RADIOMETRIC STUDIES IN THE LOWER PROTEROZOIC WILLYAMA COMPLEX BROKEN HILL DISTRICT, NEW SOUTH WALES

by

Dost Mohammad Khan, M.Sc., Karachi

A thesis submitted to the University of Adelaide
in fulfilment of the requirements for the degree
of Master of Science.

February, 1978.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

INDEX OF FIGURES, PLATES AND TABLES

INDEX OF FIGURES, PLATES AND TABLES (cont'd)

The thesis contains no material which has been accepted for the award of any other degree or diploma in any university, and to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text.

D. M. Khan

SUMMARY

The aim of this thesis is to make the interpretation of airborne radiometric survey data in the Lower Proterozoic Willyama Complex, Broken Hill district, New South Wales, in which uranium and thorium mineralisation is known to occur. In this thesis the airborne total count radioactivity survey data from the 1959 survey and airborne spectrometer survey data from the 1975 survey of the Bureau of Mineral Resources, Geology & Geophysics (B.M.R.) are analysed and related to the known uranium and thorium mineralisation in an attempt to establish the relation between the airborne survey results and the known mineralisation. The 1959 airborne total count radioactivity survey covered approximately one-third of the total area which lies south of Broken Hill, whereas the remaining two thirds of the area, north of Broken Hill, was covered by the airborne spectrometer survey in 1975; and the total area thus surveyed was about 4,000 square miles mostly occupied by the Willyama Complex outcrops.

The Willyama Complex occupies a triangular-shaped block of approximately 2,800 square miles in extent, mainly consisting of a series of phyllites, slates, quartzites, schists and gneisses, multiply deformed and metamorphosed in the Middle Proterozoic and partly granitised and migmatised and extensively subjected to pegmatisation and aplitisation. Folding was predominantly northeast and north. The Willyama Complex was intruded by granite, pegmatite, amphibolite, dolerite and serpentine. The Willyama Complex was overlain to the northeast by less metamorphosed younger Precambrian sediments of the Torrowangee Series (Group). The Torrowangee Series mainly consisted of quartzites, tillites, limestones, dolomites, shales and claystones.

The airborne radiometric surveys gave some information on the radioactivity of the ground surface in the study area. The results obtained from the airborne spectrometer survey (1975) gave extremely useful information for uranium, thorium and potassium mineralisation and proved that

airborne radiometric measurements made with advanced instrumentation could yield useful information for uranium exploration and mapping. On the radiometric response it was possible to differentiate between the Willyama Complex rocks and the Torrowangee rocks as well as the geologic units within the Willyama Complex. The results of the spectrometer survey showed that the highest radiometric response was seen to have been associated with the outcrops of sillimanite gneiss, carbonaceous schist, mica-quartz schist and davidite-bearing veins. Variably moderate radioactivity is observed over the exposures of granite gneiss, granitoid, granite, whereas amphibolite, dolerite, serpentine and the thick Cainozoic deposits showed low to very low radiometric response. The spectrometry has further allowed two types of pegmatites, K-feldspar and Na-feldspar in the area to be recognised. Over the areas of known mineralisation, spectrometry has been beneficial in classifying these anomalies as uranium, thorium or potassium.

As far as localisation of mineralisation is concerned, the structural features were important in localising uranium and thorium. These favourable structures ranged from large shear zones, faults and fissures down to minor joints and bedding planes, microfractures and interstitial openings.

At the present stage, it is not possible to classify the uranium deposits on a genetic basis, because the primary davidite deposits occur in the Thackaringa area as late pegmatitic to hydrothermal high temperature emplacement in sheared zones. Secondary deposits are found where no primary minerals have not yet been located and in several cases, the workings or testings have not penetrated the primary zone. Further, it has not been proved that any uranium ore minerals are disseminated in the older Willyama metasediments, the possibility that uraniferous-forming minerals in this suite might have furnished uranium for later deposits cannot be excluded (e.g. Copper Blow and Great Western).

The relationship of uranium mineralisation to granites seems to be obscured in some cases. The Thackaringa davidite belt is related to end-phase granite activity; in the Mundi Mundi, Brinkworth, Eldee Creek, and

Hen-and-Chickens areas there is a close spatial relationship to the Mundi Mundi granite; and other minor deposits are in pegmatites. The Mundi Mundi granites and pegmatites, with a few exceptions, show a higher U/K ratio. It is therefore suggested that these Mundi Mundi type granites and associated pegmatites could possibly be the potential source for uranium mineralisation in the area.

Only two uranium deposits, i.e. Thackaringa and Brinkworth are suggested for further investigation mainly based on detailed ground geophysical surveys.

ACKNOWLEDGEMENTS

This thesis was prepared in the Department of Economic Geology, University of Adelaide, under the supervision of Professor D. M. Boyd, to whom the author is very much indebted for his keen interest, stimulating guidance, valuable discussions, continuous encouragement, and of course, his extraordinary patience throughout the duration of the project. His critical reading of the final draft of the thesis is especially appreciated.

I should particularly like to thank my friend, David Isles, in the Department of Economic Geology, for his expert computing work and for his valuable time which he spent in processing the digital tapes. Most of the presentations of the airborne spectrometer survey data 1975, appearing in the thesis, are the result of his generous help. I would also like to thank him for allowing me to make use of his unpublished reports, unpublished gravity data and cooperation during all the field trips. I especially express my gratitude to my Japanese friend, Koya Suto, Department of Economic Geology for his generous help in computer programming and for allowing me to make use of his unpublished reports. During the early stages of this investigation, Dr. I.R. Plimer, W.S.& L.B. Robinson College, Broken Hill, University of New South Wales, conducted the author on field visits and was most helpful in the discussion of various aspects of the geology. His liberal and cooperative attitude is gratefully acknowledged.

Extreme gratitude is expressed to Evert Bleys, Department of Economic Geology, who painstakingly produced photographic reductions of all the figures. I want to thank John Willoughby, Department of Economic Geology for helpful discussions and advice on electronics; he also provided the block diagram for airborne spectrometer (Fig. 5.1, Appendix 5) with explanatory notes on portable and airborne gamma-ray spectrometers.

The opportunity to visit, study and work at the Bureau of Mineral Resources, Geology & Geophysics, Canberra, was readily granted by the Director, and in particular, Mr. J. Quilty, Bruce Wyatt and John Rees provided stimulus and valuable information through both discussions and their publications. Their liberal and cooperative attitude is gratefully acknowledged.

In many ways, assistance was forthcoming from other company staff and members of the department. Special thanks are due to Professor R.W.R. Rutland, Dr. R.A. Both, Dr. R.A. Glen, Dr. John Cottle, Dr. Mubashar Ahmed, Dr. Sita Bhaskaran, Mr. John Webb, Doug Roberts, Robin Gerdes and D.A. Rao. I express my extreme gratitude to Maud McBriar, Department of Geology, for helpful discussions and continuing encouragement throughout the duration of the project. Mr. Amanullah Nasir Khan, Principal Geologist, Atomic Energy Minerals Centre, Lahore, and Mr. Aftab Umar Khan (my brother) are also thanked for their continuing encouragement and advice.

Most of the drafting and colouring of the base maps and overlays were done by the author. I would like to thank Emelia Rossi for drafting Fig. 5.1, Appendix 5. Half of the base maps and overlays were coloured by Marie Perdikis and P.S. Arora and their assistance is gratefully acknowledged.

The Secretary of the Department, Helen Malby, has been extremely helpful at all times. The final and arduous task of typing was undertaken by Joan Brumby for whose extraordinary patience and diligence I am indeed most grateful.

The thesis work was carried out under the Colombo Plan Scholarship Scheme for which the author was nominated by the Pakistan Atomic Energy Commission and the financial support was provided by the Australian Development Assistance Bureau. Without their cooperation this thesis would not have eventuated.

CHAPTER 1

INTRODUCTION

1.1 Aims of Thesis

1.2 Location and Extent

1.3 Physiography

1.3.1 Topography

1.3.2 Drainage

1.3.3 Climate and rainfall

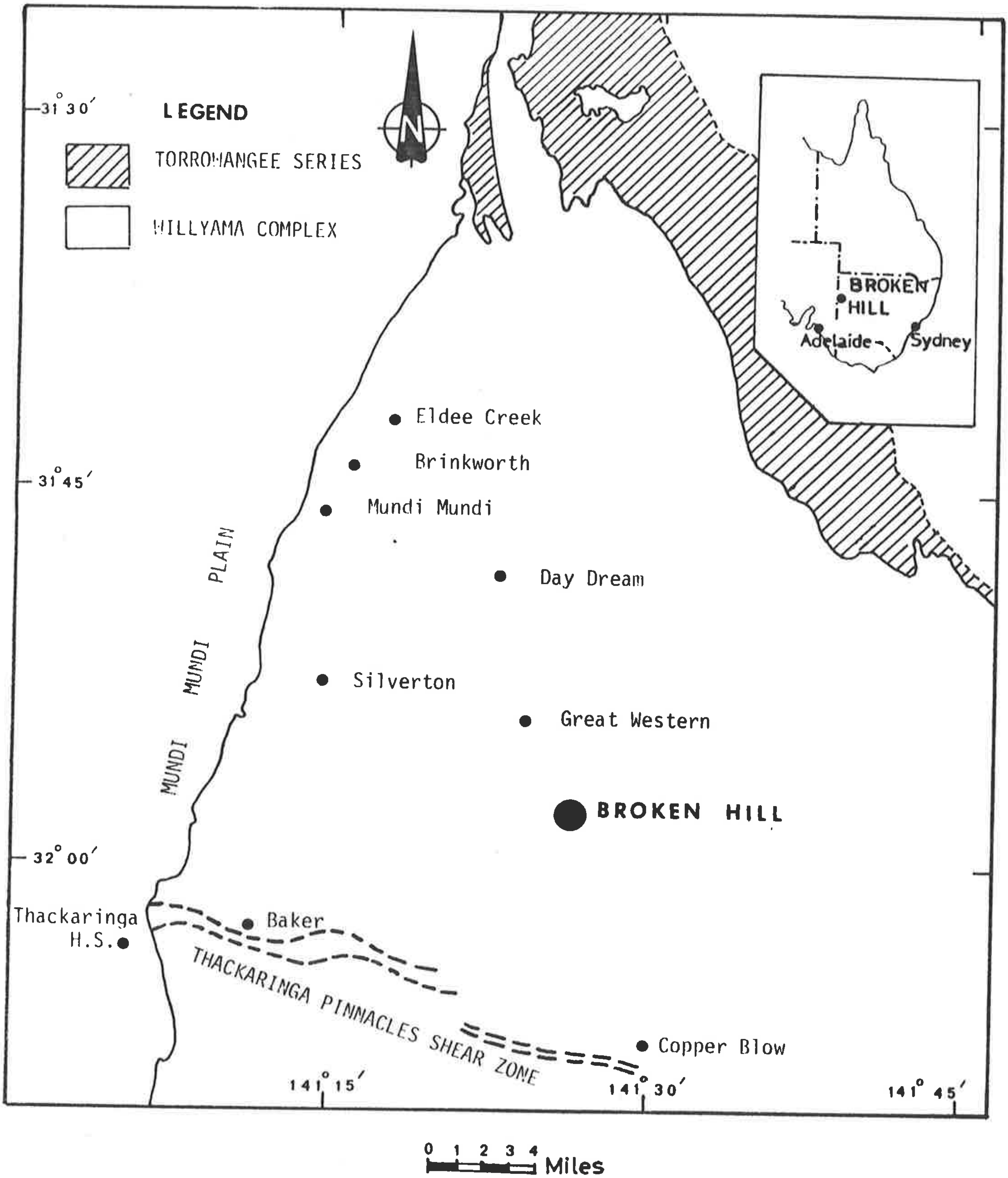
1.3.4 Water supply

1.3.5 Cainozoic geology

1.3.6 Vegetation

1.3.7 Accessibility

1.4 Human Occupation and Population



LOCALITY MAP

Fig. 1.1

1.1 Aims of Thesis

The thesis topic concerns the interpretation of airborne radiometric data over an area in the eastern part of the Willyama Complex in which the main mineralisation is known to occur. In this thesis the scintillometer data from one survey and spectrometer airborne radiometric data (gamma radiation) from a later survey are analysed and related to the known uranium and thorium mineralisation in an attempt to establish the relation between the airborne survey results and the known mineralisation by examining:-

1. the geological factors which control the uranium mineralisation;
2. the geological environments for uranium mineralisation;
3. the uranium association with certain base-metal sulphides;
4. leading to the recommendation for further research and investigations required in the study area.

In doing this it was intended to try to introduce a uniformity of procedure which could be applied to results obtained from other airborne radiometric surveys.

1.1.1 Data studied

The work was commenced studying the airborne radiometric (scintillometer) survey data, total count only, obtained from a survey which was carried out by the Bureau of Mineral Resources, (later referred to in this thesis as the B.M.R.) in 1959. The survey covered the lower half portion of the study area; this area being bounded by latitude 31°53' and 32°20'S, longitude 141°00' and 141°37'30"E, flight line spacing of one quarter of a mile in an east-west direction and 500' in height. No published account of the survey was available. The airborne radiometric survey data was received in the form of analogue profiles photographed on an 8 mm film provided by the B.M.R.

In July, 1975, the B.M.R. flew regional airborne geophysical surveys (magnetic and spectrometric) which covered the whole of the Broken Hill

Geological Series Sheet (1:250,000), and a detailed survey which covered most of the area of the Willyama Complex outcrops. The survey data was published by the B.M.R. as stacked profiles for total magnetic intensity, total count, potassium, uranium, thorium, and altitude along with flight path maps. The magnetic data have also been published as contoured maps at a scale of 1:250,000 for the regional survey and 1:25,000 for the detailed survey. Later, access was made to the digital data recorded on the magnetic tapes provided by the B.M.R. All digital data tapes were merged and processed in the Department of Economic Geology, University of Adelaide, using Computing Centre's CDC 6400 and CYBER 173.

1.1.2 Presentation of results in this thesis

From a presentation and interpretation of the survey data viewpoint, very simple and basic techniques have been employed in the thesis. The presentation of radiometric data in juxtaposition with the geological data is a major problem for the reader, due to the size and number of the map. For the thesis, maps have been simplified and generalised as much as possible and have been kept to the minimum practical size without losing important details. In some cases, overlays have been used. Overlays used in the figures were drawn from maps on a different projection from the base diagrams which makes precise comparison difficult. They have been photographically adjusted to conform as closely as possible with the base diagrams.

1.2 Location and Extent

The eastern part of the Willyama Block comprises the whole of the Broken Hill district situated between latitudes 31°00' and 32°15'S and longitudes 141°00' and 141°45'E, and lies at a distance of 450 kilometers north-east of Adelaide. The Broken Hill district is the western district of New South Wales, lying on the border of South Australia and New South Wales (Fig. 1.1).

The Willyama Complex, approximately 7040 square kilometers (2,800 sq. miles), is covered by two geological sheets, i.e. Geological Series Sheet

SH 54-14 (Broken Hill 1:250,000), (Plate 1A) and Geological Series Sheet SI 54-3 (Menindee 1:250,000) (Plate 1B), in folder. The Willyama Complex outcrops as a triangular block approximately 110 km (70 miles) from north to south by 64 km (40 miles) from east to west.

1.3 Physiography

In the study area, the Barrier Range is the only dominant topographic feature which rises abruptly along the Mundi Mundi Fault scarp in the west. The range extends in a wide belt north-northwest of Broken Hill until it ceases to be a significant topographic high north of the northern boundary of the Broken Hill sheet 1:250,000 (Plate 1A). The average height of the Barrier Range with respect to the surrounding plains is approximately 150 m, although several localities, i.e. Robe, Umberumberka, and Dering Trignometric Station, are in excess of 430 m above sea level.

1.3.1 Topography

> "A bird's eye view of the Broken Hill district from the south-west would give the impression of a long and low structure of the skillion-roof or broken shield type, dismantled and partly buried under alluvium. It rises abruptly from the plain to the west, dipping gently thence in all directions under the plain." (Andrews, 1922).

The Barrier Ranges are an elongate group of low hills surrounded by flat, soil-covered plains of the Lake Frome, Darling and Murray drainage basins. The outcrop is variable. Good exposures are extensive in the far west, northwest, far north and east of the Willyama Complex. In the south and southwest, the exposures are very poor. Most of the rock-types are deeply weathered. Outcrops are generally surrounded by soil rather than rock rubble. The ranges die away gently eastwards and southwards, but elevation of the land surface increases northwards and westwards to about 900 feet above the plains. The elevation of plains above sea level ranges between 300 and 700 feet.

1.3.2 Drainage

The drainage of the Broken Hill district, in general, is centrifugal, as the main streams of the area flow in all directions. The main streams of the eastern drainage are Stephen's Creek, Yancowinna and Gardiner's Creeks; the main drainage to the south is by means of Pine Creek; and the main drainage to the west by the Campbell's, Eldee, Mundi Mundi and Umberumberka Creeks.

Most of the creeks terminate in outwash fans. As the average rainfall for the Broken Hill district is less than 10 inches, the creeks seldom run.

1.3.3 Climate and rainfall

The climate is continental, (semi-arid) mean temperature being 24.3°C. In winter the air is crisp and bracing with frosty nights. The summer climate is at the extreme. Daily temperatures from June to August (winter) are generally cool and occasionally very cold when conditions are dominated by southerly and south-westerly air-streams. From October to April (summer), the daily temperatures are warm to hot. The conditions of humidity during the summer months rarely exceed the human comfort level.

The mean annual rainfall for Broken Hill district is 9-10 inches. The rainfall occurs intermittently throughout the year. The wettest periods are February-March and October-November.

1.3.4 Water supply

The Broken Hill district is served with water from two sources, viz. Stephen's Creek Reservoir, lying at a distance of 10 miles to the north and Umberumberka Reservoir, about 19 miles to the west of Broken Hill city.

The Stephen's Creek supply, which is the major source of supply, has been in operation for more than the last 80 years. Its catchment area is about 200 square miles.

The Umberumberka Scheme was started in 1912. Its catchment area is 125 square miles.

There are some other mines service reservoirs situated at Block 10 Hill and Mica Street.

1.3.5 Cainozoic geology

Cainozoic, colluvial and residual deposits are common throughout the

Willyama Complex and occur adjacent to outcrops. The soil cover varies in thickness from 2-3 feet to 15 feet within a distance of 2000 feet from the outcrops (Langford-Smith and Dury (1964) and Dury (1966)). The thickness of Cainozoic deposits along the western edge of Mundi Mundi scarp and along the north of the Kantappa Lineament ranges between 252 feet and 702 feet (Rose, 1975).

