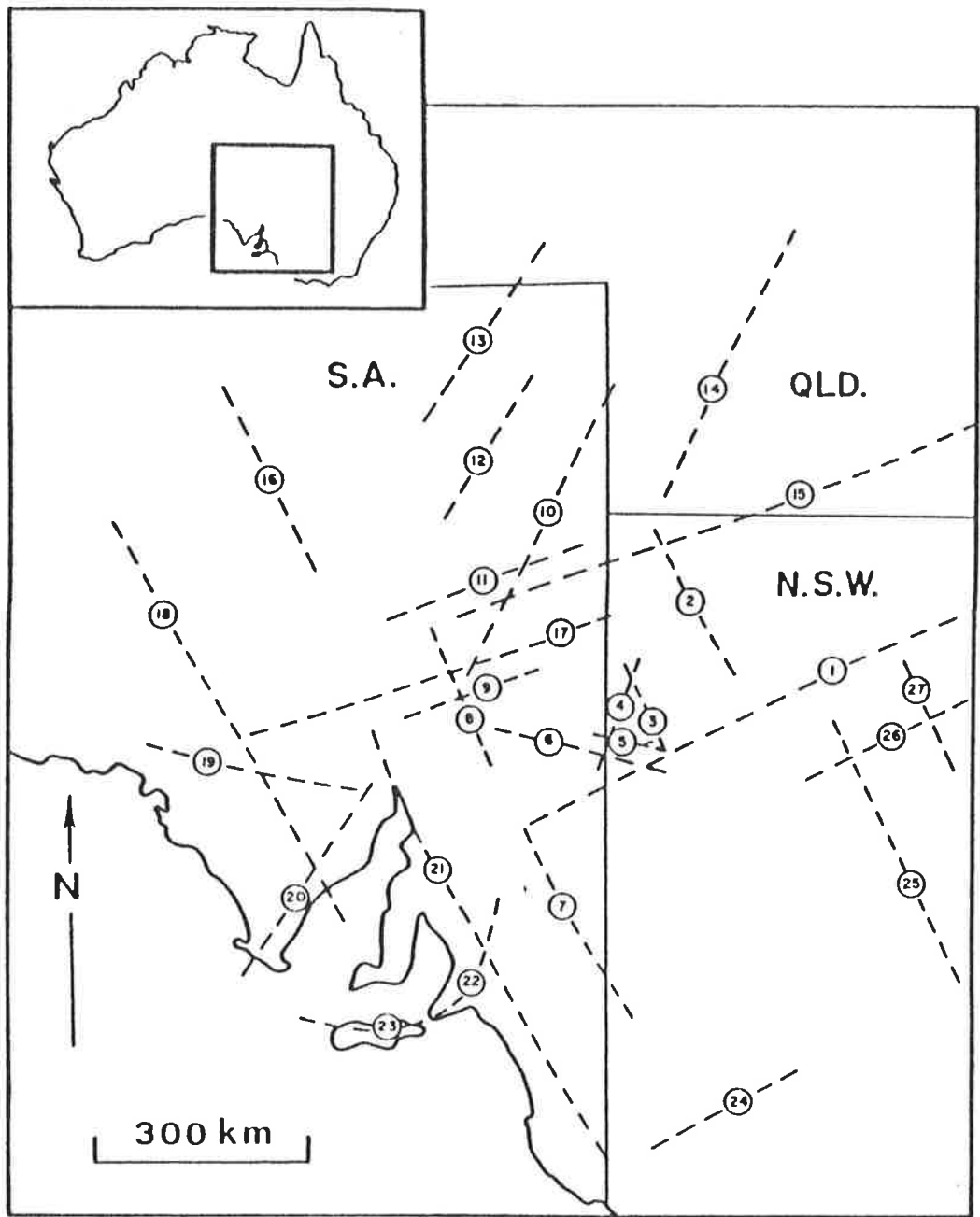


Figure A3.2 Lineament pattern over south central Australia (O'Driscoll (1985)).

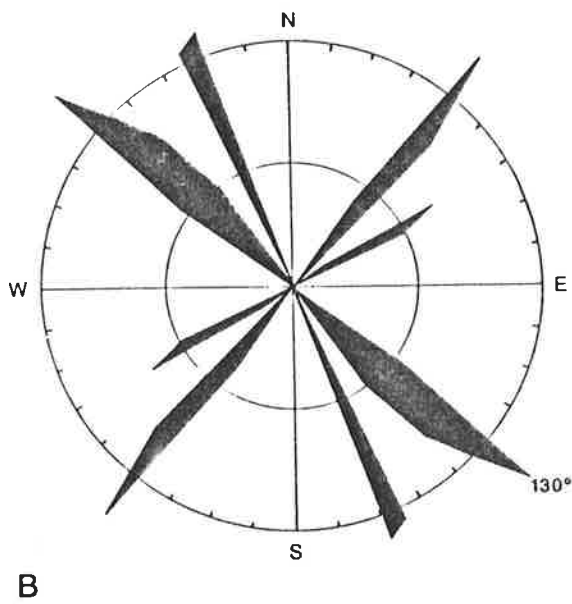
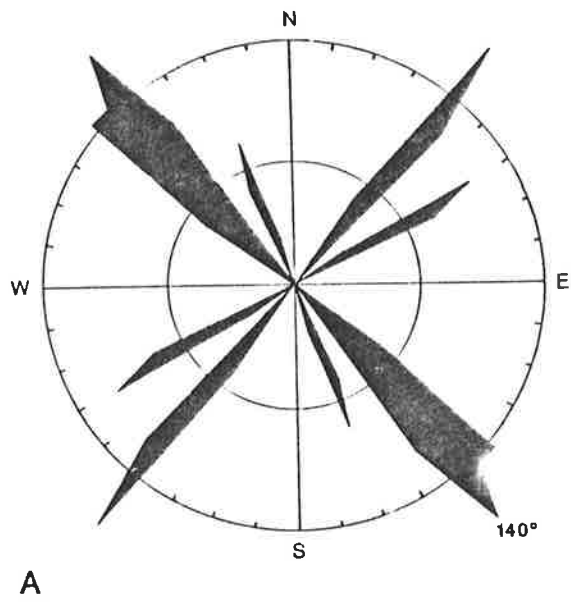


Figure A3.3 Rose diagrams of Firman's (1974) lineaments in the Gawler Ranges and surrounding areas (A) by number (B) by length.

Plate 1.1 Mt Allalone, an isolated inselberg of conglomerate located in the southern piedmont of the Gawler Ranges (C. R. Twidale).

Plate 1.2A Dacitic inselbergs north of Yarna, on the western margin of the Gawler Ranges.

Plate 1.2B. Low inselberg of Gawler Range Volcanics located on the southern piedmont of the Gawler Ranges (C. R. Twidale).



1.1

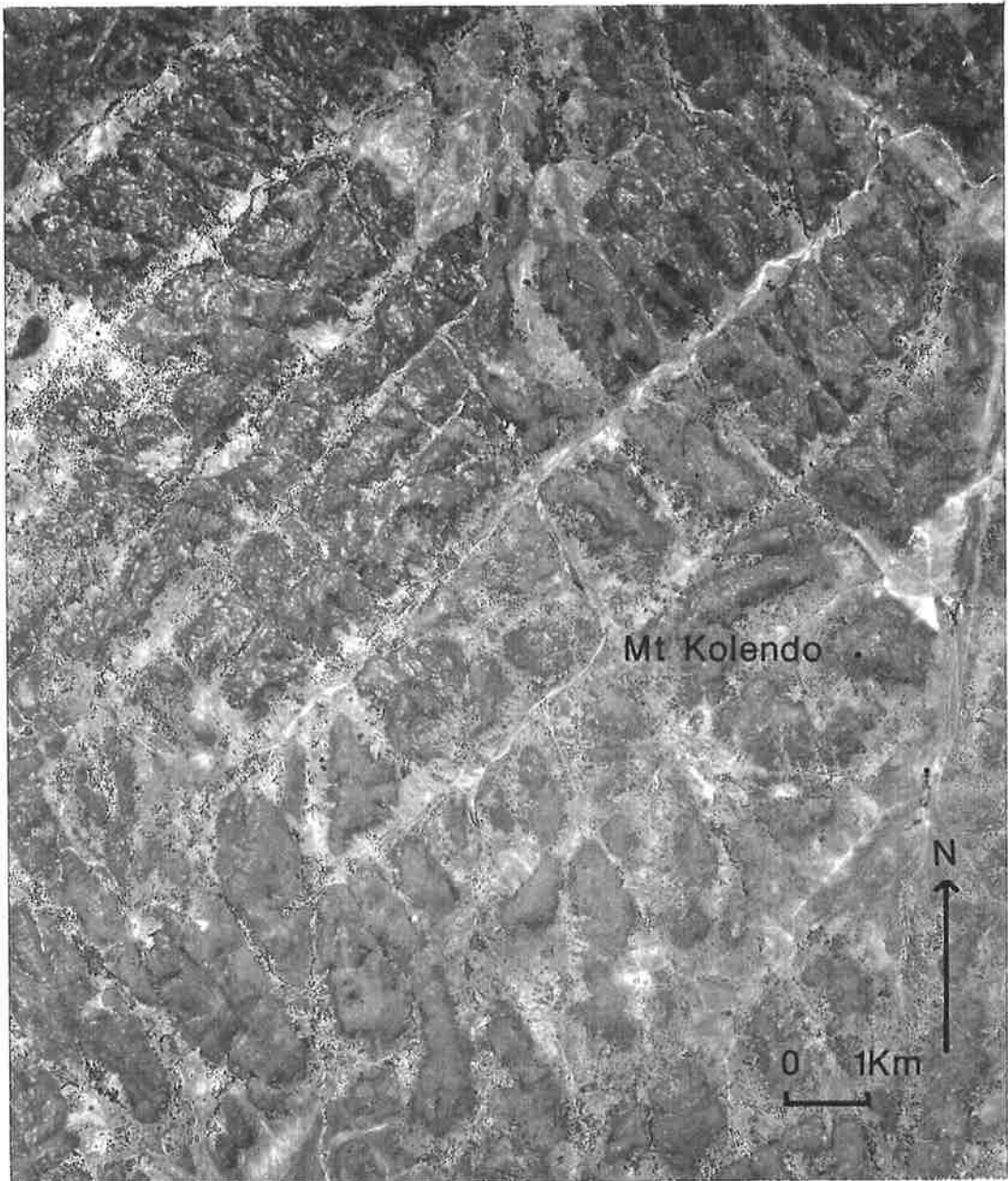


1.2A



1.2B

Plate 1.3A *Dacitic bornhardts* standing in ordered rows, Kolendo area, central Gawler Ranges
(South Australia Department of Lands aerial photograph 2481/189).



1.3A

Plate 1.3B Closely juxtaposed dacitic bornhardts, Scrubby Peak area, southern Gawler Ranges

(South Australia Department of Lands aerial photograph 2361/138).



1.3B

Plate 1.4A Bevelled bornhardts, southwest of Yardea H.S., southwestern Gawler Ranges.

Plate 1.4B Bevelled summits together form a prominent summit surface, southern Gawler Ranges. Mt Nott in middle distance.

Plate 1.5 A small vein (X-X) of granite (G) intrudes Eucarro Dacite (D), southeast of Hiltaba O.S., western Gawler Ranges.



1.4 A



1.4 B



1.5

Plate 2.1 Dacitic hills with pronounced summit surface and, in foreground, bare platform standing 2-3 m above the valley floor, Peterby area, southwestern Gawler Ranges (C. R. Twidale).

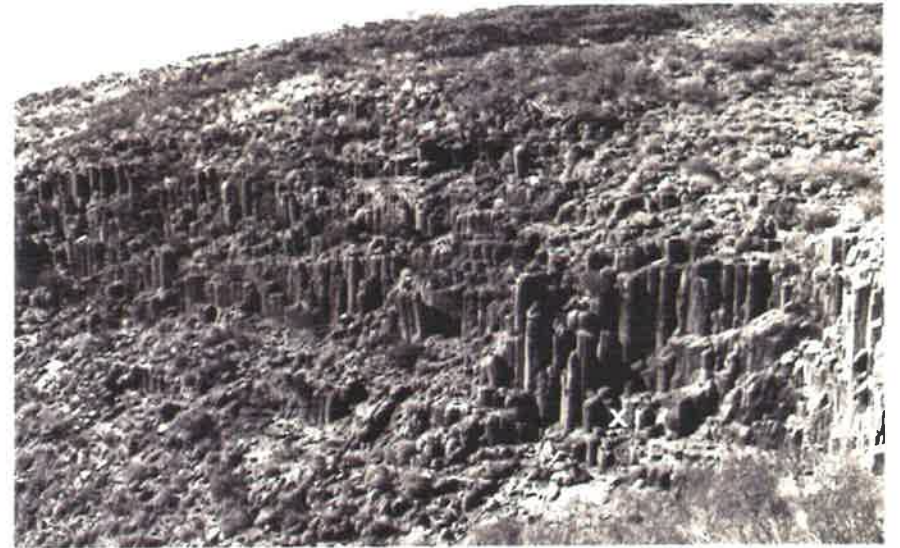
Plate 2.2 Sheet fractures parallel to the topographic surface, as at Spring Hill, southern Gawler Ranges, are well and widely developed.

Plate 2.3 Banks of columns on the slopes of Yandinga Hill, southern Gawler Ranges are characteristic of the bornhardts of the Gawler Ranges and are found in few other bornhardt landscapes. Note figure (X) for scale.

Plate 2.4 Well-defined piedmont angle in granite, Kokatha area (C. R. Twidale).