In the Cainozoic deposits, the upper part of the soil profile consists of very fine to medium-grained sub-rounded clear to limonite stained, occasionally opaque quartz, in a sparse white to yellow silty kaolinitic matrix with some gypsum. The clay is yellow, light brown, grey to dark grey, sandy in parts. Gypsum is present in quantities varying from a trace, to as much as 20% (Dury, 1966).

1.3.6 Vegetation

In the hills areas, Mulga (Acacia aneura) and its associated forms such as the wild fuschia (Eremophila masculata), the native peach (Quondong) (Fusarius aluminatus and F. persicarious) scrubs are dominant. Their leaves are excellent food for stock.

On the plains, mulga is less common and its place is taken by the so-called sandalwood (Myoporum playtycarpum) and other trees. The prevalent flora consists of husky plants, such as the annual and perennial saltbush (Atriplex nummularis) and bluebush (Chenopodium auricomum).

Shortly after a fall of rain, spear-grass and several varieties of herbs spring up. A variety of a desert pea (Olianthus dampieri) flowers in spring time. The sandy surfaces support spinifex (Festuca irritans). Southward, in the vicinity of the Murray River, the oak trees (Casuarina suberosa) are prevalent. The plains are covered in a dense mallee scrub composed of eucalyptus (including E. dumosa, E. uncinata, and E. oleosa). The beds of creeks support the growth of box (E. largiflorens) and red gum (E. rostrata). Swampy areas support the growth of polygneum bush (Muchlenbeckia canninghami). Broken Hill makes a good centre for field work in this area.

1.3.7 Accessibility

Access to the area is excellent as there is a network of roads and tracks (bituminous, non-bituminous and dirt). Most points within the area can be reached when using a four-wheel drive vehicle and are within about 1 hour's drive from Broken Hill.

1.4 Human Occupation and Population

The history of Broken Hill starts with Captain Sturt's party. The first white men, (Mawson, 1912) crossed the country in 1844. Shortly afterwards pastoralists took up the country for sheep and cattle stations. At that time, there were quite a few aboriginal inhabitants living near the rock holes, the only source for water supply. In 1867 there was a rumour of an abundance of quartz reef (which was thought would carry gold) which caused a rush to set in, but nothing eventuated. Several years later, small copper and silver-lead showings were opened up which proved to be of no importance.

In 1876, silver-lead ore was discovered at Thackaringa, and six years later (in 1882) the doors were opened for a new rush. In 1882 gold was discovered at the Mount Brown gold field to the north. From the year 1882 to the end of 1886, the western side of the Barrier Ranges, including Thackaringa, Umberumberka, Silverton, Nevada and Parnamoota was a scene of great activity. The Broken Hill Lode, the main ore formation in the Barrier Silver Field, was pegged as a mineral claim in 1882 by a boundary rider from the adjoining sheep station of Mount Gipps. In the beginning, the results were disappointing as the outcrop was mainly manganiferous ironstone. It was not until 1884 that chlorides were struck at a depth of 100 feet. Later on various sections along the outcrop were pegged out by large mining companies which are still working with good prospects ahead.

The 5 mile length of operating leases is now held by four companies being from north to south. They are:

1. North Broken Hill Limited;
2. Broken Hill South Limited;
3. The Zinc Corporation Limited;
4. The Broken Hill Consolidated Limited.

A total of 120 million tonnes of ore (Both & Rutland, 1975), has been mined from the Broken Hill Lode, from the beginning of operations in 1884 until the end of 1974, from which approximately 13.5 million tonnes of lead, 21 million kg of silver and 11.8 million tonnes of zinc have been recovered.

The immense importance of this mining field from an economic point of view is obvious when the production figures, mentioned earlier, are accounted for. The township of Broken Hill (according to Mawson (1912)), comprised a population of 40,000 people in 1907. At present the population does not exceed 30,000.

CHAPTER 2

REGIONAL GEOLOGY AND GEOPHYSICS

2.1 Previous Work and History

2.2 Regional Geology

2.2.1 Psammites and pelites

2.2.2 Quartzo-feldspathic gneisses

2.2.3 Banded iron formations

2.2.4 Amphibolites and calcareous rocks

2.2.5 Dolerites

2.2.6 Sulphide-rich rocks

2.2.6.1 Broken Hill Type

2.2.6.2 Thackaringa Types

2.2.7 Pegmatites

2.2.8 Mundi Mundi Granite

2.3 Metamorphism

2.4 Regional Structure

2.5 Regional Geophysics

2.5.1 Magnetic studies

2.5.2 Gravity studies

CHAPTER 2

REGIONAL GEOLOGY AND GEOPHYSICS

The following brief account of the geology of the area provides a background which is necessary for understanding the interpretation of the radiometric surveys. All geophysical surveys of this kind either resolve problems already posed by geologists or reveal new facts about the geology which must be incorporated into the overall study of the area: in either case the geology of the area must be understood to get most value out of the geophysical survey. A part of the purpose of this work was to study the relationship between the radiometric survey results and the known geology so that future interpretation of airborne survey data is based more soundly on experience.

2.1 Previous Work and History

A great deal of voluminous literature is available on the economic geology of the study area because of the silver-lead-zinc deposits of Broken Hill. Aspects of the geology and mining of the Broken Hill area are referred to in over 684 published and unpublished reports (Campbell, 1974). The Broken Hill area was visited by Charles Sturt in 1844. Charles Rasp made the discoveries of minerals and pegged the first claim on Broken Hill in 1883. Jaquet (1894) described geologic features of Broken Hill in 1894. Mawson (1912) named the Willyama Complex and the overlying sediments, the "Torrowangee Series". Andrews (1922) published a detailed report on the Broken Hill area, concentrating mainly on the rocks in the vicinity of Broken Hill. King and Thomson (1953) gave an account of the regional geology of the area. The earlier major investigations of Jaquet, Mawson and Andrews along with the later major publications of Gustafson, Burrel and Garretty (1950) and King and Thomson (1953) are standard references.

Binns (1964) made a major contribution to the understanding of the metamorphic grade distribution and history of the Willyama Complex. Hobbs (1966) contributed to the understanding of the structure of the lode and later contributions to this aspect were made by Anderson (1966), Williams (1967), Hobbs and Norman (1968), Ransom (1968) Rutland (1973), and Glen et al. (1977), the area being remapped by the New South Wales Geological Survey.

Several airborne geophysical studies have been carried out in the study area. The airborne magnetic and radiometric surveys were carried out in 1957, 1959 and 1975 by the B.M.R. No detailed published accounts have yet been available. The processing and presentation of the airborne spectrometer survey data 1975 (Wyatt, pers. comm. 1977) is in progress, and some of the results have been presented as stacked profiles (Regional and Detailed surveys) and contour map (Regional Total count). The description of the aeromagnetic surveys (Cooper, 1975), have been given by E. Weiss (1950), R.O. Crosby (1963) and A.G. Spence (1963). Gravity surveys have been described by W.F. Stacker (1965) and G.F. Lonsdale and L.M. Ingall (1965) and work has been done by the New South Wales Mines Department.

2.2 Regional Geology

The Willyama rock assemblage, which will be referred to here as the Willyama Complex are known since Mawson's time (Mawson, 1912). The geology of the study area is shown on two geological sheets, i.e. Geological Series Sheet 5H 54-14 (Broken Hill 1:250,000) (Plate No. 2A) and Geological Series Sheet SI 54-3 (Merrindee 1:250,000), (Plate No. 2B in pocket). They occupy a triangular shaped block of approximately 2,800 square miles in extent. Its boundaries in the west, northeast, southeast and south are defined by the Mundi Mundi Fault scarp, Grand Unconformity, the Redan Fault and alluvial cover respectively. The Willyama rocks are also exposed to the northeast in a narrow belt known as the Euriowie Inlier. A Lower Proterozoic age, i.e. exceeding 1800 m.y. is assigned to the original sediments from which the complex was derived. This age is suggested by the framework of Australian radiometric dating and the presence of iron formations

TABLE 2.1

AVERAGE CHEMICAL COMPOSITIONS (mean wgt.% ± 1 standard deviation) OF MAJOR ROCK TYPES FROM THE WILLYAMA COMPLEX

	Upper granite gneiss*	Lower granite gneiss*	Potosi gneiss*	Amphibolite**	Sillimanite gneiss*	Thorndale gneiss***
SiO_2	70.85 ± 2.66	67.00 ± 3.38	68.42 ± 3.38	48.59 ± 2.92	60.38 ± 5.95	64.35 ± 4.25
TiO_2	0.47 ± 0.15	0.72 ± 0.17	0.76 ± 0.15	1.68 ± 0.58	0.96 ± 0.23	0.81 ± 0.10
Al_2O_3	14.74 ± 0.59	15.92 ± 1.29	15.00 ± 1.26	14.77 ± 2.31	21.75 ± 4.18	19.78 ± 2.99
Fe_2O_3	0.23 ± 0.19	0.64 ± 0.28	0.75 ± 0.47	1.45 ± 1.18	1.22 ± 0.86	0.75 ± 0.25
FeO	3.60 ± 1.26	5.23 ± 1.53	5.72 ± 1.41	13.54 ± 2.23	7.01 ± 2.34	4.96 ± 1.05
MnO	0.06 ± 0.02	0.13 ± 0.06	0.38 ± 0.25	0.28 ± 0.10	0.26 ± 0.19	0.03 ± 0.07
MgO	0.80 ± 0.29	1.35 ± 0.40	0.99 ± 0.33	6.44 ± 1.66	1.83 ± 1.66	1.96 ± 0.12
CaO	1.75 ± 0.48	3.14 ± 0.94	3.00 ± 0.82	10.56 ± 0.86	0.63 ± 0.65	0.28 ± 0.08
Na_2O	2.92 ± 0.64	2.61 ± 0.50	1.87 ± 0.90	1.47 ± 0.66	0.44 ± 0.44	2.10 ± 0.52
K_2O	4.15 ± 1.36	2.65 ± 1.04	2.95 ± 1.21	0.25 ± 0.19	4.45 ± 1.13	4.09 ± 0.78
P_2O_5	0.16 ± 0.01	0.14 ± 0.04	0.18 ± 0.04	0.16 ± 0.28	0.14 ± 0.05	0.10 ± 0.01
No. of specs.	10	18	52	22	63	8

*From analyses by Shaw (1973) of samples from Broken Hill mine sequence.
**From analyses by Binns (1964) of amphibolites widely distributed through Willyama Complex.
***From analyses by Shaw (1973) of an horizon within the sillimanite gneisses.

(After Both & Rutland, 1975).

(Thomson, 1973). The subdivision of the complex has been proposed by Andrews (1922), King and Thomson (1953), Thomson (1956), Campana and King, (1958).

Due to the complex structural and metamorphic history of the area, it is not possible to present the rocks in their sequencial order. The extreme southeastern portion of the Willyama Block consists principally of the Redan Group (Thomson, 1956). The group was mapped by E.O. Rayer and L.R. Hall in 1947 and consists of well banded quartz-feldspar-mica-magnetite gneisses and mica schists. The portion lying between the Redan Group and the extreme northwestern end consists of a distinctive group of all the known occurrences of granitic gneiss, Potosi gneiss, banded iron formation (B.I.F.), quartz-magnetite rock. The group can be assigned to two facies, e.g. granular-feldspathic (psammites) and argillaceous (pelites), (Andrews, 1922; Browne, 1922; Stillwell, 1922; Thomas, 1961 and Binns, 1962). Table 2.1 shows the chemical composition of the rocks.

2.2.1 Psammites and pelites

These two main sedimentary facies are represented in the Willyama Complex and have extensively been studied in the vicinity of the Broken Hill Lode. They show a wide range of variation from immature arkosic sediments (e.g. at the base of Thorndale facies) to mature shallow-water sediments (e.g. Broken Hill facies) and in spite of local transposition, the observed layering represents deformed bedding. In sillimanite gneisses (Glen and Laing, 1975) there is a good evidence of metamorphosed graded bedding.

2.2.2 Quartzo-felspathic gneisses

The most controversial rocks in the geological history of Broken Hill are the granitic and intermediate quartzo-feldspathic gneisses. Andrews (1922) concluded their igneous parentage, whereas King and Thomson (1953) interpreted them as metamorphosed or metasomatised sediments. In the Broken Hill facies they occur as concordant layers of variable thickness. All these gneisses have been deformed and recrystallised. They fall into two chemical groups: 1. the Augen Gneiss, Platy Gneiss, Hanging Wall Gneiss and non-garnetiferous granitic gneisses (Andrews, 1922; King and Thomson, 1953), corresponding chemically to calcalkali granite and 2. garnetiferous gneisses (Andrews, 1922) and are known variously as Potosi Gneiss, Footwall or Parnel Gneiss, and have lower silica, higher iron and calcium contents with little corundum (Table 2.1).

There is no good geological evidence of a layering which might be inherited from sedimentary bedding. The contacts of the granitic gneisses, where observed, (e.g. Browne, 1922) are best interpreted as intrusive contacts subsequently deformed and metamorphosed (Stillwell, 1922); and some bodies contain xenoliths. Therefore, it seems unlikely that they are of sedimentary origin as proposed by King and Thomson (1953), Thomas (1960) and Lewis et al. (1965). The granitic gneisses are best exposed in Lakes Grove, Britannia and Broken Hill regions.

2.2.3 Banded iron formation (B.I.F.)

Magnetite-rich rocks are thin metasedimentary beds and occur in several places within the Willyama Complex. A major investigation of these rocks has been carried out by Richards (1966). Apart from iron oxide minerals, the rocks are also rich in quartz. Many of them contain abundant almandine-spessarite garnet and chlorapite. The rocks occur as linear series of discontinuous, elongate outcrops, ranging from less than 30 cm to several metres across. They are generally layered.

The banded iron formations are generally accepted as metamorphosed chemical sediments (King and Thomson, 1953; Richards, 1966), although some earlier workers (e.g. Andrews, 1922; and Browne, 1922) suggested that the iron-rich rocks were formed by metasomatic replacement.

2.2.4 Amphibolites and calcareous rocks

Bodies of amphibolites and pyroxene-plagioclase gneisses occur in many places in the Willyama Complex. They form persistent horizons of up to, and sometimes exceeding 100 metres in thickness. The maximum length is 8 km (Andrews, 1922). Some of the amphibolites and pyroxene-plagioclase gneisses may be derived from calcareous sediments, but their consistently basaltic composition (Binns, 1964) favours an igneous origin as sills, flows or tuffs (Andrews, 1922; Vernon, 1969).

2.2.5 Dolerites & ultrabasic rocks

Bodies of dolerite and altered dolerite occur in many places in the southern part of the area (Browne, 1922). These dykes are a few metres in width and the maximum length reported is 8 km (Andrews, 1922). Most dykes are transgressive to the foliation of the enclosing rocks. The rocks consist largely of amphibole and plagioclase, but exhibit relict doleritic texture and some remnant pyroxene is present. Plagioclase is also locally altered to epidote. The plugs of serpentine and pyroxenite are also present in places.

2.2.6 Sulphide-rich rocks

Lead-silver-zinc sulphide mineralisation is widely distributed through the Willyama Complex. There are mainly two types of sulphide-rich rocks:

1. sulphide-silicate type (Broken Hill type) and
2. sulphide-carbonate type (Thackaringa type).

2.2.6.1 Broken Hill Type

The Broken Hill type deposits are characterised by apparent conformability of the mineralisation with respect to the foliation of the enclosing rocks. They are represented by the Broken Hill Lode, The Pinnacles Lode and about 50 small bodies occurring mainly around Broken Hill, in the dominantly high-grade metamorphic area. Andrews (1922) listed the following small deposits as having once been productive: extension north and south of the Broken Hill Lode, Potosi, Globe, Piesses Nob, Eaglehawk, Southern Cross, Centennial, Great Western, Nine Mile, Hardings, Laurel, Little Broken Hill and Rupee. The mineralogy of these deposits is complex, but these are characterised by galena, sphalerite, associated with manganese silicate minerals, green and grey alkali feldspar (orthoclase), calcite, fluorite, gabrite, and blue or opalescent quartz (King and Thomson, 1953), along with a large number of other minerals in minor amounts (Stillwell, 1953).

2.2.6.2 Thackaringa Type

These types of ore deposits occur in ore bodies as veins occupying weak, gently-dipping fractures (King and Thomson, 1953). Most of the sulphide-carbonate bodies are mineralogically simpler than the Broken Hill type deposits. The primary ore consists largely of coarse-grained galena in a gangue of coarse to very coarse-grained siderite with quartz (King and Thomson, 1953).

There were over 100 mines, the majority being in the western and northwestern part of the area. Most of them produced oxidised ore. The most productive groups of mines were the Thackaringa, Umberumberka, Purnamoota, Maybell, Day Dream, and Apollyon Valley Groups (Andrews, 1922; King & Thomson, 1953).

2.2.7 Pegmatites

Pegmatites are very abundant in many parts of the Willyama Complex, especially in the northern and northwestern parts of the area. On the eastern side of the area, pegmatite is relatively uncommon. They range in occurrence from large, coarse-grained masses down to thin, impersistent lenticules in schist. The larger irregular bodies of pegmatite are up to 6 miles long (King and Thomson, 1953, pl. 3). Pegmatites occur within all main rock types of the Willyama Complex, as sills, dykes and irregular masses. Many of the pegmatite bodies enclose residual patches of other rocks (e.g. schist or metaquartzite), many of them do not appear to have been disoriented. Some masses consist of pegmatite intimately interlayered with schist, especially at their margins (Andrews, 1922; Leslie and White, 1955). Sill-like bodies occur parallel to an earlier foliation in schist (Leslie and White, 1955) and to later foliations (Stillwell, 1922; Leslie and White, 1955).

Leslie and White (1955) reported pegmatite cut by dykes of Mundi Mundi Granite. Therefore, they are clearly of more than one generation.

Mineralogically the pegmatites are of simple types, consisting largely of quartz and feldspar. Other minerals such as muscovite, garnet, biotite, tourmaline, magnetite, rutile, apatite, sillimanite and davidite, are also known to occur in the pegmatites.

2.2.8 Mundi Mundi Granite

The Mundi Mundi granite (Mawson, 1912) is an intrusive granite that postdates the schists, quartzo-feldspathic gneisses, amphibolites and most, if not all, of the pegmatites. It occurs in small bosses, sills, and dykes in the Mundi Mundi, Silverton, Thackaringa, Day Dream, Brewery Creek, Paps and Euriowie areas. It is generally massive, but the southern-most body is slightly gneissic (King and Thomson, 1953). The smaller masses may be apophyses, but Leslie and White (1955) have reported the contact between granite and schist being flat in their study area. Some of the smaller masses are thin dykes which commonly follow the foliation in the schists.

The Mundi Mundi Granite is a leucocratic, muscovite-microcline granite and appears to fall within the classification of alaskite (Johannsen, 1932) typically containing less than 4% by volume of ferromagnesian minerals. The plagioclase, which is slightly more abundant than microcline, is albite (Leslie and White, 1955) and oligoclase (Binns, 1962). The granite is mostly relatively fine-grained, but locally is medium to coarse-grained. The chemical composition of both fine and coarse-grained is similar (Leslie and White, 1955), (Table 2). Muscovite commonly comprises 10% by volume of the rock and plagioclase grains enclose many small plates of white mica. Biotite, tourmaline, apatite and zircon also occur in the granite.

The Mundi Mundi granites of the Broken Hill field appear to be the counterpart of the Boolcamatta granite in South Australia and the Templeton granite of the Cloncurry-Mount Isa field (Rayner, 1957). Associated with the Mundi Mundi granite are a number of variants which are considered to have a connection with the emplacement of some of the uranium minerals

TABLE 2.2

CHEMICAL COMPOSITION OF THE MUNDI MUNDI TYPE GRANITE

	I	II
SiO_2	74.07	74.50
Al_2O_3	14.77	13.72
Fe_2O_3	0.51	0.60
FeO	0.46	0.90
MgO	0.16	0.44
CaO	0.51	0.52
Na_2O	3.89	3.45
K_2O	4.43	5.13
H_2O-	0.15	0.18
H_2O+	0.70	0.26
TiO_2	0.19	0.17
P_2O_3	0.10	0.27
MnO	0.01	0.03
BaO	-	0.05
ZrO_2	0.03	-
S	0.03	-
Others	-	0.11
	100.01	100.35

I. Mundi Mundi Granite from Brewery Creek pluton, S. of Poolamacca, Barrier Ranges, N.S.W. Analyst: R.B. Leslie

II. Mundi Mundi Granite, N.W. of Paps, Barrier Ranges, N.S.W. Analyst: J.C.H. Mingaye

(After Leslie & White, 1955).

(Rayner, 1957). These late-phase associates are microgranite, aplite, some pegmatites (transgressive to earlier gneissic suite) and quartz veins.

The granites are regarded intrusive in the Willyama Complex being pre-Torrowangee (Mawson, 1912; Andrews, 1922; Leslie and White, 1955), while King and Thomson (1953) regard them as post-Torrowangee. Pidgeon (1967) has discussed the ages of the main geological events in the Willyama Complex, and assigns an age of 1560 m.y. to the intrusions of the Mundi Mundi granite.

2.3 Metamorphism

Binns (1963) after making the petrological studies and K-Ar determinations suggested that the Willyama Complex had been subjected to several periods of metamorphism. He referred to these periods as M_1 (Willyama Metamorphism), M_2, M_3 and M_4. M_1 (or Willyama Metamorphism) was regarded as a high-grade regional event and the others as later retrograde events. The products of the Willyama metamorphism were, later on, described in greater detail by Binns in 1964. He concluded that the grade of metamorphism increased in the Willyama Block from northwest to southeast with three recognisable zones of progressive metamorphism. The distribution of these zones is shown in Fig. 2.1.

Binns found the colour change in hornblende to be more useful criterion, so he mapped the boundaries between Zones A and B on the basis of a change from blue-green to brown-green. The boundary between Zones B and C was located on the basis of the first appearance of orthopyroxene in the mafic rocks; this boundary was termed the "orthopyroxene isograde".

The metamorphic facies represented by these zones are:

Zone A - sillimanite-almandine-muscovite subfacies of almandine-amphibole facies (as defined by Turner and Verhoogen, 1960).

Zone B - Sillimanite-almandine-orthoclase subfacies of almandine-amphibolite facies (as defined by Turner and Verhoogen, 1960).

Zone C - Orthoclase-biotite subfacies of granulite facies (as defined by Binns, 1962).

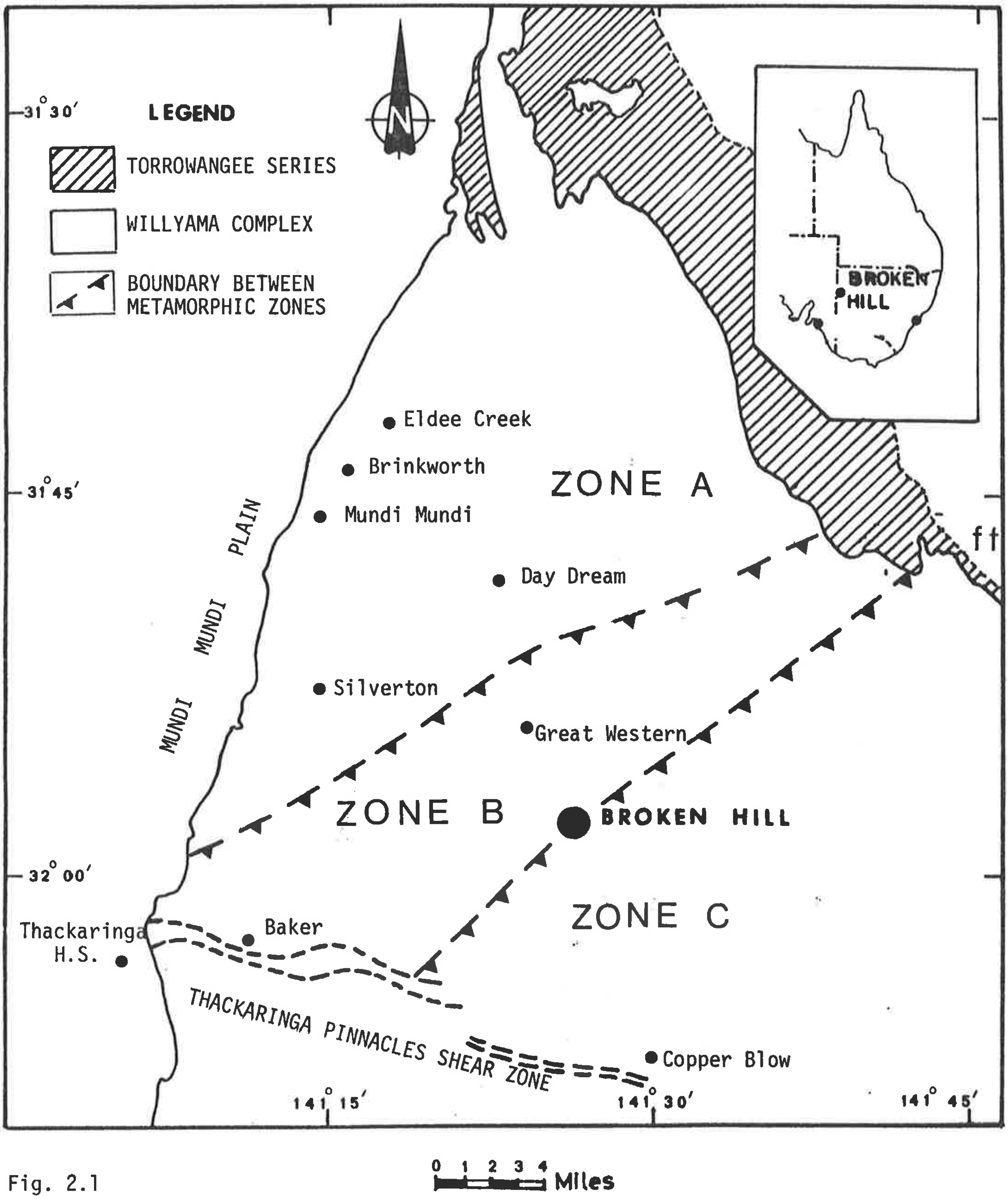


Fig. 2.1

METAMORPHIC ZONES IN THE WILLYAMA COMPLEX (after Binns, 1964)

Several authors have described retrogressive features in the rocks of the Willyama Complex (e.g. Browne, 1922; Binns, 1963; Vernon, 1969; Vernon and Ransom, 1971), but according to Both and Rutland (1975) it does not appear possible at present to classify these as discrete metamorphic events in terms of a chronological series. Hobbs et al. (1968) proposed that M_1-M_4 terminology of Binns (1963) be abandoned and the term "retrograde metamorphism" be used for all retrograde events with "the implication... that the events in the retrograde metamorphism are probably quite complex in nature".

In the northern part of the Willyama Block (i.e. within Zone A) the retrograde metamorphism is widespread, while in the southern part (Zones B and C) retrogression is most conspicuous in association with distinct planar zones, referred to in the literature as "shear zones", "crush zones", "faults" and more recently, "retrograde schist zones". The typical rocks within these zones are quartz-white mica-biotite schists, some chlorite-bearing (Vernon, 1969). There are some other patchy retrograde schists outside the retrograde schist zones which are characterised by the pseudomorphous development of chlorite after biotite, and white mica after sillimanite, feldspar and cordierite.

2.4 Regional Structure

The Willyama Complex has been strongly folded and faulted and the nature of the structure has long been a matter of debate. A general plasticity of movement in these deformations attests to deep burial and high temperature-pressure conditions. Andrews (1922) first described the structural features of the Willyama Complex and postulated a number of broad "basins" separated by tight anticlines. King and Thomson (1953) in a later study, introduced a number of additional tight folds within the broad basins on the basis of recognition of repetition by folding of conformable layers of amphibolite and granitic gneiss. During the last decade the Willyama Complex has extensively been studied by applying the modern structural methods in an attempt to analyse the effects of the various deformation episodes (e.g. Hobbs, 1966; Hobbs, et al. 1968; Williams, 1967; Rutland, 1973; Rutland and Etheridge, 1975; Glen, Laing, Parker and Rutland, 1977). They all agree that the Willyama Complex has a complex deformation history so that major folds of more than one generation are present. According to Hobbs et al. (1968, p. 305):

> "Workers in the Broken Hill district have recognised two distinct groups of folds in the high-grade pelitic rocks. The first of these fold groups ("Group One") has the widespread schistosity of the area as the axial plane schistosity and a lineation defined by needles of sillimanite parallel to the fold axes. Throughout the entire Broken Hill region these fold axes and the associated lineation are observed to plunge fairly consistently towards the SW at low angles...." "Group Two folds deform the older axial plane schistosity and often fold the sillimanite lineation. Their axial plane orientations, and hence their plunges, are variable and in some instances, their plunge is co-axial with Group One fold axes".

The complex structural history of the Willyama Complex makes the identification of the original stratigraphic succession extremely difficult. Later periods of deformation "have been recognised but are restricted to the widespread areas of retrogression to the northwest of Broken Hill or to the retrograde schist zones" (Hobbs et al. 1968, p.305). Glen et al. (1977) have recognised four periods of deformation (e.g. D_1, D_2, D_3 and D_4).

2.5 Regional Geophysics

The B.M.R. has made extensive geophysical studies (i.e. aeromagnetic, aeroradiometric, gravity and seismic) in the study area and have produced the contour maps of bouguer anomaly, total magnetic intensity and radiometric (total count). To discuss the geophysical studies such as aeromagnetic and gravity, is beyond the scope of this thesis, therefore, a brief account of these studies is described under this section to give an overall picture of the study area on a regional scale. The detailed account of radiometric studies (regional and detailed) is given in Chapter Nos. 3, 4 and 5.

2.5.1 Magnetic studies

Aeromagnetic coverage of the area is provided by the B.M.R. (Preliminary Edition H54/B1-63, 1975). The aeromagnetic anomalies can be divided into five zones on the basis of differences in character (Fig. 2.2).

Zone A

In the far northeastern corner of the area is a zone of partially isolated, narrow, sharp anomalies that show a common elongation trend which is parallel to the general geological strike in this area. Zarzavatijian (1965) suggested that the sources lie at depths of generally less than 300 m below the surface, which leads to the conclusion that the sources are within Precambrian rocks which crop out in this area.

Zone B

In the upper central part of this area there is some evidence for a similar zone related to a shallow Precambrian basement. The magnetic contours in this portion show some alignment in a northwest-southeast direction, parallel to the geological strike.

Zone C

Zone C lies between Zones A and B and is occupied by an extensive zone of broad elliptical and circular anomalies. This zone correlates with the gravity low. As the Zones A and B correlated with Precambrian rocks, it is probable that the broad anomalies in Zone C indicate a substantial thickness of non-magnetic sediments.

Zone D

This zone consists of elongate and circular anomalies separated by regions of relatively low magnetic activity. The magnetic anomalies have a northeast-southwest trend and show the characters of shallow depth anomalies. These anomalies are correlated with outcrops of amphibolite or quartz-magnetite rock of the Willyama Complex. The area occupied by the Torrowangee Group outcrop show lack of magnetic activity.

Zone E

This zone of intense knotted anomalies lies in the southwest portion

Fig. 2.2 Base map - total magnetic intensity contour map of Broken Hill.

Overlay - Interpreted magnetic response:

A : magnetic high

B : magnetic high

C : magnetic low

D : magnetic high

E : magnetic high

Source of data - Airborne magnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W. B.M.R. survey, 1975.

BROKEN HILL

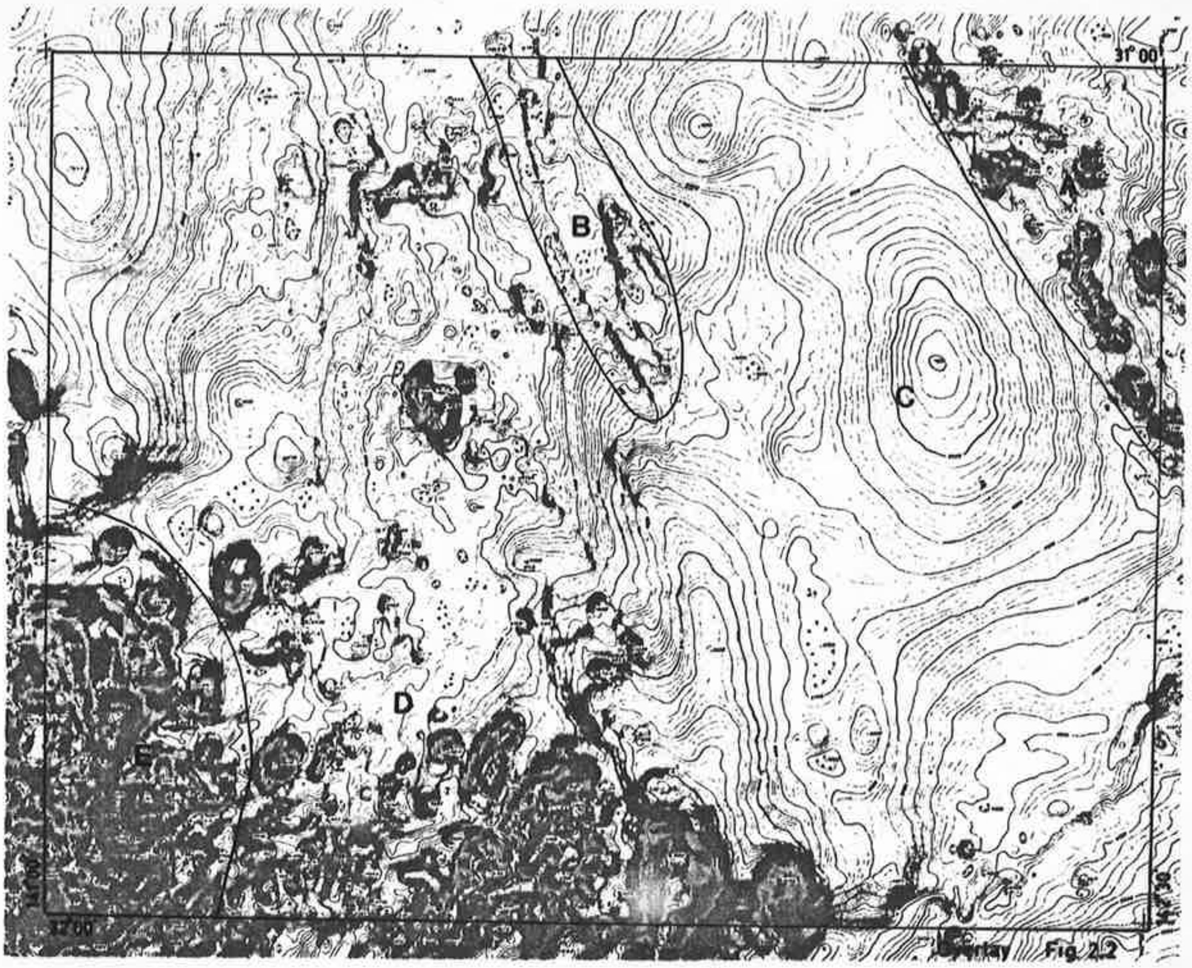


Fig. 2.2

TOTAL MAGNETIC INTENSITY

BROKEN HILL N.S.W.

of the figure. The anomalies in this zone represent variations in magnetisation within the similar lithology. The nature of lithology is not certain since outcrop is obscured by sand and alluvium in much of this area. They are believed to be the metamorphics of the Willyama Complex.

2.5.2 Gravity studies

Fig. 2.3 is a Bouguer Anomaly map compiled by Isles (1977) and shows the salient gravity features of the study area. The areas underlain by the Willyama Complex rocks show a distinctly different Bouguer Anomaly pattern to the surrounding areas. The Bancannia Trough to the east, the Mundi Mundi Fault to the west and the Anabama Fault to the south of Broken Hill form the boundaries of the Precambrian outcrop in this region and these boundaries cause clearly recognisable features in the gravity map (Isles, 1977).

Within the area of Precambrian outcrop itself, the Younger Torrowangee Series of metasediments are characterised by areas of lower Bouguer anomaly values than the surrounding Willyama. Two major zones of anomalous density contrast are observed. There is a central NE-SW trending rectangular high lying immediately to the south-west of Broken Hill. Directly to the south-east of this feature, there is a long NE-SW trending gravity trough which is commonly correlated with the Redan gneiss sequence. Distinct gravity lows and highs within the Redan gneiss sequence lead Isles to postulate that there are several distinctly different units within what are presently classified as Redan gneiss.

Fig. 2.3 Bouguer anomaly contour map of the Broken Hill district. The contour interval is 1 milligal.

Source of data - Bouguer anomaly map of the Broken Hill district from Isles (1977a).