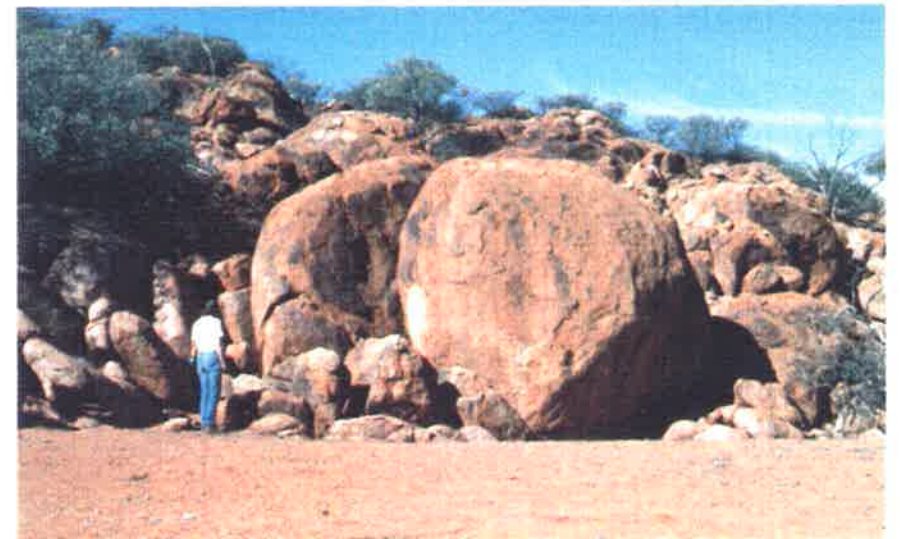
2.1



2.3



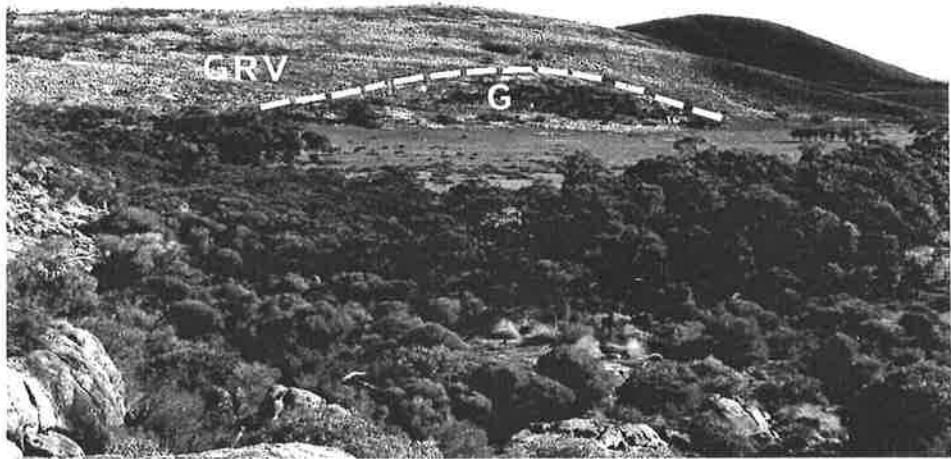
2.2



2.4

Plate 2.5 Partly exposed granitic stocks: (A) in the Hiltaba area, (B) east of Kondoolka H.S. (C. R. Twidale) (G - granite, GRV - volcanics).

Plate 2.6 The summit of Spring Hill in the southern Gawler Ranges consists essentially of bare rock surfaces with only small patches of regolith preserved in fracture-controlled depressions.



2.5A



2.5B



2.6

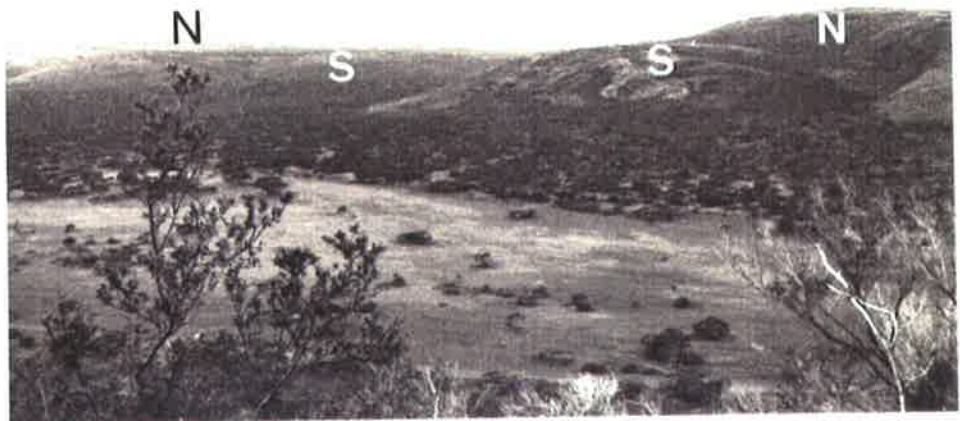
Plate 3.1 · A low mesa of weathered Gawler Range Volcanics overlain by Pandurra Formation and capped by silcrete (S) stands above this remnant of the Scrubby Surface (foreground) located north of Scrubby O.S. in the eastern Gawler Ranges (C. R. Twidale).

Plate 3.2 Remnants of the Spring Surface (S) stand some 30 m below the summit or Nott Surface (N), northwest of Paney H.S., southern Gawler Ranges.

Plate 3.3 Kaolinised regolith with small corestones, Mt Cooper, northwestern Eyre Peninsula (C. R. Twidale).



3.1



3.2



3.3

Plate 3.4A Corestones in weathered matrix, north of Paney H.S., southern Gawler Ranges.

Plate 3.4B The weathered corestones north of Paney H. S. are preserved on midslope, well above the present valley floor.

Plate 3.5A A veneer of hematitic material is preserved on these rocky outcrops on the summit of a hill east of Yardea H.S., central Gawler Ranges.

Plate 3.5B A veneer of purplish-brown hematitic material, associated with a pitted surface developed on Yardea Dacite. Scale in millimetres (R. Barrett).



3.4A



3.4B



3.5A



3.5B

Plate 3.6 Flared slopes: (A) north of Paney H.S. in the southern Gawler Ranges and (B) on Mt Sturt on the southern piedmont of the Ranges.

Plate 3.7 Coralbignie Rocks, south of Nonning H.S., southern Gawler Ranges, fracture-controlled masses of Gawler Range Volcanics on which platforms and cones are developed (C. R. Twidale).



3.6A



3.6B



3.7

Plate 5.1 In Kolay Valley, north of Paney H.S., southern Gawler Ranges, the valley axis is aligned coincident with a zone of dense vertical fractures (X).

Plate 5.2 Two steeply dipping sheet fractures meet in the axis of a minor valley cut in Peterby Hill, southern Gawler Ranges. Note the convex-upward sheet fractures and the traces of columnar joints.

Plate 5.3 This tributary valley cut in Spring Hill, southern Gawler Ranges, bottoms on a synformal sheet structure. Note the columns and wedging out of the sheets.

Plate 5.4 The trace of orthogonal fractures is apparent on this rocky outcrop in Peterby Valley, southern Gawler Ranges. The axis of the valley at this site is oriented diagonal to the fracture pattern.



5.1



5.3



5.2



5.4

Plate 6.1A Sheet fractures (X) parallel to the land surface, as on this bornhardt in the southern Gawler Ranges, are widely developed.

Plate 6.1B On this bornhardt south of Spring Hill, southern Gawler Ranges, sheet fractures and the land surface are coincident, but both clearly cut across columnar joints.

Plate 6.2 Convex-upward sheet fractures in a small valley in Yandinga Hill, south of Scrubby Peak, southern Gawler Ranges.