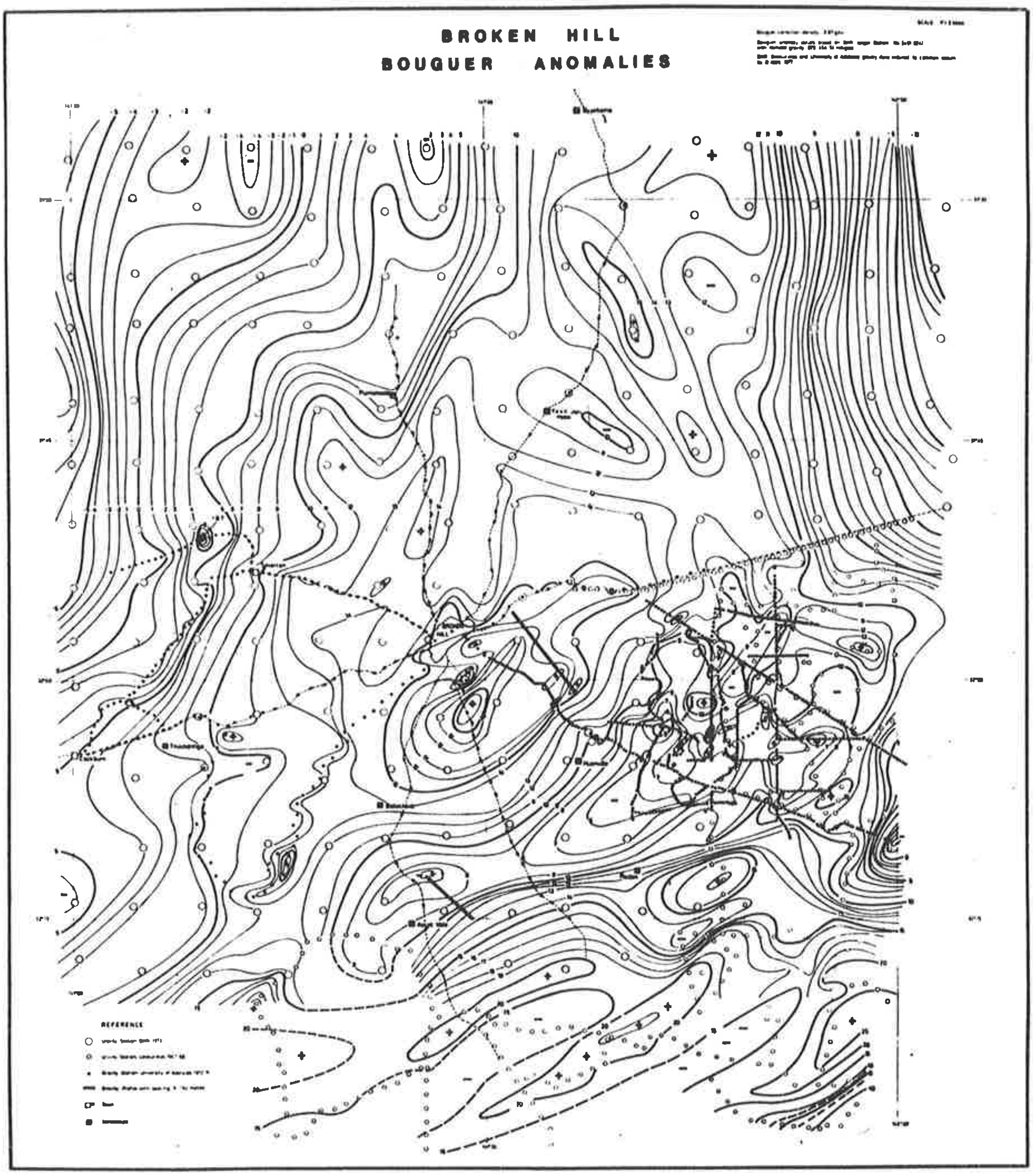


Fig. 2.3

Compiled by D.J. Isles (1977).

CHAPTER 3

REGIONAL AERORADIOMETRIC STUDIES

3.1 Introduction

3.2 Airborne Gamma-ray Scintillometer Survey, 1959

3.2.1 Processing and presentation of data

3.2.2 Interpretation

3.3 Regional Airborne Spectrometer Survey, 1975

3.3.1 Presentation of data

3.3.2 Interpretation

CHAPTER 3

REGIONAL AERORADIOMETRIC STUDIES

3.1 Introduction

During the past twenty five years, airborne radiometric surveys have been employed on an increased scale in regional studies for uranium exploration. Research and investigational programmes have been carried out (and are still being carried out) in Canada, U.S.A. and other parts of the world to improve upon the present radiometric survey techniques; and the literature on this subject has been published by numerous workers such as Bates (1966), Charbonneau and Darnley (1970), Charbonneau et al. (1973), Darnley (1970, 1973), Darnley et al. (1969), Duval et al. (1971), Grasty (1975 and 1976), Gregory and Horwood (1961), Kellogg (1968), McSharry (1973) and Pitkin et al. (1968).

> "There are no revolutionary new methods of uranium exploration on the horizon. Continuing improvements in existing methods and types of instrumentation are to be expected, but the main scope of improvement will hinge upon using the best of the available methods more meticulously and systematically, and paying more attention to the analyses of data"

(Darnley, 1975, p.21). Airborne instrumentation was first extensively used in the search for uranium mineralisation in 1949. Since then instrumentation developed from geiger counter installations, through small total count radiation detectors to gamma-ray spectrometers with very large detector volumes. It is a well known fact that the areas containing uranium mineralisation generally fall within or on the margins containing above-average abundances of all the radio-elements. These above normal radioactive areas can be readily found by airborne surveys which measure only total count radioactivity. The airborne spectrometer surveys are used to identify anomalies containing significant amounts of uranium and wherever the costs of ground work are high. The most sensitive spectrometers available these days are capable of measuring the mean ground level abundances of potassium, uranium and thorium, which can be expressed in conventional units of concentration.

As far as the airborne radiometric survey methods are concerned there is a great deal of agreement among the authorities about the acquisition of survey data such as height, speed of aircraft, line spacing, detector volumes, (Appendix 6). They all emphasise on the quality of collection, processing and presentation of airborne radiometric survey data. The data collected must provide a sufficiently high count rate after all corrections have been applied to be statistically meaningful at the required sensitivity and must merit comprehensive presentation by automatic compilation methods. The data collected must be corrected for background radioactivity, height, atmospheric absorption, residual radioactivity (related to instruments in aircraft), energy stripping and reduced to nominal ground clearance or to ground level.

From a presentation standpoint the survey data must be presented in digital form, preferably recorded on magnetic tape for automatic compilation purposes through computers. The survey data must be presented in the form of profiles for each line flown to show terrain clearance, total count, potassium, uranium and thorium count rate and the ratios of the U/Th, U/K and Th/K count rates plotted against distances along the flight line. Profiles provide the most precise means of correlating data but contour maps permit more rapid examination by giving the overall distribution of a perpendicular parameter. According to Darnley (1971) one of the advantages of monitoring abundance ratios is that this provides a means of filtering count-rate anomalies besides recognising unusual radioelement distribution where high-count rates may not occur. This is important since the measured count rate is influenced by the area of exposed rock, and the solid angle it subtends relative to the aircraft, as well as by absolute abundance in the rock.

The B.M.R. processed and presented the spectrometer survey data for 1975 on the same principles as outlined above. The data obtained by the

B.M.R. (July, 1977) was in the form of digital tapes, profiles along each line for total count, potassium, uranium, thorium, terrain clearance and total magnetic intensity. Profiles for ratios (U/Th, U/K, Th/K) and contour maps for various channels and ratios are still in progress and may be made available within a year or so. The detail is given in Appendix 2.

For the thesis work the full use of digital tapes, profiles for various channels was made. The survey data have been presented in the form of profiles for various channels and ratios (U/K, U/Th and Th/K) and contour maps for channels and ratios wherever possible to obtain the maximum value and information.

Airborne radiometric surveys are a valuable aid to geologic mapping and exploration programs (Agoes (1955), Adams (1954), Bates (1966), Bell (1954), Darnley and Grasty, (1971), Demnati and Naudy (1975), Gregory (1955) Gregory (1956), Foote (1967) and Ketola et al. (1975)). The radiometric data did aid in rapid compilation of provisional geologic maps where geology is not known. The rocks obscured by deep weathering can often be mapped.

Reported concentration values for uranium, thorium and potassium for various rocks have been given by numerous workers; no satisfactory summary exists. The values shown in Table 3.1 are the average values from different sources. The radioactivity of igneous rocks varies in fairly wide limits, depending upon their uranium, radium, thorium and potassium contents. In general, the contents of radioactive elements in igneous rocks increase with their acidity. Table 3.1 shows that thorium is more abundant in igneous rocks compàred to uranium. The U/Th ratio in these rocks is fairly constant, at about 3.2. Granites tend to be rich in radioactive elements due to a high percentage of silica and thus possess the highest radioactivity among the igneous rocks. Less radioactive are the intermediate rocks. Potassium granitoid (alaskites, leucocratic granites, granidiorites and quartz diorite) are also highly radioactive but less than granites. Basic and ultrabasic rocks show lower radioactivity. The differences in uranium of identical rocks from different regions and also from the same region are not only due

TABLE 3.1

General amounts of uranium, thorium and potassium in common rocks

Rock type	Uranium ppm	Thorium ppm	Potassium %
1. Acidic rocks	4.3	12.7	4.3
2. Intermediate rocks	2.4	8.7	2.6
3. Basic rocks	0.8	3.1	1.4
4. Ultrabasic rocks	0.7	2.1	0.5
5. Clays (variable)	4.5	13.0	2.6
6. Shales (variable)	3.4	10.2	2.8
7. Sandstone (variable)	2.1	5.3	1.2
8. Limestones	1.3	0.6	0.2

Average values from Adams (1954), Bell (1954) and Pitkin (1968).

to differences in composition of the magma from which the rocks were crystallised, but also due to the geological conditions that prevail during their formation. The maximum concentration of uranium and thorium is found in the youngest members of rocks from the same region; and also, in general the content of radioactive elements decreases with the geological age of the rocks.

The sedimentary rocks derive the radioactive minerals from the disintegration of primary uranium and thorium minerals. The highest concentration of uranium is in clays and shales, especially in black marine sapropelic shales. Sandstones tend to be lower than clays and variable in radioactivity. Carbonate rocks are considerably poor in uranium and so show very weak radioactivity. In sedimentary rocks the uranium content increases with increasing amounts of organic matter in sedimentary rocks. The soils derived from or overlying a bed-rock of granites or syenites show a higher concentration of uranium, thorium and potassium compared to those derived from sedimentary, metamorphic and basic igneous rocks. The radioactivity of black and chestnut coloured is found to be higher than that of silver and ash coloured soils.

Fig. 3.3 shows how the airborne radiometric surveys can be employed in delineating the geologic units. When compared with the aerial geology it was observed that the zone of higher radioactivity, Zone A, 500-700 counts per minute, corresponds to a group of rocks which are acidic and mainly composed of sillimanite gneiss, granite gneiss (auger gneiss, platy gneiss, etc.), pink microgranite, aplite, pegmatite and davidite-bearing veins in the Thackaringa area. No. 1 is related to the sillimanite gneiss with high K-feldspar (Glen, 1978), No. 2 overlies the portion where davidite-bearing veins are present, No. 3 is probably due to aplite or pink microgranite and No. 4 is associated with the sulphide-rich rocks (silver-lead sulphide) probably mine dumps. Radiometric Zone B, 200-300 counts per minute consists of granite gneiss, pegmatite, sillimanite gneiss, amphibolite and aplites. A low level of radioactivity is possible due to increasing thickness of overburden. Zone C generally consists of pegmatites (K-feldspar), sillimanite schists, granite gneiss and amphibolites. No. 5 is associated with K-feldspar pegmatite and No. 6 follows the creek bed. The rock exposures are poor. In Zone D the rocks are mainly sillimanite schists with amphibolites. In this region the sillimanite schists are less radioactive and the exposures are also limited. No. 7 is related to the mine dumps of Copper Blow which are moderately to highly radioactive and uranium mineralisation occurs in association with copper.

An examination of radioactivity (total count) over the Thackaringa-Copper Blow shows that the sillimanite gneiss, sulphide-rich rocks, pegmatites (K-feldspar) are more radioactive than aplites (davidite-bearing), schists, granite gneiss, whereas pegmatites (Na-feldspar) quartz veins amphibolite, serpentine and dolerite exhibit very low radioactivity. Distribution of radioactivity over Cainozoic cover is very variable.

An interpretation has been made of two combined magnetic and radiometric airborne surveys conducted by the B.M.R. in the eastern part of the Willyama Complex (Broken Hill district). The first radiometric survey was carried out in 1959 with a scintillometer and the second was flown in 1975 with a spectrometer.

The 1975 survey was flown in two parts. In one the survey covered the entire Broken Hill 1:250,000 sheet (Pl. 2A in pocket) and employed a line spacing of 1.5 km and ground clearance of 100 metres.

In the other, a detailed survey which covered most of the area of the Willyama Complex outcrop on the Broken Hill sheet was flown along east-west lines 300 metres apart with 100 metres clearance. This survey was flown with a Twin Otter aircraft VH-BMG fitted with fluxgate magnetometer, four channel gamma-ray spectrometer, radio altimeter, doppler navigation system, computer and digital recording system and strip camera. Full details are given in Appendix 1B.

The data acquisition is given in Appendix 1B, and data processing and presentation is given in Appendix 2. Details of the equipment are given in Appendix 1A.

The purpose of the surveys was to obtain magnetic and gamma-ray radiometric data to assist mapping and mineral exploration carried out in the Broken Hill area by the Geological Survey of New South Wales and several mining companies.

3.2 Airborne Gamma-ray Scintillometer Survey, 1959 Thackaringa-Copper Blow Area

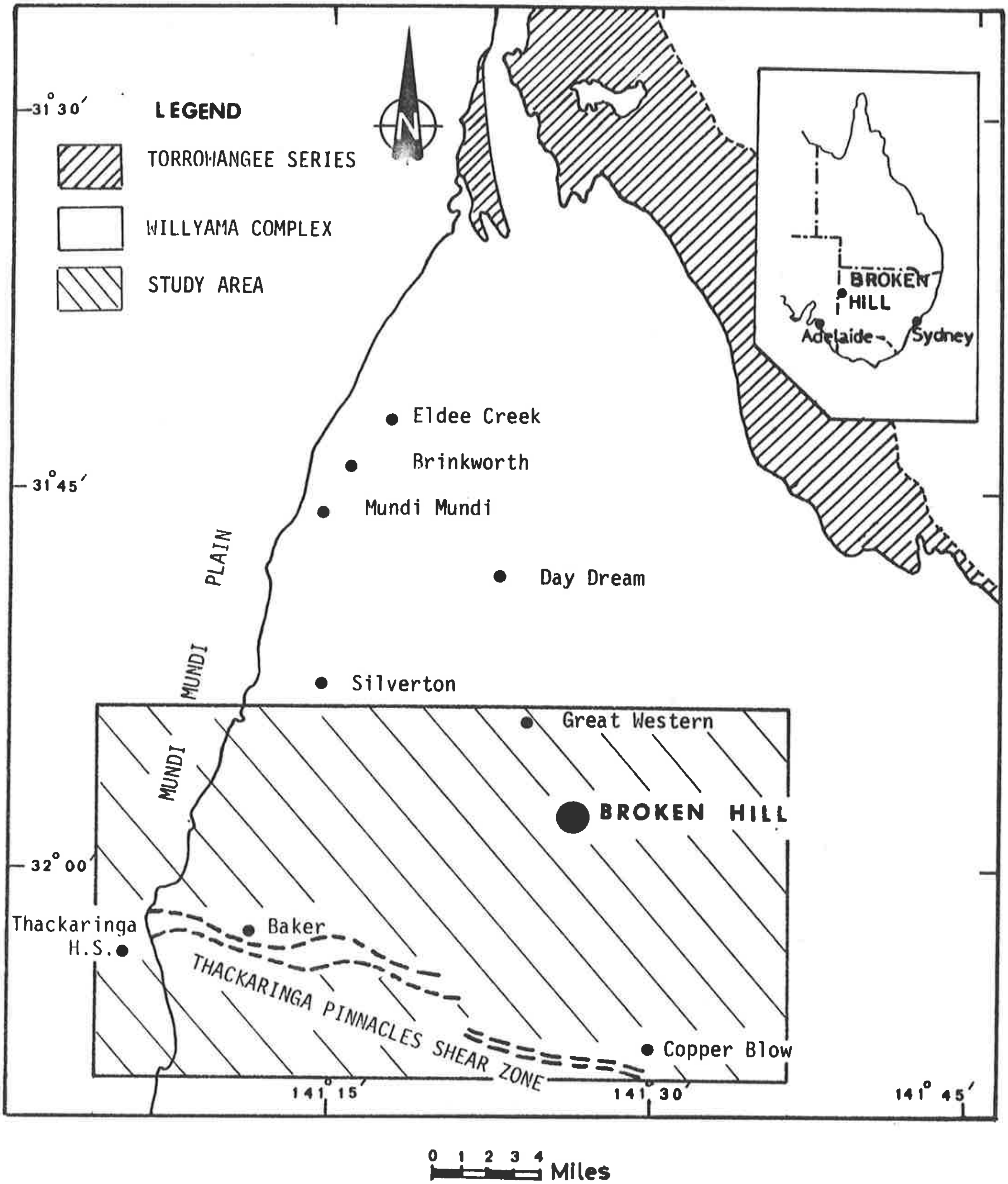
The airborne magnetic and radiometric (total count) survey was made over the area, the location of which is shown in Fig. 3.1 and is situated between longitudes 141°00' and 141°37'30" E and latitudes 31°53' and 32°20' S and is conveniently referred to as the Thackaringa-Copper Blow area from the principal mine at the eastern and western edges of the area.

The survey was carried out with a DC-3 aircraft flown at an average line spacing of one quarter of a mile apart and a terrain clearance of 500 feet along east-west oriented flight lines. The height of the aircraft was monitored by a radio altimeter. Aerial photographs were used for navigation. The radiometric background was obtained by subtracting the measured count at 2000 feet above ground level at the start and end of each flight. It was assumed to be constant throughout the flight. Details of the survey are given in Appendix 1A.

3.2.1 Processing and presentation of data

The record of the 1959 survey, in which the gamma radiation from the ground was recorded continuously along flight lines by an airborne scintillograph. The original records were photographed on an 8 mm film which was obtained from the B.M.R. No altimeter record for this survey was available in Adelaide.