6.1A



6.1B



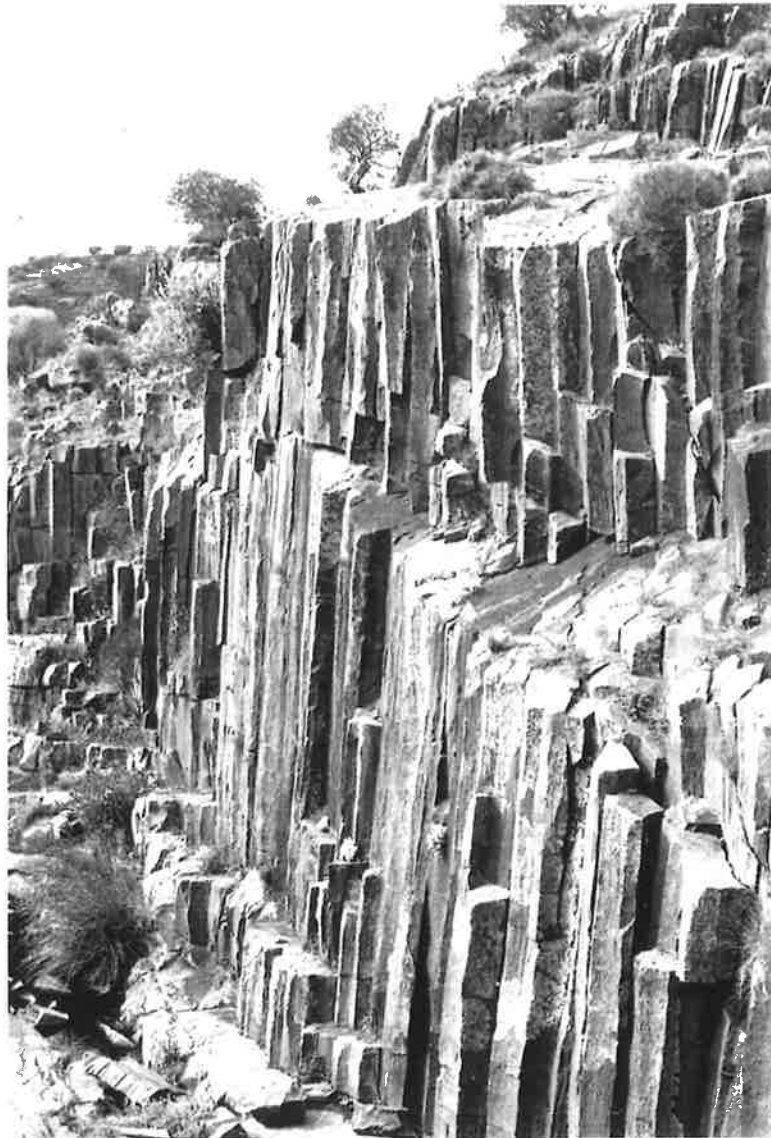
6.2

Plate 6.3A Lenticular banks of columns exposed on the slopes of Peterby Hill, southern Gawler Ranges.

Plate 6.3B Irregular and non-parallel sheet fractures cut across columnar joints in Kolay Valley, southern Gawler Ranges.



6.3 A



6.3 B

Plate 6.4 Sheets approximately 1 m thick are interbedded with thinner sheets on this exposure in a valley in Spring Hill, southern Gawler Ranges. The columns in the foreground are offset relative to those in the sheet below.

Plate 6.5 Sheet fractures are well displayed at the surface of Mt Cooper, located on northwestern Eyre Peninsula.



6.4

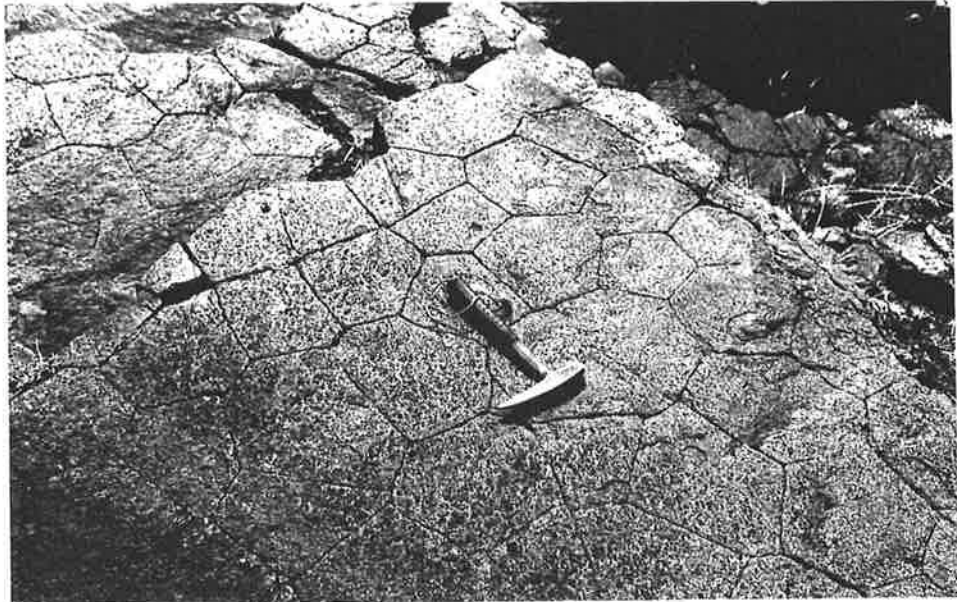


6.5

Plate 7.1 Traces of polygonal joints exposed on the surface of a sheet, Kolay Valley, southern Gawler Ranges.

Plate 7.2 A set of closely spaced fractures results in the formation of slabs, Mt Kolendo, central Gawler Ranges.

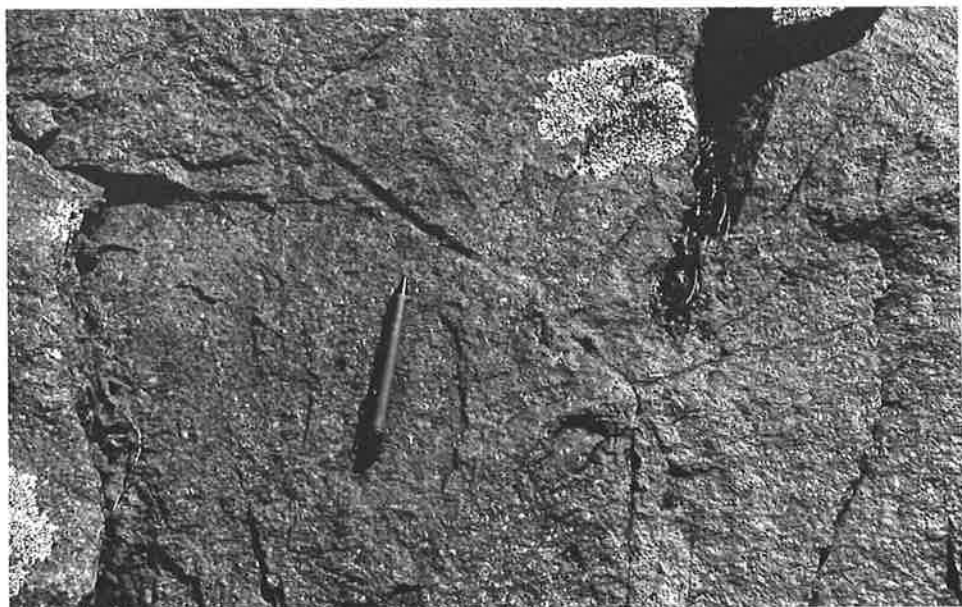
Plate 7.3 Parts of the trace of these columnar joints on a sheet fracture, Spring Hill, southern Gawler Ranges, are marked by shallow depressions (near the point of the pen) which coincide with the sheath of albite surrounding the columns.



7.1



7.2

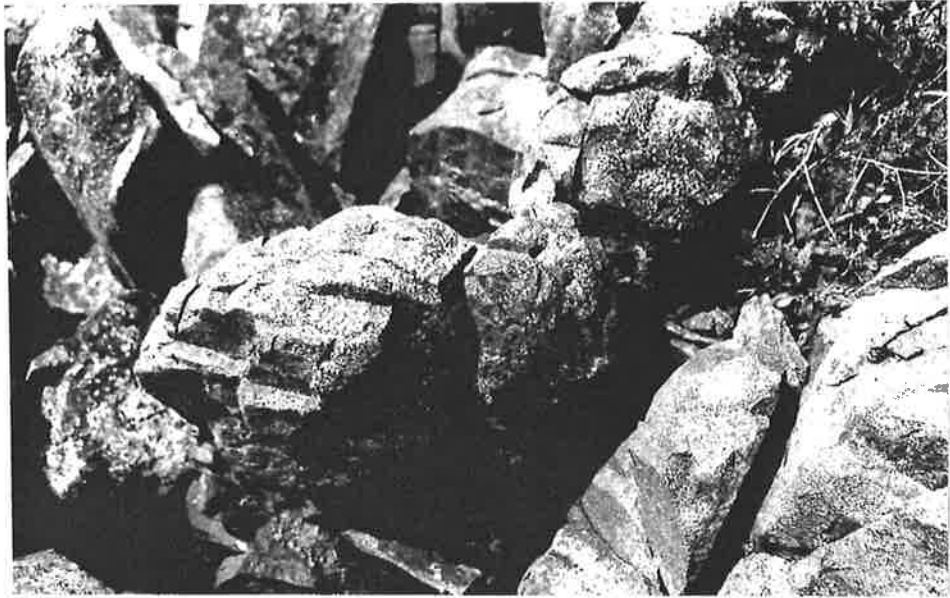


7.3

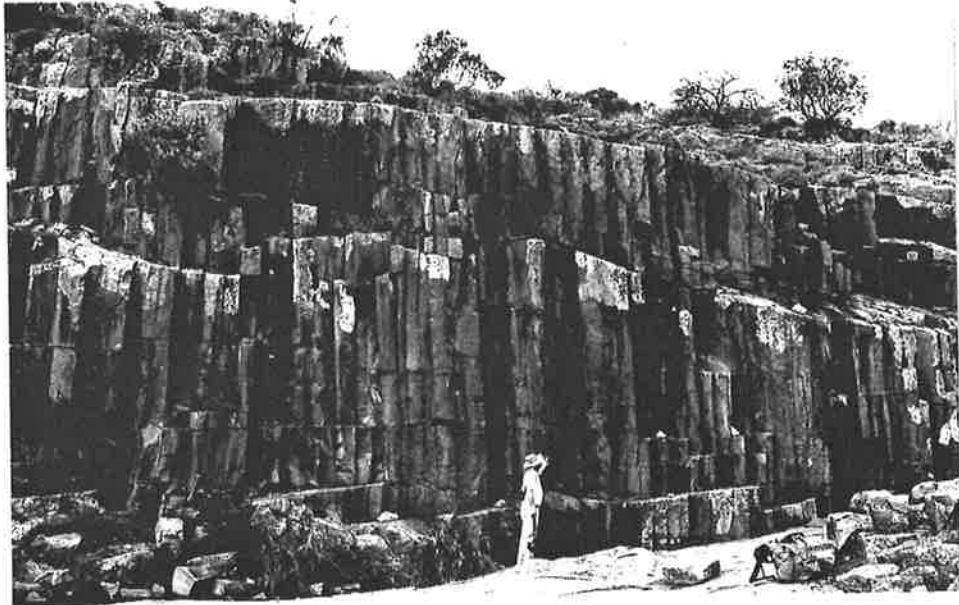
Plate 7.4 The partially rounded tops of these columns, Spring Hill, southern Gawler Ranges, show the influence of an orthogonal system of joints which subdivides the columns along their length.

Plate 7.5 The columnar joints exposed in this cliff in Kolay Valley, southern Gawler Ranges, extend from one sheet to the next. Note the undulating sheet fractures.

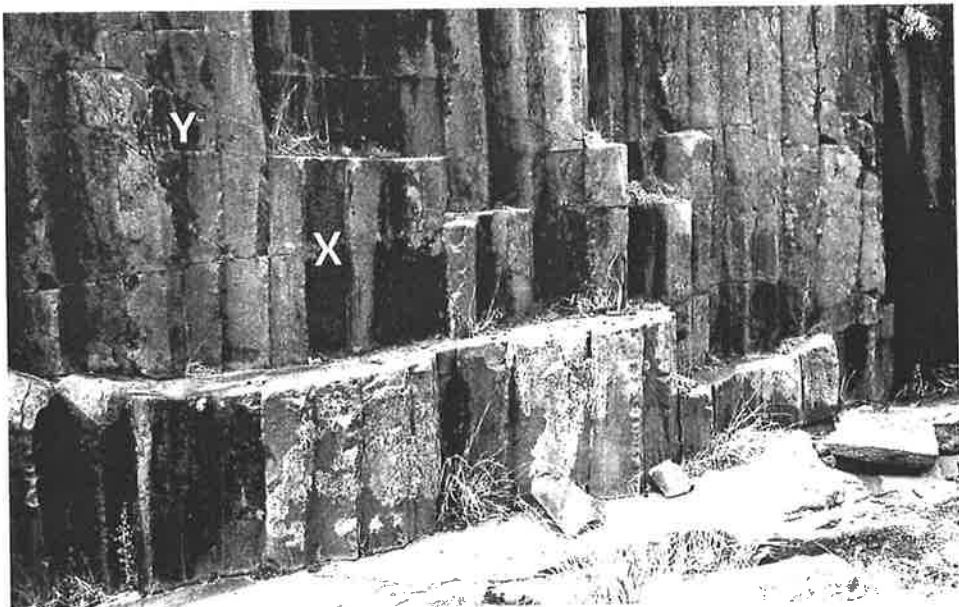
Plate 7.6 Some of the sheets which cut across the columns at Kolay Valley, southern Gawler Ranges, are discontinuous (X). Oblique joints (Y) subdivide some of the columns.