The first step towards processing this sort of survey data was to project the microfilm image on a microfilm reader and trace the analogue profiles along 70 flight lines (out of 110) on an enlarged scale (2 inches to one mile) on separate strips of tracing paper. The profiles thus prepared



LOCALITY MAP

Fig. 3.1

Fig. 3.2 Total count aeroradioactivity contour map of the Thackaringa - Copper Blow area. The contour interval is 200 counts per minute.
The figure shows the demerits of not applying the datum correction to the survey data, particularly the strong gradient (northern part of the map) and strong linear anomalies parallel to the flight lines (east-west), although the data was smoothed before contouring.

Source of data - Radiometrics compiled from a study of original airborne scintillographic flight charts, photographed on an 8 mm film, B.M.R. survey, 1959.

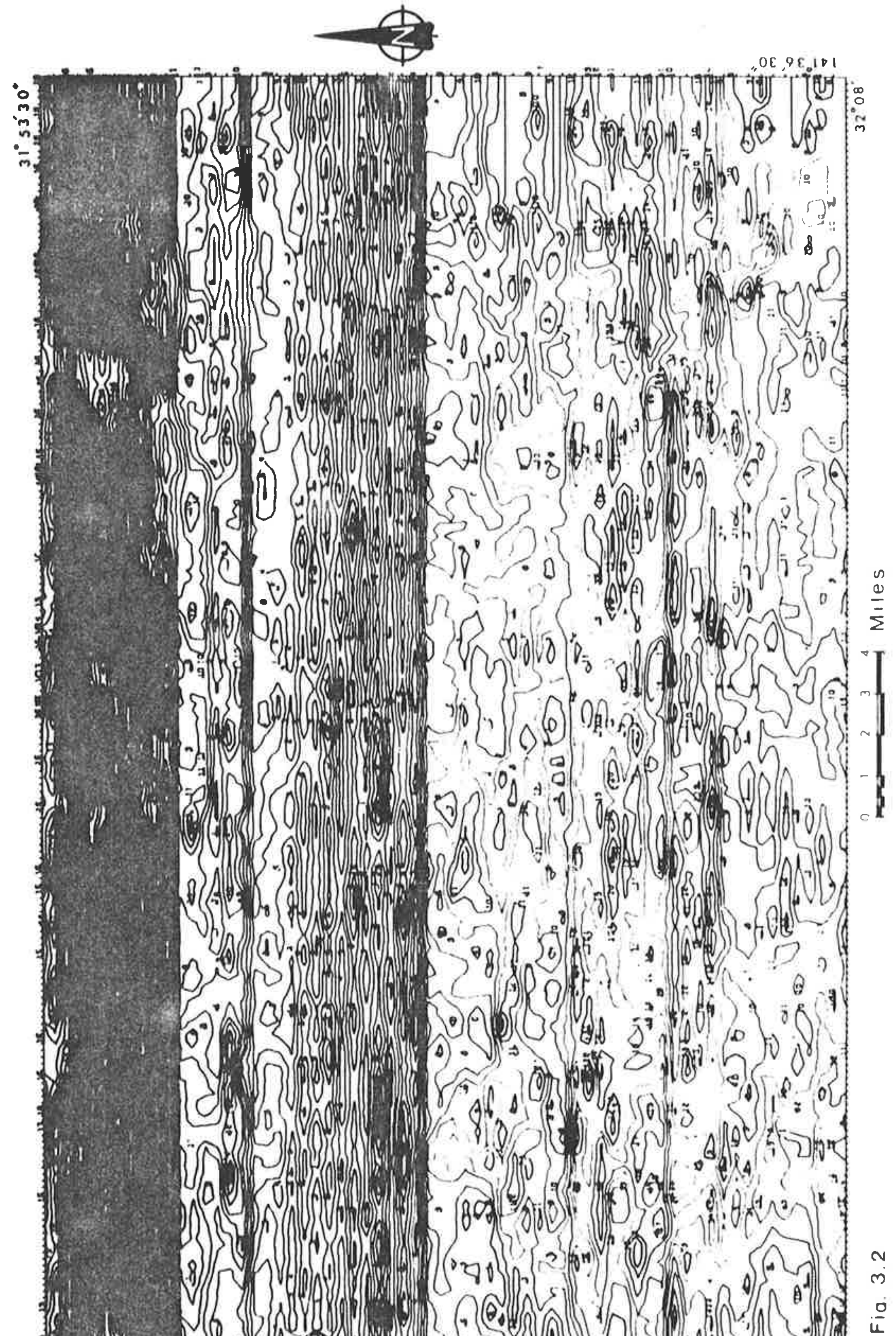


Fig. 3.2

were then digitised on Mini Mac Digitiser. The values along Y-axis (radioactivity) and X-axis (distance) were punched on computer input cards for further processing and presentation of survey data, as stacked profiles, isoradiation contour maps and three-dimensional diagrams using the CDC 6400 and the plotting routines.

It is necessary to adequately smooth or filter both the observed radioactivity and terrain clearance data, if reliable terrain clearance corrections are to be applied (Kellogg, 1968). As mentioned earlier, no altimeter record was available, therefore only the observed radioactivity was smoothed using the Low-Pass filter after subtraction of non-geological background. All the data samples were smoothed using the method of running averages. It is a convenient and useful Low-Pass filter. This and other filters have been described in detail by Blackman and Tukey (1958).

It is obvious that the datum used for the lines to produce the map, Fig. 3.2 is not correct. To overcome this, a new datum was calculated for each line by calculating the average radioactivity for each line and by comparing the average value of each line with the other lines establishing a new datum level which was subtracted from each value on the line. The results thus obtained are shown in Fig. 3.3 showing a better correlation with the areal geology as compared to Fig. 3.2.

The results of the survey are presented as follows:

1. Anomalies plotted along the flight lines and shown by symbols, Fig. 3.5.
2. Isoradiation contour map, Fig. 3.3.
3. Three-dimensional presentation of radioactivity, Fig. 3.4

3.2.2 Interpretation

Fig. 3.3 is an aeroradioactivity (total count) contoured map over the Thackaringa-Copper Blow area. From a geology standpoint the Thackaringa-Copper Blow area is composed of the Willyama Complex which consists of a group of metasediments in the form of schists and gneisses, Fig. 3.5. The whole area lies within the high-grade metamorphic Zone C of Binns (Binns, 1964), Fig. 2.1. The rocks have been folded and faulted, partly granitised and extensively subjected to pegmatisation and aplitisation. As a whole, the rock exposures are from poor to good. The only good exposures are present in the western, northern and eastern parts of the map. The Cainozoic deposits occupy approximately two-thirds of the area. The white colour in Fig. 3.5 shows the distribution of the Cainozoic deposits. The thickness of the cover varies from 2-3 feet to within a distance of 2000 feet from the outcrops (Langford-Smith and Dury, 1964). The cover consists of very fine to medium-grained subrounded clear to limonitic stained, occasionally opaque quartz, in a sparse white to yellow silty kaolinitic matrix.

The outcrops in the western part of the map running along the Mundi Mundi Fault generally consist of a series of schists and gneisses which have been partly granitised and migmatised. Sillimanite schists, mica schists, sillimanite gneiss and granitic gneiss form prominent outcrops in this part. The granitic gneiss and garnetiferous gneiss are of the Hanging Wall type of the Central Broken Hill Zone. The other type of granitic gneiss is augen gneiss with large feldspar "augens" and crops out in the central part of this area. The outcrops of pegmatites, aplites and microgranite are common associates of the Willyama metasediments. Amphibolites are present throughout the area and appear to be interbedded with the Willyama metasediment. Serpentine and dolerite are found in central and southern parts of this zone. Quartz veins are also abundant and vary in thickness from a few inches to 4 feet, especially in the Thackaringa Pinnacles Shear Zone.

The central and eastern portions of the map also consist of the same rock types described above. Their surface expressions are extremely limited and poor.

The main structural features of this area are the Thackaringa Pinnacles Shear Zone, East West Shear Zone which trend approximately east-

Fig. 3.3 Airborne total count contour map of the Thackaringa-Copper Blow area. The contour interval is 200 counts per minute.

Overlay - interpreted radiometric response over various geologic units.

Source of data - radiometrics compiled from a study of original airborne scintillographic flight charts photographed on an 8 mm film, B.M.R. survey, 1959.

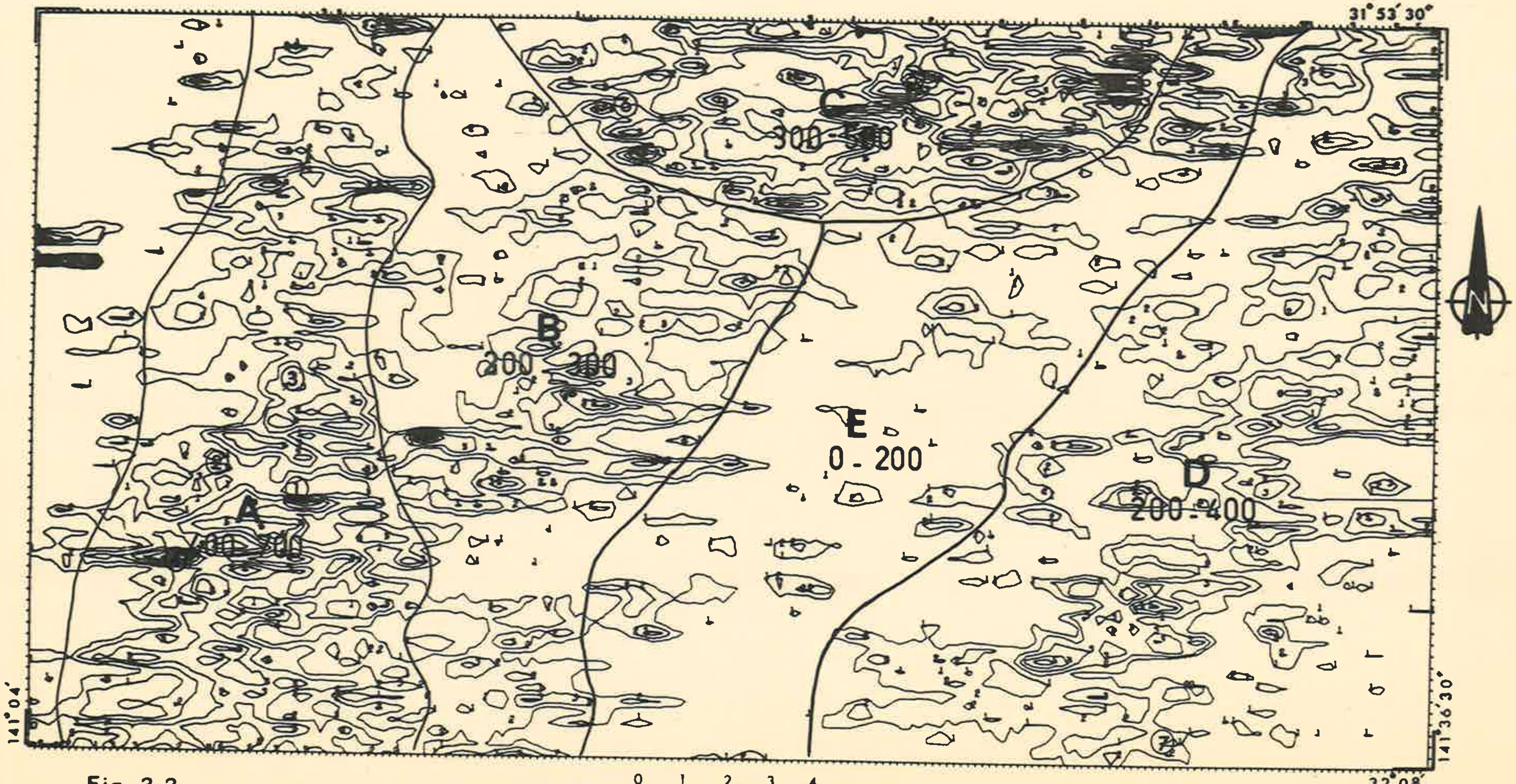


Fig. 3.3

Overlay Fig. 3.3

west. The Globe Vauxhall Shear Zone trends northeast-southwest. There are some other minor shear zones in the area which have a bearing on the uranium mineralisation particularly north of the Thackaringa Pinnacles Shear Zone, in the central western part of the map.

An inspection of Fig. 3.3 shows that the area can be subdivided into five levels of radioactivity (i.e. A,B,C,D and E) on the basis of response of aeroradioactivity. These levels of aeroradioactivity may be correlated to different geologic units present in the area with varying amounts of radioactive elements. The levels of aeroradioactivity show a generalised distribution pattern of radioactivity (with some spurious anomalies). When compared with the geological map of the area, it is observed that the levels do not necessarily follow the geologic boundaries closely, the reason being that the data could not be corrected for height as previously mentioned. To overcome this problem, an average radioactivity value was calculated and subtracted from the total radioactivity intensity along each flight line. The above-average radioactivity thus obtained was then contoured. However, the results obtained still contained much useful geological information if the presence of the spurious anomalies, especially strong linear and parallel to flight lines, is taken into consideration. The levels of higher radioactivity generally correspond to the outcrops and the low level (E) corresponds to the thick Cainozoic deposits in the area.

The aeroradioactivity (total-count) survey data has been presented in the form of stacked profiles in three-dimensional plane over the Thackaringa-Copper Blow area and is shown in Fig. 3.4. The use of such a type of presentation facilitates the recognition of radiometric highs and lows in a better way as compared to the stacked profiles in two-dimensional plane. The aeroradioactivity highs occur over the Willyama Complex outcrops whereas the lows occur over the drainage and the Cainozoic alluvial deposits in the area. The figure can also help in finding the trend of radioactive mineralisation in

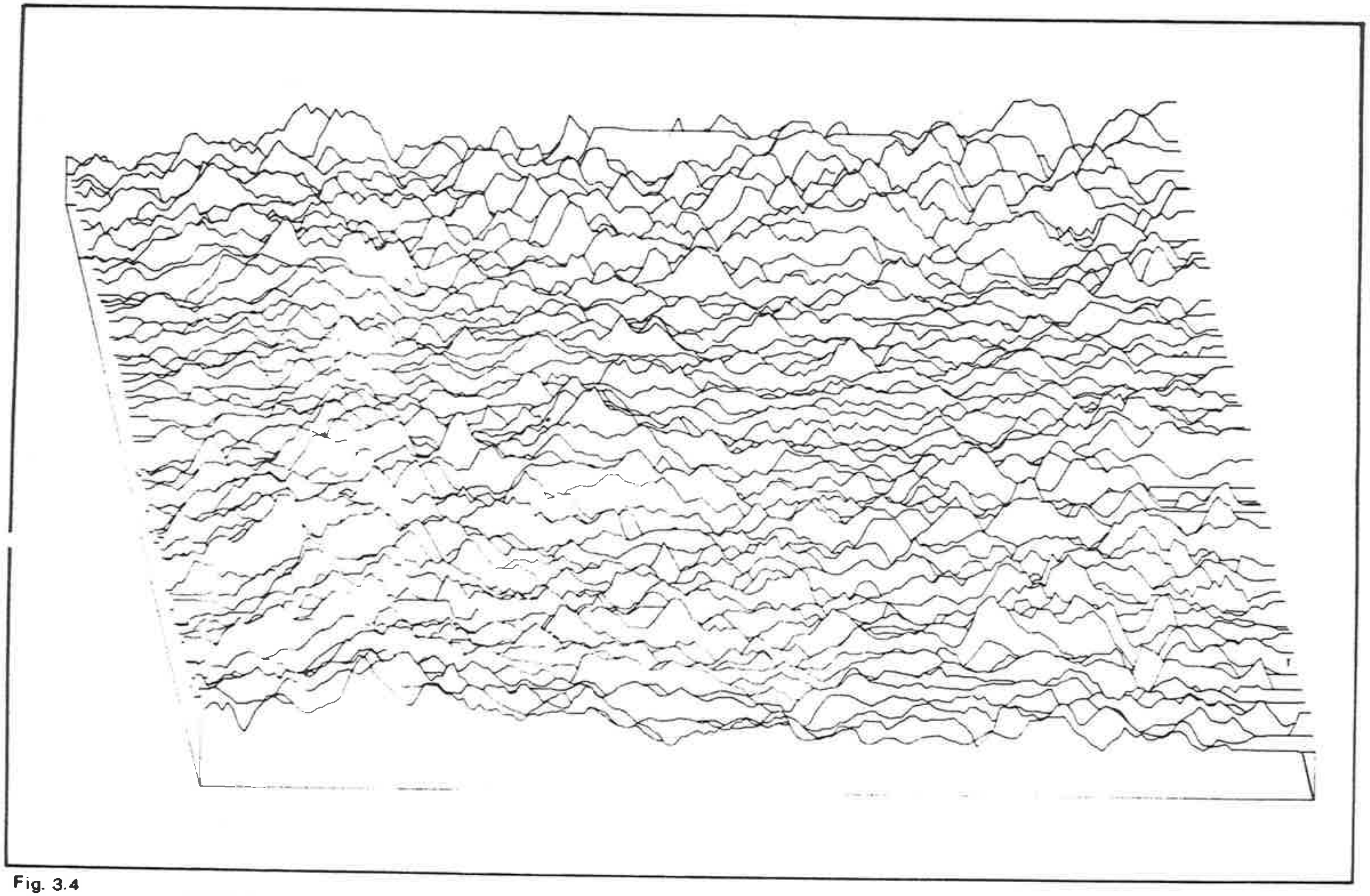


Fig. 3.4

MASKED PERSPECTIVE VIEW OF TOTAL COUNT DATA IN THE THACKARINGA - COPPER BLOW AREA

(VIEW LOOKING FROM SOUTH WEST)

the Willyama metasediments. It is observed by joining the peaks of the radiometric highs, that the radioactive mineralisation trends predominantly on two directions, i.e. northeast-southwest and northwest-southeast. These trends of radioactive mineralisation, with some local variations, correspond to the strike trends of the Willyama rocks in the area.

Fig. 3.5 is a geological map of the Thackaringa-Copper Blow area and shows that good rock exposures are only present in western, northern and eastern portions of the map. The western part of the area consists of low to moderate high hills deeply dissected by the creeks, and rocks are excellently exposed. In this zone the rocks generally consist of sillimanite and granite gneisses intruded by pegmatites, aplites, microgranite, serpentine, amphibolites and dolerites with a larger number of quartz veins. The northern and central portions of the map also consist of similar geologic units but their surface expressions are very poor and limited. The eastern area of the map is occupied by the sillimanite schists interbedded with amphibolites and form a group of low hills covered with thick overburden. The rest of the map (shown in white) is covered with the thick Cainozoic deposits.

An overlay of Fig. 3.5 is a flight-line system of airborne radiometric (total count) survey carried out by the B.M.R. in 1959, on which anomalies have been plotted from the original analogue record photographed on an 8 mm film. The anomalies are designated as high amplitude and medium amplitude anomalies rather than some multiples of "background". As background terminology is often a source of confusion, Fig. 3.6 has been included to show how such a term has been used in this thesis. The medium amplitude anomaly has been taken two times that of the "Local Background" and the high amplitude anomaly is three or more than three times that of the "Local Background". As said earlier, the original scintillographic data could not be corrected for height, due to the non-availability of radio altimeter record, therefore, it had not been possible to show the exact outcrop width of radioactive rock units along the flight lines. Solid circles and diamonds have been used for high

Fig. 3.5 Geology of the Thackaringa-Copper Blow area and airborne total count anomalies.

Legend

1 Dolerite
2 Granite
3 Pegmatite
4 Granite gneiss
5 Augen granite gneiss
6 Aplite
7 Potosi gneiss
8 Amphibolite
9 Undifferentiated metasediments, mainly schist and sillimanite gneiss
10 Redan gneiss and granulite
11 Lode rocks of Broken Hill type
12 Banded iron formation
13 Copper lode rocks
14 Shear zones and faults
15 Trend line, photo interpretation
16 Trend line, mapped

*

Overlay - Airborne Total count anomaly map

Source of data - geology base from the Australasian Institute of Mining & Metallurgy, (AIMM) Map, 1968. Radiometrics compiled from a study of the original airborne scintillographic flight charts, photographed on an 8 mm film, B.M.R. survey, 1959.

*Note: White colour on the geological map represents alluvium.

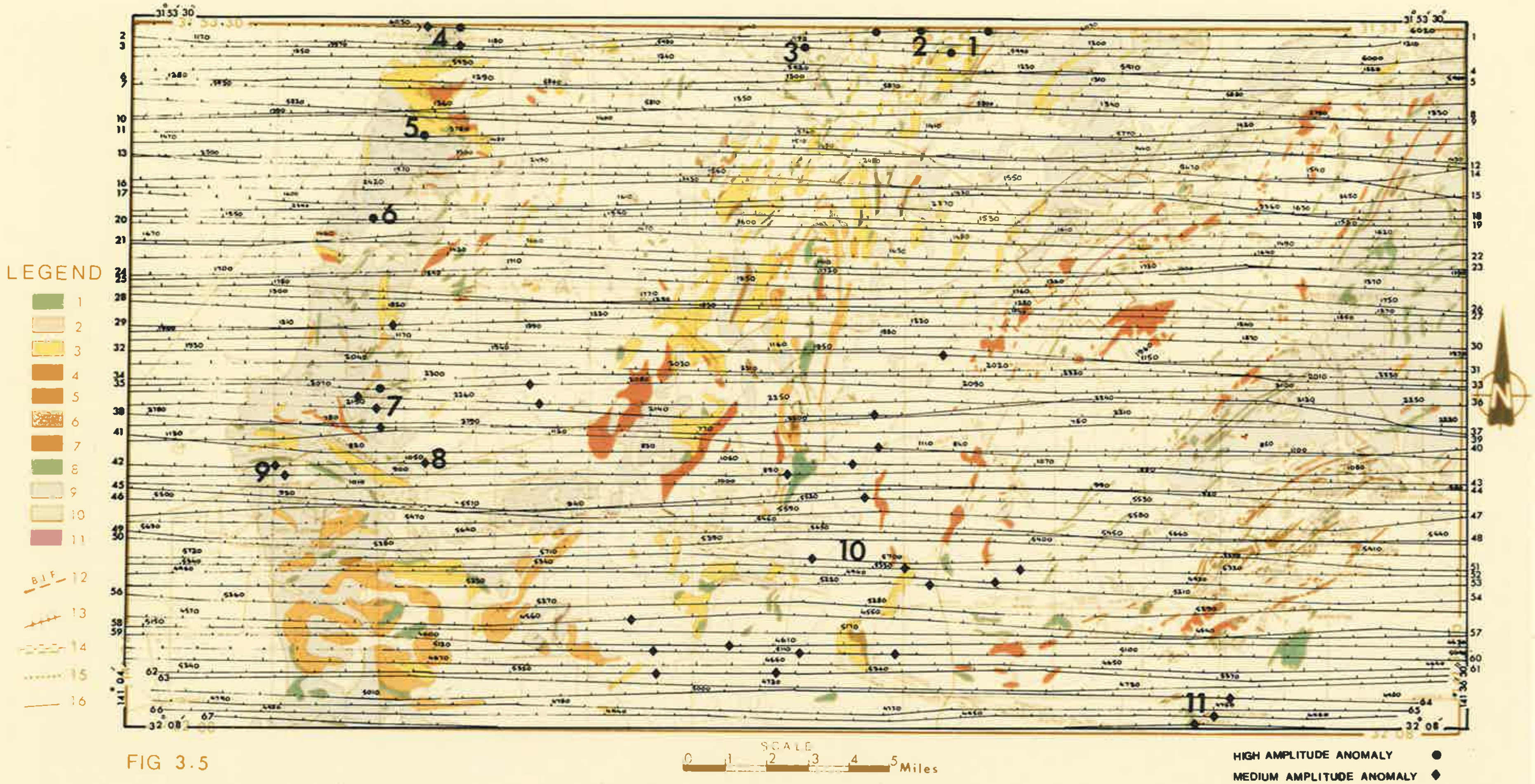


FIG 3.5

GENERALIZED GEOLOGY OF THACKARINGA — COPPER BLOW

TOTAL COUNT ANOMALIES

Overlay Fig 3.5

SECTION OF IDEALIZED SPECTROMETER CHART

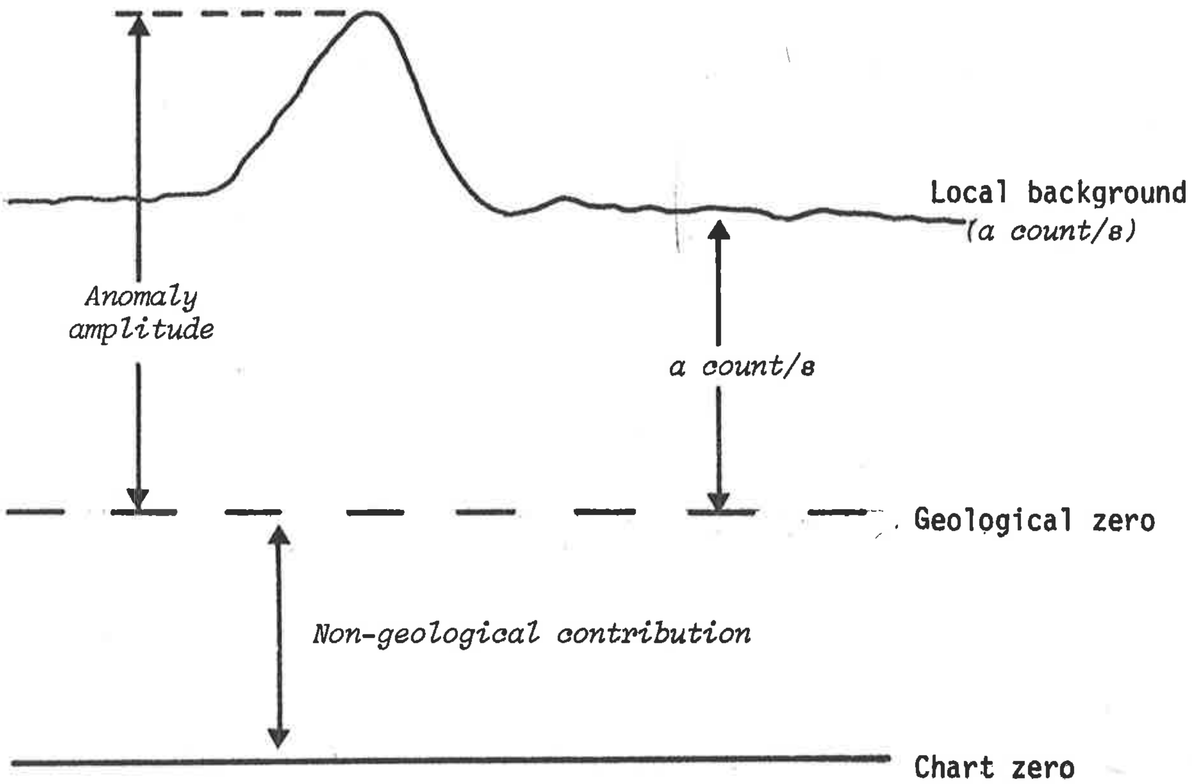


DIAGRAM TO ILLUSTRATE USE OF BACKGROUND TERMINOLOGY
AS USED IN THIS THESIS
(after Horsfall & Wilkes, 1975).

Fig. 3.6

and medium amplitude anomalies respectively. During the ground follow-up geologic and radiometric investigations of these anomalies, it was observed that certain high amplitude anomalies did not correlate with the high radioactive geologic units but they were merely the geological expressions along the flight lines with low or moderate radioactivity. However, the radiometric results (overlay, Fig. 3.5) when compared with the aerial geology were fairly good and proved to be helpful during the ground investigations. During the ground radiometric survey a portable four-channel gamma-ray differential spectrometer was used. The details of this instrument are given in Appendix 4.

The aeroradiometric anomaly No. 1 overlies the Nine Mile area and is caused by the outcrops of pegmatites. The pegmatites are coarse-grained and mainly consist of feldspar and quartz with small amounts of muscovite (small books of mica measuring up to one inch in diameter). The radiometric response in total count and potassium channels suggests that they are dominantly K-feldspar pegmatites. The radioactivity in the vicinity of the Centennial area (No. 2) is possibly due to thorium mineral (monazite) as referred to by Rayner (Rayner, 1957). This particular anomaly could not be located during the ground survey. In the Great Western area (anomaly No. 3) the radioactivity is related to the mine dumps. The Great Western is an old silver-lead-zinc mine, 6 miles northwest of Broken Hill. The mine dumps, mainly oxidised, showed radioactivity (uranium) 2-3 times that of the normal background. Higher radioactivity was recorded in the shaft. The higher radioactivity was possibly due to solid angle effect. Rayner has reported radioactivity in the order of 0.05 percent U_3O_8 from the sulphide zone. In this area the country rocks are sillimanite schists with pegmatites. No statistically higher radioactivity was found over these rocks. Uranium mineralisation in the sulphide zone (primary) is noteworthy which might have been a source of secondary uranium mineralisation in the oxidised Zone 1.

A group of medium to high amplitude anomalies (No. 4) was thought to be related to the sulphide-rich rocks in Silverton which is an old silver-lead mine. The mine dumps and shafts were checked radiometrically. No statistically, above average radioactivity was found in this area. The country rocks which are generally sillimanite schists interbedded with amphibolites gave weak radiometric response. Anomaly No. 4 may be a combined effect of high relief and exposed rocks. The validity of anomaly No. 5 and 6 is also doubtful. No such high radioactivity was recorded in these areas. The areas consist of highly rough and rugged hills, deeply dissected by the creeks. It is possible that these two anomalies are spurious. Their cause is either instrumental such as a sudden change of height during flight, or they could be related to outcrops with high relief. If they are not spurious, they were missed during the follow-up program.

The airborne total count anomaly Nos. 7 and 8 overly the Thackaringa area where uranium and thorium mineralisation is known to occur (Rayner, 1955). Thackaringa is situated 18 miles west-south-west of Broken Hill, adjoining the northern side of the Broken Hill-Adelaide road (Barrier Highway). The deposits were first discovered by H.H. and G.L. Baker in February, 1955. The first davidite mineral (an iron-uranium titanate), (Table 3.2), was discovered in the vicinity of anomaly No. 8 (about one furlong north of the Barrier Highway) on a slope of a low hill. The area consists of schists and gneisses which have been partly granitised and migmatised. Schists and gneisses are mainly sillimanite, mica and granite. Bands of amphibolites are present throughout the area and appear to be interbedded with the Willyama rocks. Pegmatitisation in the area is widespread and is probably related to more than one period of formation (Rayner, 1957). The pegmatites which are host to the uranium minerals are of late introduction into the Willyama Complex. They are commonly coarse-grained and transgressive to other rocks and are aligned in/or parallel to certain shear zones known as Albert and Baker Shear Zones. Associated with these pegmatites are the development of aplite and pink microgranites. The uranium mineralisation lies within the Albert and Baker Shear Zones where

TABLE 3.2

CHEMICAL ANALYSIS OF DAVIDITE (THACKARINGA AREA)

	Percent
SiO_2	1.33
Al_2O_3	1.24
BeO	0.01
TiO_2	50.17
Cr_2O_3	0.35
V_2O_3	1.18
Fe_2O_3	13.06
PbO	0.76
U_3O_8	4.16
FeO	15.93
ZrO_2	0.12
MnO	0.21
Na_2O	0.07
CaO	0.64
MgO	0.18
ThO_2	0.08
Ce_2O_3	1.34
Ce group	6.34
Y group	0.65
CO_2	0.13
P_2O_5	0.28
H_2O+	1.43
	99.66

(after Rayner, 1957, p. 75).

davidite is the main principal uranium mineral present. The mineral is present in veins and irregular lenses of pegmatites rich in quartz, disseminated in microgranite and biotitic schistose rock in the Albert Shear Zone. In detrital form it is found on the surface and as grains in creek sands. Several pits, costeans and shafts were checked in the vicinity of pegmatites which gave 15-20 times the radioactivity, due to uranium. The uranium mineral, davidite is closely associated with rutile, hematite, ilmenite, magnetite, mica, and quartz. Several prospectors started working in different areas which seem to be abandoned now. The areas are the Baker's area, Fyfe's area, Boston's area, Kenny's area, Jeffrey's area and many others. Since 1960, there have been no activities in these areas, the reason being that the lack of finance and no big deposits of economic importance were discovered.

Moderate radioactivity, due to uranium (anomaly No. 9) was found to be associated with one of the mine dumps in the Thackaringa area known as Gypsy Girl. It is an old silver-lead mine and lies within the Willyama Complex metasediments mainly sillimanite schists and gneiss. The sillimanite gneiss was found to be radioactive, 3 times that of the local background due to potassium.

In the centre of the map there is a group of medium amplitude anomalies (No. 10). Their sporadic distribution along the creek beds suggests that they are caused by the concentrates of heavy minerals along the creeks.

Anomaly No. 11 is associated with the mine dumps in the Copper Blow area which is caused by the uranium mineralisation (secondary mineral, metatorbernite), (Rayner, 1957), and lies at a distance of 12 miles south-south-east of Broken Hill. The radioactivity was first noted by Daly and White in 1952. The copper and iron lodes are narrow, forming a strongly linear group about one mile in length. The lodes are confined within a zone which is up to 150 feet in width and strikes parallel to the enclosing rocks, i.e. northeast-southwest. The enclosing country rocks are the Willyama Complex consisting of biotite-sillimanite-garnet schists, granitic gneiss, amphibolite and pegmatite. The host rock for the lode is in part a quartz-biotite-sericite schist with grains of magnetite. During a ground radiometric survey radioactivity due to uranium 2-4 times the local background was found over the mine dumps and open cuts. The highest radioactivity (10-15X local background) was recorded over the southern end with increased copper mineralisation, Warren open cut. According to Rayner (1957) the uranium values are in the range of 0.1-0.3 percent U_3O_8. In the oxidised zone hematite, limonite, magnetite, malachite, azurite and chrysocolla are present. Moderate to high radioactivity (2-3X local background) was recorded over the sulphide dumps (Warren shaft, extreme southern end of the area). Rayner reported slight radioactivity associated with the drill cores obtained from the sulphide zone and suggested that the primary uranium mineralisation was associated with copper in the primary zone (sulphide zone). The area seems to be low grade uranium and copper deposit.

The radioactivity when compared with the total magnetic intensity of the Thackaringa-Copper Blow area, it was observed that the radiometric highs are associated with the magnetic highs, especially in the Thackaringa and Copper Blow areas.

3.3 Regional Airborne Spectrometer Survey, 1975

The regional spectrometer survey covered the Broken Hill 1:250,000 sheet (Pl. 2A in pocket). The line spacing was 1.5 km and ground clearance 100 metres. The details of processing and presentation of the survey data performed by the B.M.R. are given in Appendix 2. The B.M.R. published the fully corrected survey data in the form of stacked profiles for four channels, i.e. total-count, potassium, uranium and thorium, at 1:250,000 scale.

3.3.1 Presentation

The presentation of the regional airborne spectrometer survey data is shown in Fig. 3.7 which was prepared using the B.M.R. channel maps (stacked profiles) on a scale of 1:250,000. The channel maps were prepared above normal radioactivity along flight lines. Transparencies and colour scheme were used to facilitate the comparison of the required channels.

The stacked profiles produced by the B.M.R. (1:250,000 map scale) give fair correlations with the aerial geology. In most instances, it has not been possible to obtain satisfactory radiometric interpretations over certain areas due to overlapping and cross-cutting of stacked profiles which could be expected on such a small-scale regional survey with a line spacing of 1.5 km. To overcome this problem it was decided that the stacked profiles be copied along the flight lines showing the radioactivity above the normal radioactivity level. The results were two-fold: (1) there seems no congestion in channel maps due to overlapping and (2) radioactivity levels in all channels stand out, prominently showing variation in radioactivity levels (low, medium and high) over various geologic units. Further, the colour contrast and transparencies made the comparison better between different channel maps. The only difficulty observed during the interpretation had been the correlations of radiometric response over the small intrusive bodies such as granite, amphibolite and pegmatite in certain areas which could possibly be due to the large exposures of the surrounding rocks. In a regional sense, the correlations with the areal geology are generally good. This method of presentation of survey data facilitated delineating the broad scale radiometric features in the study area which are the reflection of various geologic units. The broad scale radiometric features have been subdivided into six zones, i.e. A, B, C, D E and F in all channel maps. Zones A and C overly the outcrops of the Willyama Complex, B and F are associated with the Torrowangee rock exposures, D shows the radiometric response over the alluvium covered plain to the east of the triangular shaped Willyama Complex and E is associated with the Cainozoic deposit in the Mundi Mundi Plain. Weak to moderate radiometric response over the areas occupying northeastern and southeastern corners of the map have been omitted as they do not make up the part of the Willyama Complex as they are younger than the Willyama Complex (Palaeozoic).

The "visual ratios", in a very broad and generalised sense, can be obtained for U/K, Th/K, U/Th comparing the channel transparencies without doing much mathematical calculations. No absolute values in counts per second have been assigned to either anomalies or geologic units, but instead, the levels of radioactivity, such as low, medium or high have been adopted.