7.4

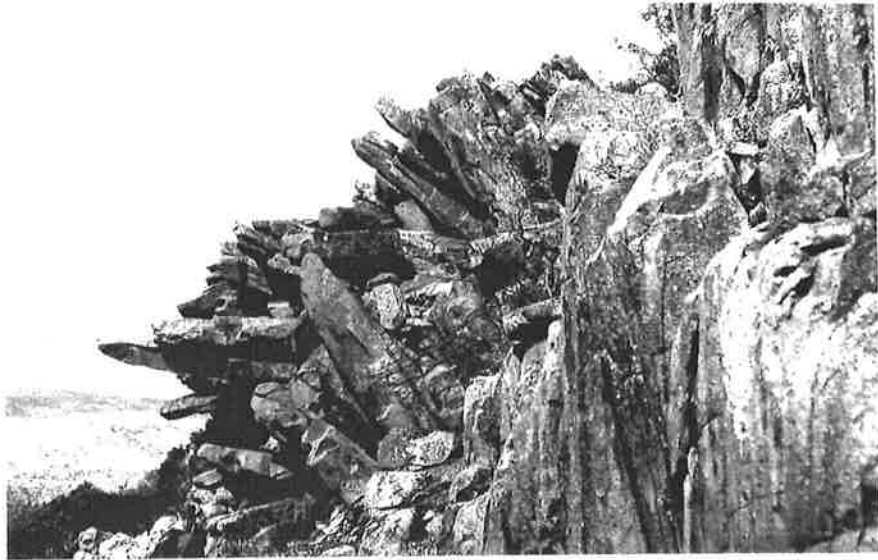


7.5



7.6

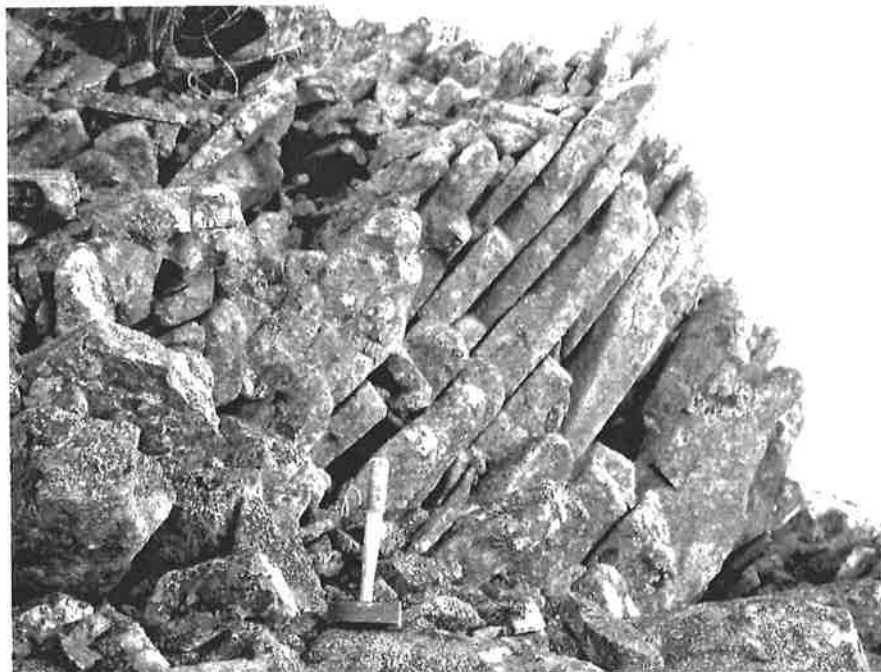
Plate 7.7 Toppled columns (A) on Yandinga Hill, southern Gawler Ranges and (B) on a hill located east of Yardea H.S., central Gawler Ranges, where toppled slabs (C) are also present.



7.7A



7.7B



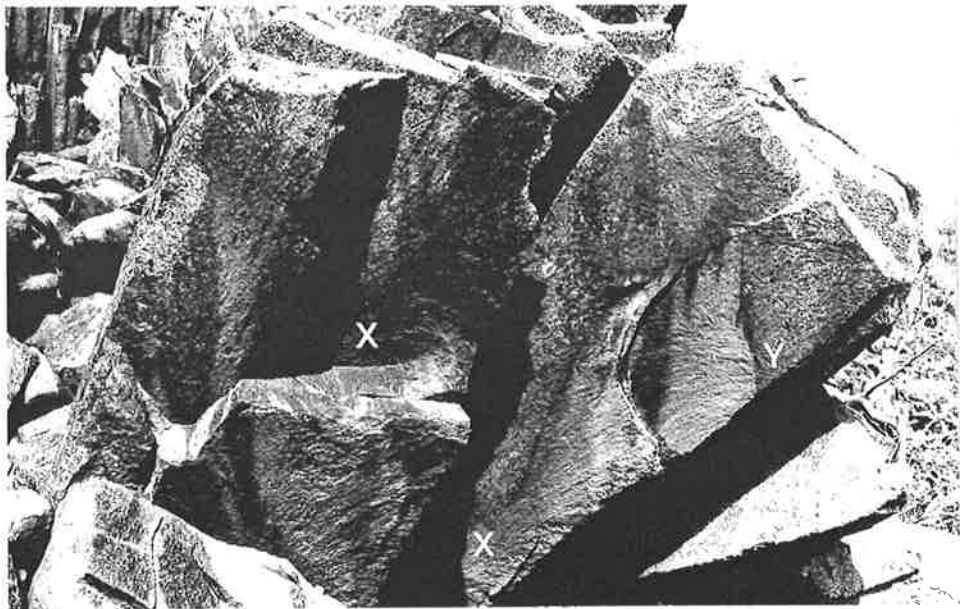
7.7C

Plate 7.8 These columns at Kolay Valley, southern Gawler Ranges, show pronounced steps.

Plate 7.9 The faces of these columns on Mt Kolendo, central Gawler Ranges, display plumose structure measuring up to 1 m in length, which demonstrates the direction of joint propagation from the base of the column upwards (X) or perpendicular to the long axis of the column (Y).



7.8



7.9

Plate 8.1 A bornhardt developed in Hiltaba Granite, north of Kokatha H. S., northern Gawler Ranges.

Plate 8.2 Aerial view of Ucontitchie Hill, northwestern Eyre Peninsula, a granitic inselberg with well developed sheet structure and showing the linear fracture-controlled eastern (right) margin (C. R. Twidale).



8.1



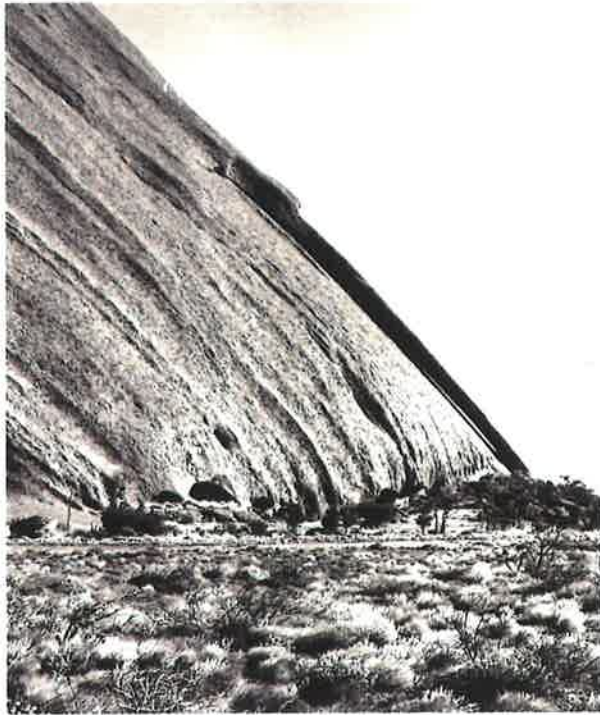
8.2

Plate 8.3 Curtinye Hill eroded in quartzite is an inselberg standing above the gently undulating surface of northern Eyre Peninsula (C. R. Twidale).

Plate 8.4 The Kangaroo Tail of Ayers Rock, central Australia, is part of a large sheet (C. R. Twidale).