3.3.2 Interpretation

The major portion of the triangular shaped area (Fig. 3.7 in pocket) is occupied by the Willyama Complex outcrops whereas Zones B and F are occupied by the Torrowangee Group. The detailed geological account of the Willyama Complex has been given in Chapter 2.

Zones B and F trending northwest-southeast, are occupied by the Torrowangee beds mainly consisting of tillite, shale, limestone, dolomite, quartzite, sandstone and siltstone. Fig. 3.7 and Plate 2A are the geological maps of the area and show the distribution of lithologic units. An inspection of overlays, (Fig. 3.7 (2-5)) shows radiometric response in all channels over these zones. From a radiometric viewpoint, no statistically above normal radioactivity (all channels) was observed over these zones. An inspection of potassium channel (overlay 3) also did not show above normal radioactivity due to potassium, so it is probable that the Torrowangee beds contain a very small amount of potassium and may be rich in Na-feldspar, calcium and silica as indicated by the presence of rocks such as limestone, dolomite, sandstone, siltstone and shale in these zones. Quite a few sporadically distributed radiometric anomalies (in nearly all channels), in Zone F, in places, are not due to the radiometric response to the Torrowangee beds. The anomalies follow the creek beds and may be due to the local concentration of radioactive minerals transported by the creeks from the nearby Willyama Complex rocks of Zone A.

The radiometric Zone A (trending northwest-southeast) is related to the outcrops of the Willyama Complex. The Willyama Complex in this zone has been shown as undifferentiated metasediments, mainly schist and sillimanite schist. Firstly, due to the lack of detailed geological data, it was not possible to definitely correlate the radioactivity to various rock units. Secondly, the radiometric response consists of very broad amplitude anomalies in nearly all channel maps. However the higher radiometric response in total count and potassium channels over the upper half of Zone A suggests that the rocks are rich in K-feldspar and may possibly show the outcrops of sillimanite. The sillimanite gneiss (high-grade metamorphic rock) usually contain a high percent of K-feldspar (Glen, 1978), whereas the radioactivity, due to uranium and thorium, suggests the normal content of uranium and thorium generally encountered in common acidic rocks. The moderate level of radioactivity (all channels) is possibly due to the exposures of granitic gneiss present in the portion of Zone A.

Radiometric Zone C (a triangular shaped part south of Zone B) consists of the outcrops of the Willyama Complex which consists of schists (andalusite, chiastolite, carbonaceous schist, sillimanite schist, etc.) and gneisses (sillimanite gneiss, granite gneiss, augen granite gneiss, etc.) associated with pegmatites, amphibolites, granite (Mundi Mundi type) and sulphide-rich rocks. Zone C represents a great deal of variation in lithology and so the variation in radiometric response. Moderate to high radioactivity generally in all channels and particularly in uranium and thorium channels (along the western and southwestern parts of the triangle over the carbonaceous schist, sillimanite schist and davidite-bearing quartz veins) occurs in the areas of known uranium and thorium mineralisation. As said earlier, the radiometric response over the smaller intrusive bodies could not be demonstrated clearly on this regional scale survey but in certain instances it had been possible to observe weak to moderate radioactivity due to uranium and potassium over the granite exposures. In this zone, carbonaceous schist and sillimanite schist seem to be more radioactive than in the areas occupied by the andalusite schist and chiastolite schist. Pegmatite shows a variation in radioactivity due to potassium and suggests that there are two types of pegmatites - Na-feldspar and K-feldspar. Very low radioactivity (all channels) was observed over the amphibolites, serpentine and dolerite outcrops. High amplitude anomalies, total count channel, No. 7 and uranium channel, No. 7, seen in the Mundi Mundi-Mt. Frank area overly the known uranium mineralisation and are described in greater detail in Chapter 5.

An examination of the thorium channel shows a high amplitude anomaly numbered as 3. At the same locality, a moderate radioactivity is also seen in uranium channel No. 8. The anomaly No. 3 due to thorium and uranium is possibly due to the presence of a mineral which consists of a variety of thorite referred to by Rayner (Rayner, 1955 and 1957). This particular thorium anomaly could not be located during the ground geologic and radiometric investigations. According to Rayner (1957) a very strongly radioactive brown mineral was found in a small vein. Tests have suggested that the mineral is a variety of thorite. It occurs as grains and nodules in a partly decomposed and ironstained veinlet of platy bronze biotite with small amounts of zircon, quartz and feldspar. Radioactive concentrates from a small water-course in this area showed garnet, magnetite, ilmenite, monazite and a little davidite.

Zone E overlies the Mundi Mundi Plain which consists of unconsolidated medium to coarse-grained, subrounded sediments, being in places clayey. The thickness of these Cainozoic sediments exceeds 500 feet (geological section, Plate 1A in pocket). Alluvial fans are generally common along the Mundi Mundi Fault scarp. These fans were formed by creeks which flow westerly from the nearby hills mainly consisting of the Willyama Complex rocks. The sediments along the fans and further down were transported and deposited by the seasonal creeks. Inspection of channel maps (Fig. 3.7) shows a number of small scattered anomalies, especially in uranium, thorium and potassium channels.

Radiometric response in the uranium channel shows a group of small uranium anomalies (No. 2). The anomalies generally follow the drainage in Zone E. The anomalies are possibly due to the concentrates of heavy minerals containing radioactive minerals. Anomaly No. 1 (total count, potassium and uranium channels) is related to the outcrop of the Mundi Mundi type granite. There is no radioactivity due to thorium over this granite exposure. Anomaly No. 2 (potassium channel) is possibly due to the local increase of clay over this patch (Qd, Legend, Plate 1A).

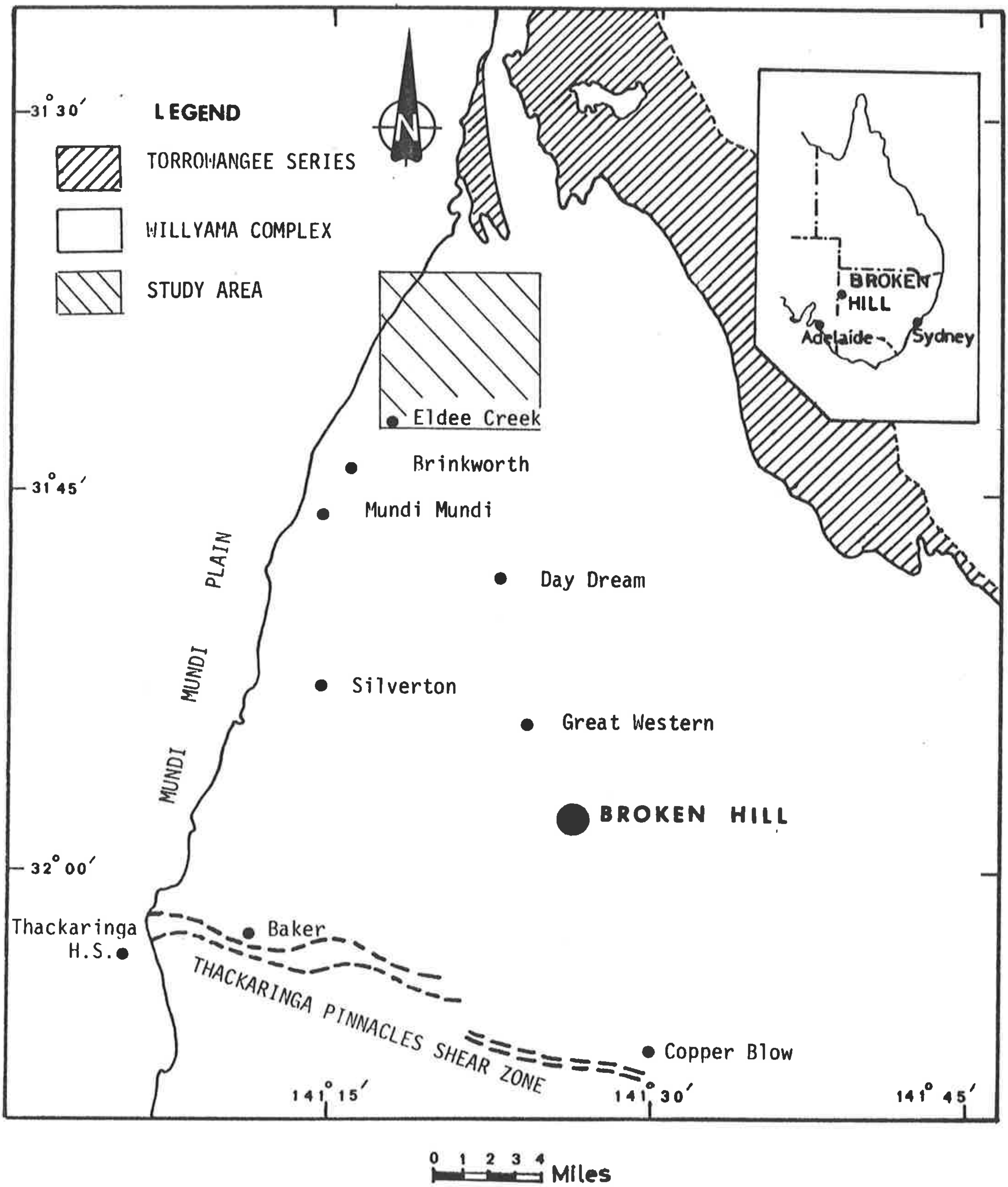
Zone D represents a plain which lies east of the main Willyama Complex. The plain mainly consists of thick Cainozoic sediments except in central, north-eastern and south-western parts of the map which are occupied by the outcrops of the Palaeozoic rocks. Sand dunes composed of red sand and clays are developed at certain places. Nodular calcrete is a common feature near the edge of the dunes. Clay pans, dessicated polygrons and playas are in this plain in places.

The radiometric anomalies are less as compared to the Mundi Mundi Plain. An examination of channel maps shows that the anomalies are small and sporadic in distribution and wherever present are associated with the creek beds (anomaly Nos. 3, 4, 5 and 6 - uranium channel; anomaly Nos. 1 and 2 - thorium channel; anomaly Nos. 3, 4, 5 and 6 - potassium). Anomalies due to uranium and thorium are due to the concentration of heavy sands whereas potassium might have been caused due to precipitation of potassium salts followed by the dessication of creeks because in most cases the streams carrying sediments lose their identity in the sand dune or sand plain areas.

Spectrometric studies over the area have shown some medium and high amplitude anomalies. The anomalies shown on the total count channel map have been selected on their response, due to uranium and thorium. The Mundi Mundi granites (except anomaly No. 1 - uranium channel) and pegmatites do not show above average radioactivity due to uranium or thorium. Their above normal response, due to potassium, is noticeable. The "visual comparative studies" of the above average radioactivity stacked profiles do not show any big uranium or thorium anomalies. They just show the normal concentration of different radioactive elements generally encountered in acidic rocks. The "visual comparative" spectrometric studies over the Mundi Mundi type granites and pegmatites (with a few exceptions) show a higher U/K ratio.

CHAPTER 4

THE MOUNT ROBE AREA



LOCALITY MAP

Fig. 4.1

CHAPTER 4

THE MOUNT ROBE AREA

4.1 Introduction

4.1.1 Location

The study area is situated 21 miles northwest of Broken Hill City in the Barrier Ranges and is shown in Fig. 4.1. It comprises approximately 56 square miles and is bounded by longitudes 141°18' and 141°25' E and by latitudes 31°35' and 31°42' S.

4.1.2 Physiography

The area is one of low to moderate relief usually sparsely covered by a typically semi-arid vegetation consisting of mulga, dead finish, beefwood, together with the ever-present saltbush. Because of paucity of vegetation and lack of overburden (soil cover), the rocks are better exposed in the area except in the northwestern (Mundi Mundi Plain) and southeastern parts where a thick cover of Cainozoic deposits is present. The country is well dissected by the creeks. The main creeks are Cartwright Cree, Big Aller Creek, Little Aller Creek and Gun Creek. All these creeks are not permanent and flow only after heavy rains.

4.2 Geology

The Willyama rocks of this area belong to low-grade metamorphism and lie within the Metamorphic Zone A of Binns (Binns, 1964).

Fig. 4.2 is a geological map of the area which shows the distribution of the Willyama rocks.

The northern part of the area is occupied by the Willyama metasediments consisting of schists, phyllites, slates and quartzites. Sedimentary structures occur in a metamorphosed and deformed sequence of interlayered quartzites and phyllites. Layering is present in both phyllites and quartzites. In phyllites it is represented by the alternation of

Fig. 4.2 Geology of the Mt. Robe area and aeroradiometric anomalies.

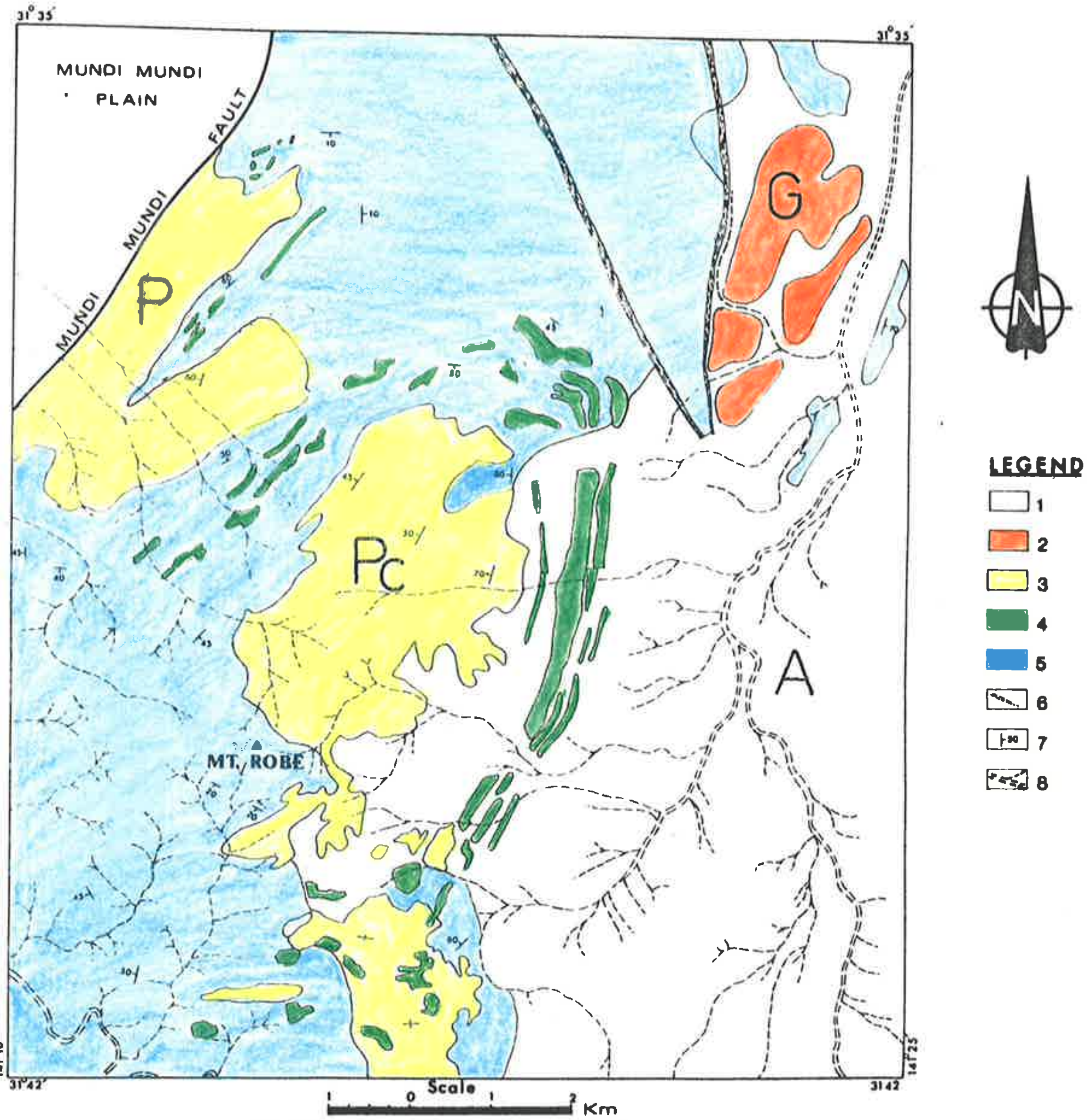
Legend

1 Alluvium
2 Granite
3 Pegmatite
4 Amphibolite
5 Willyama Complex
6 Shear Zone
7 Dip & strike of schistosity
8 Creek.

H.A.A. = High Amplitude Anomaly
M.A.A. = Medium Amplitude Anomaly

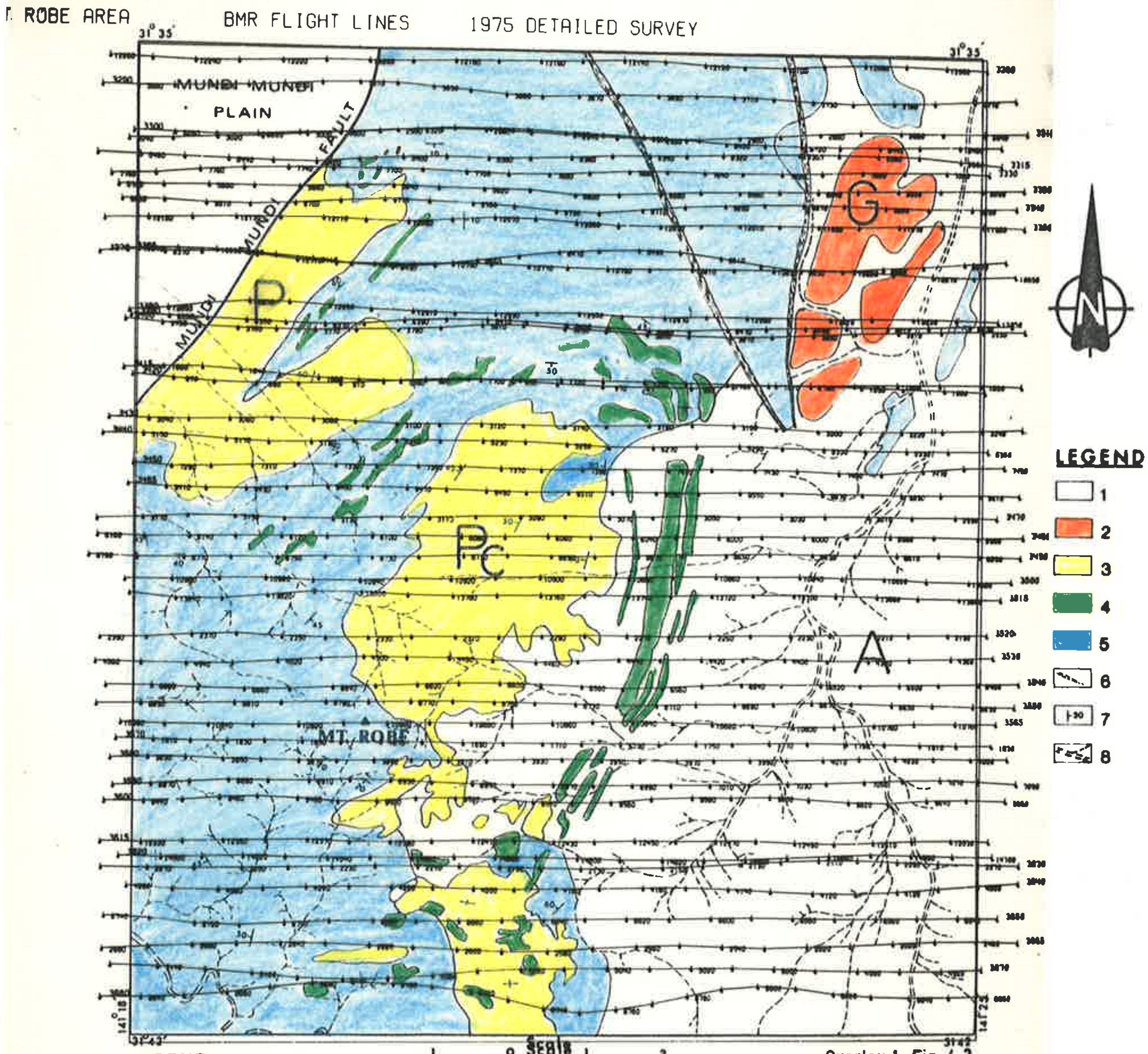
Overlay 1. Flight line system
Overlay 2. Total count anomaly map
Overlay 3. Potassium anomaly map
Overlay 4. Uranium anomaly map
Overlay 5. Thorium anomaly map.