8.3



8.4

GEOLOGICAL SETTING OF THE GAWLER RANGE VOLCANICS

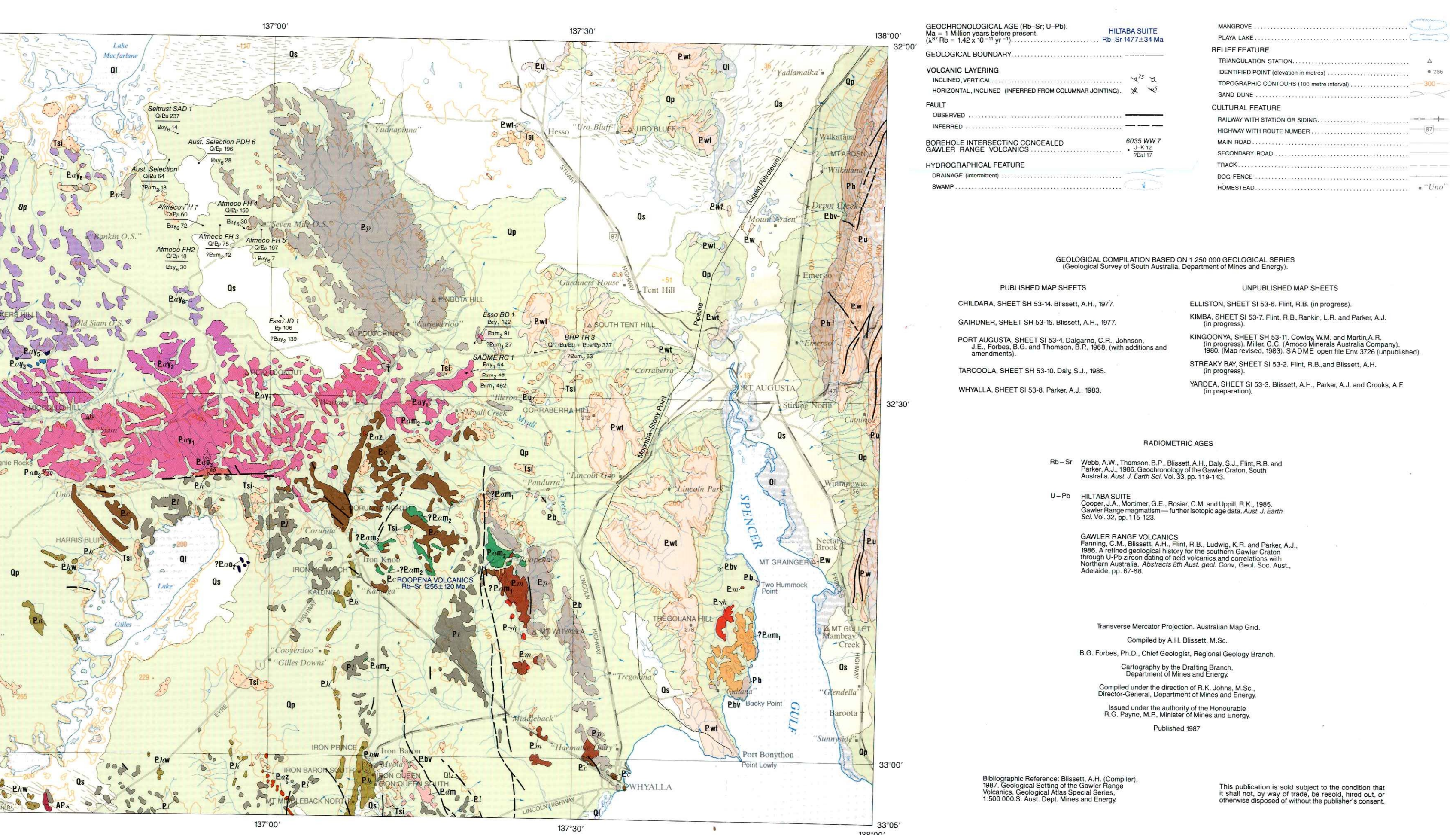
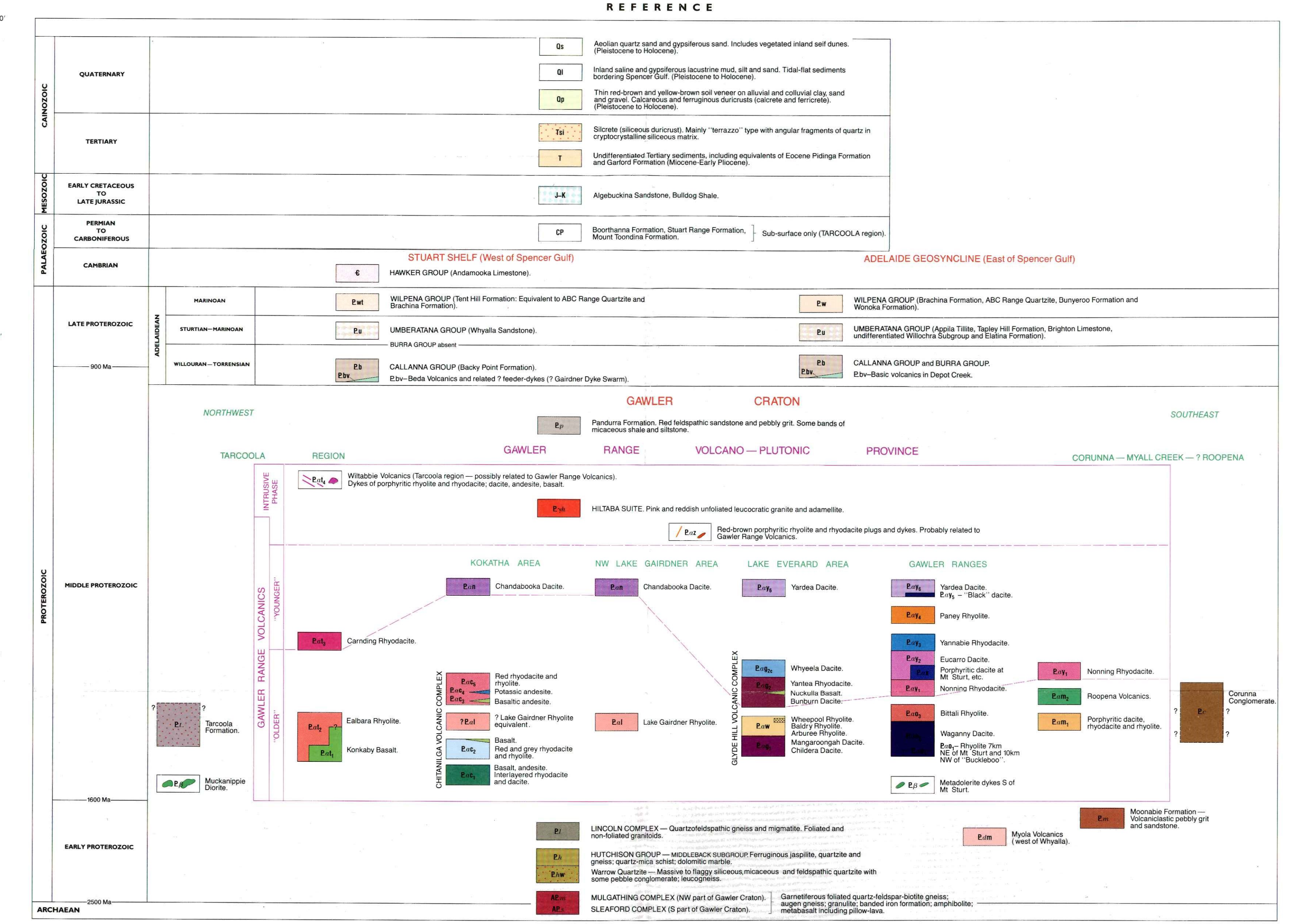
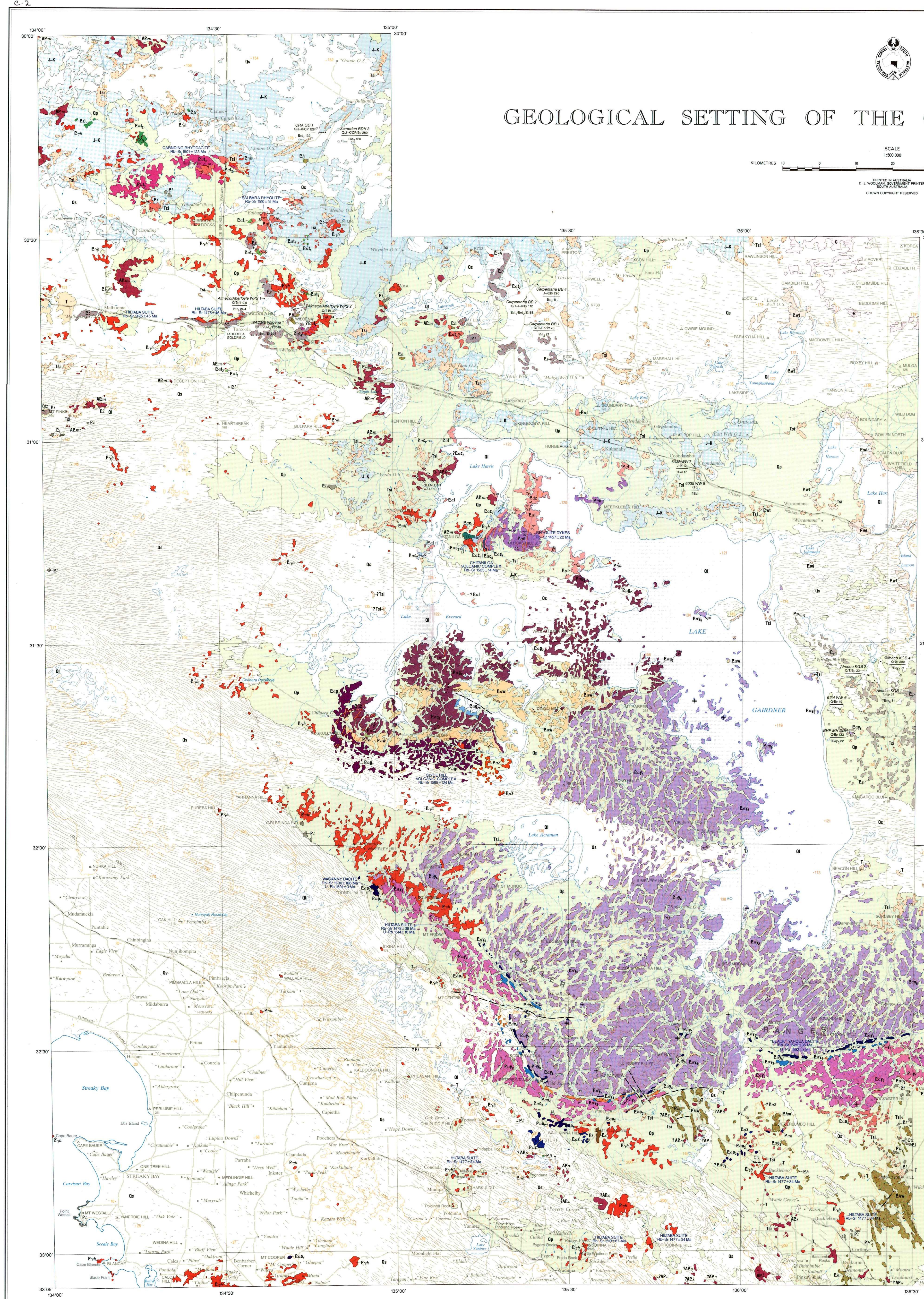
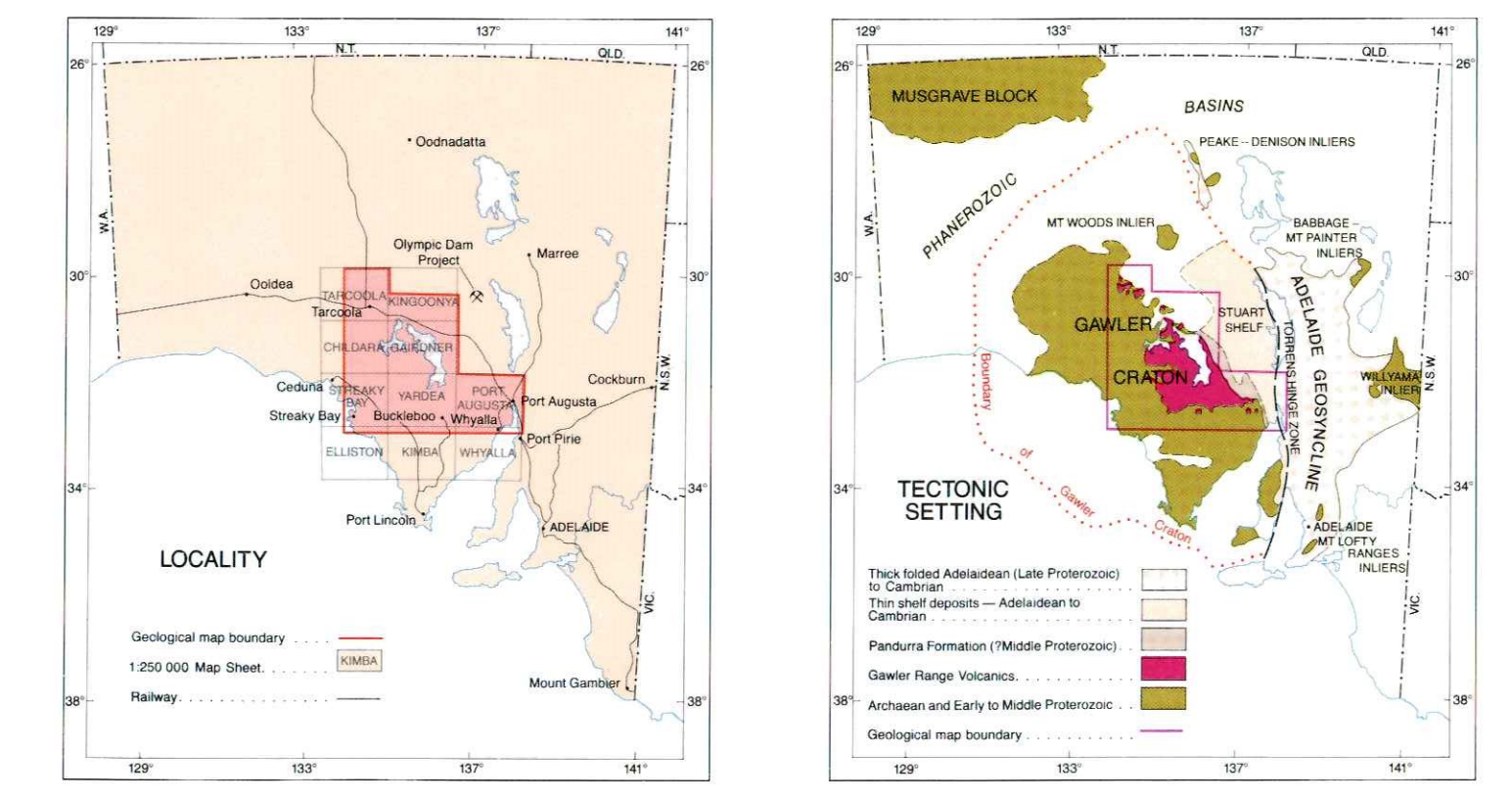
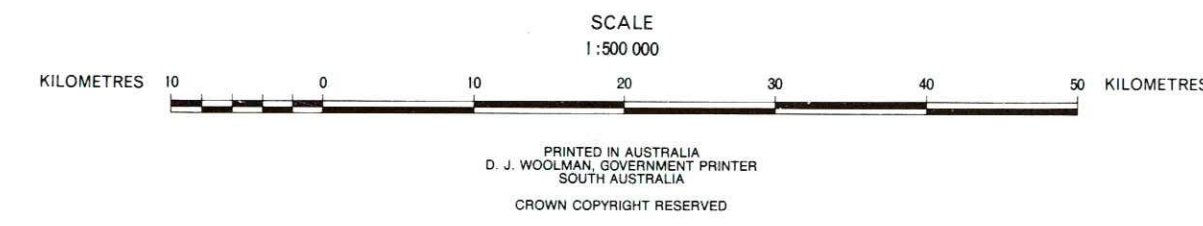


Figure 13