Source of data - geology base from Glen (1978).
Radiometrics compiled from a study of the original airborne spectrometer survey data digitally recorded on magnetic tapes.
Airborne magnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W., B.M.R. survey, 1975.



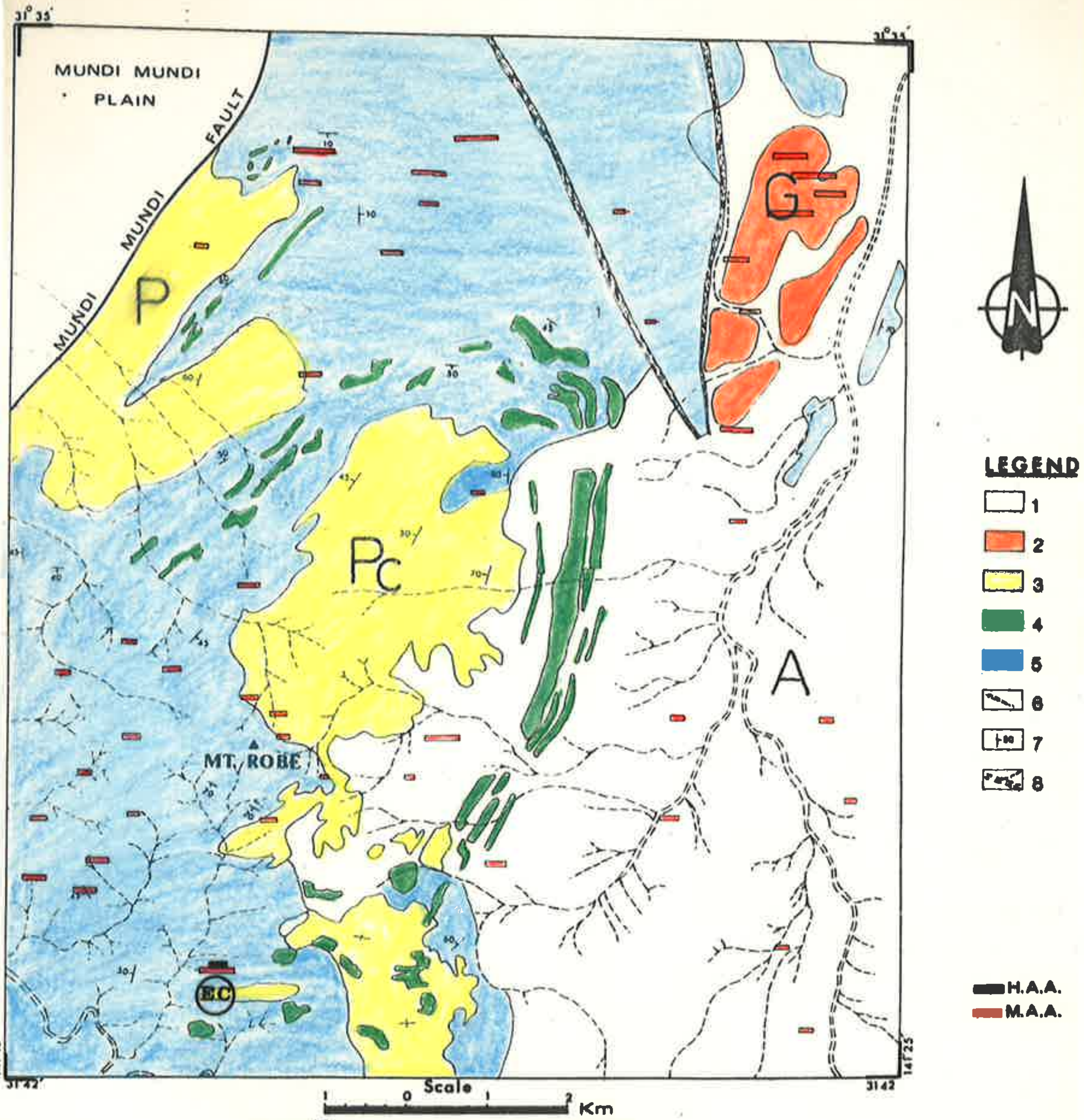
GENERALIZED GEOLOGY
OF THE
MOUNT ROBE AREA

Fig. 4.2



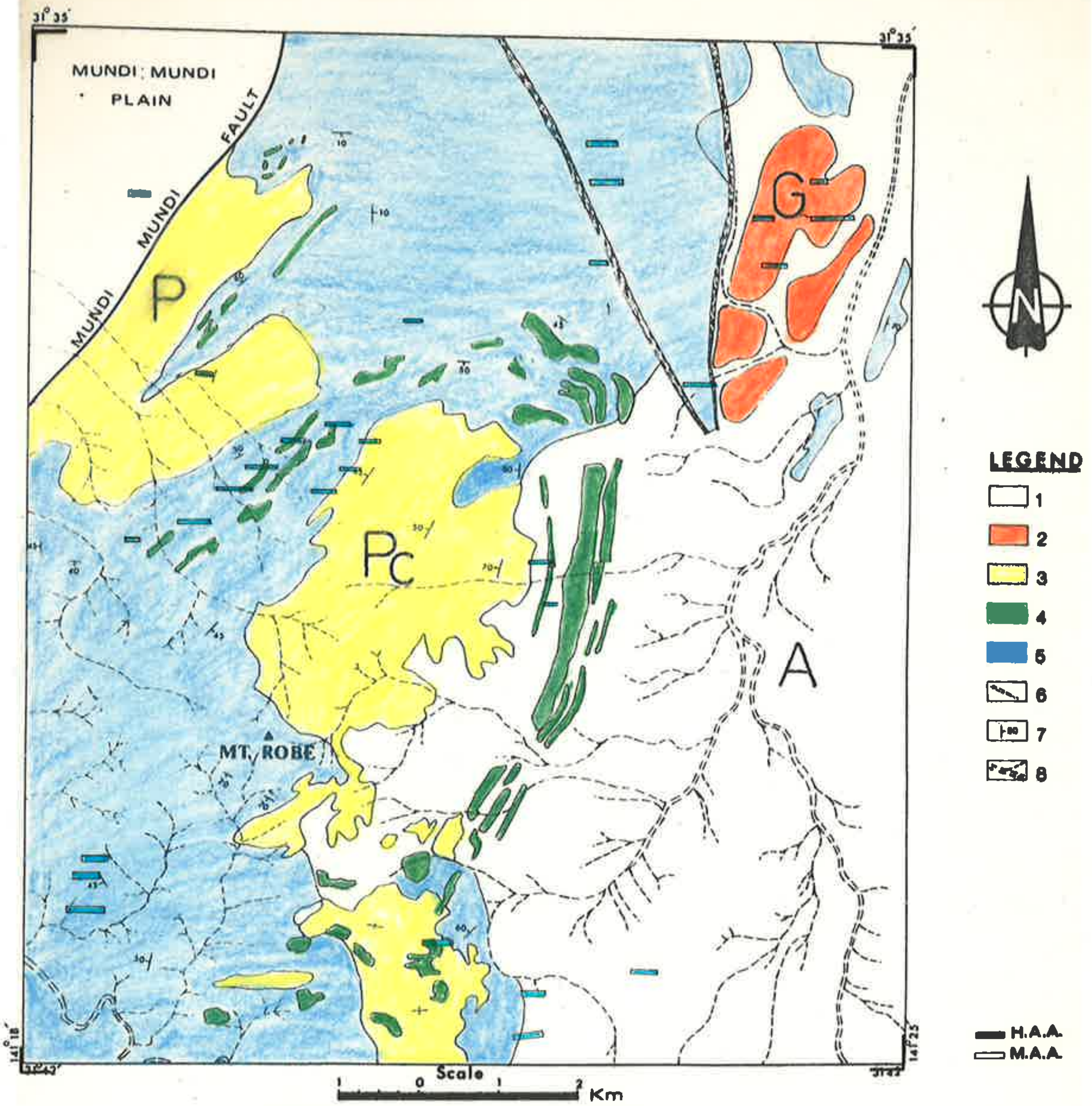
LEGEND
3570 —— Flight-line number
1610 —— Fiducial count

GENERALIZED GEOLOGY
OF THE
MOUNT ROBE AREA
Fig. 4.2

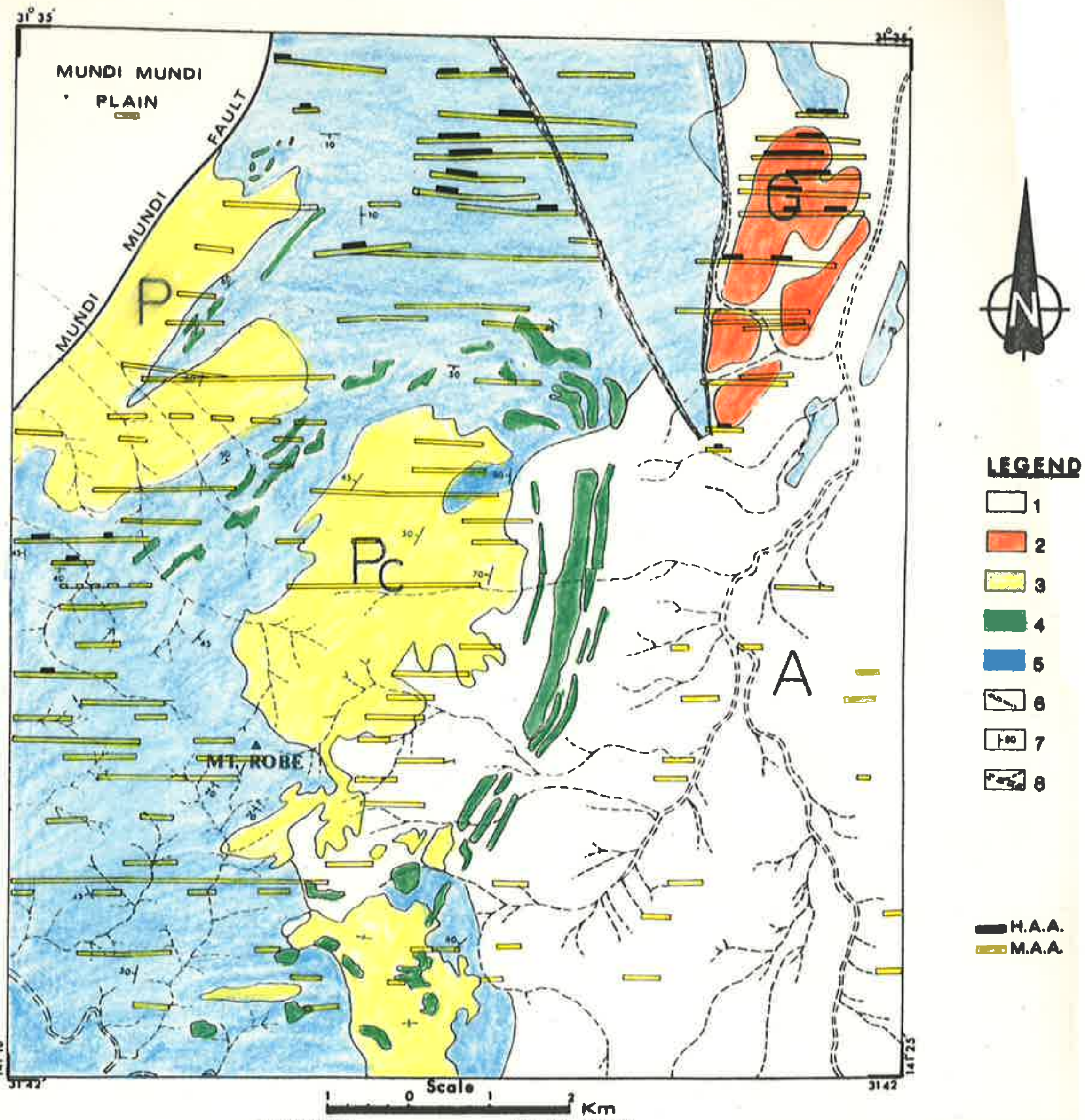


GENERALIZED GEOLOGY
OF THE
MOUNT ROBE AREA
Fig. 4.2

Overlay 4 Fig 4.2 **URANIUM**

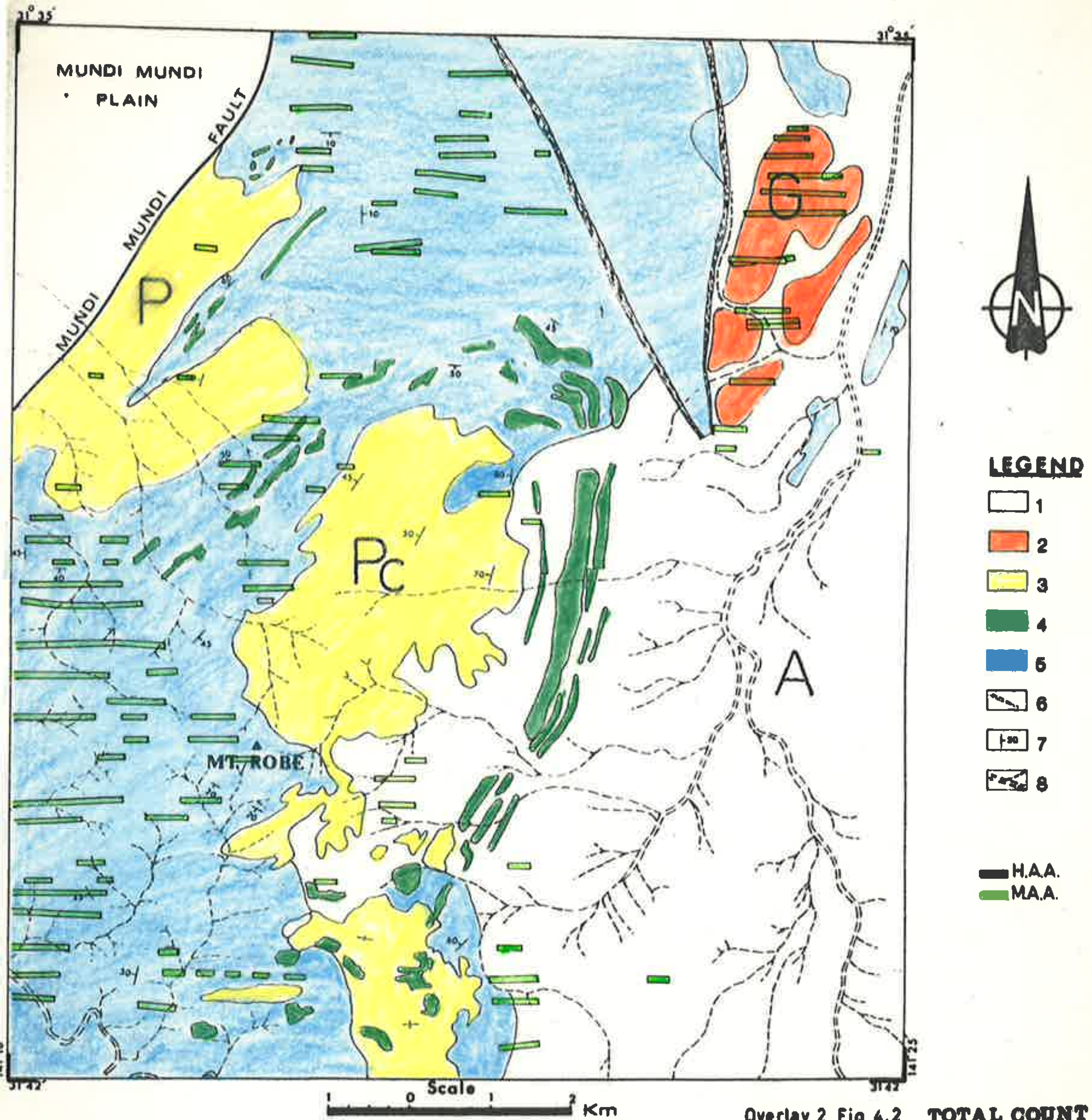


GENERALIZED GEOLOGY
OF THE
MOUNT ROBE AREA
Fig. 4.2



Overlay 3 Fig 4.2 **POTASSIUM**

GENERALIZED GEOLOGY
OF THE
MOUNT ROBE AREA
Fig. 4.2



Overlay 2 Fig 4.2 **TOTAL COUNT**

GENERALIZED GEOLOGY
OF THE
MOUNT ROBE AREA
Fig. 4.2

thin carbon-poor and carbon-rich bands while in quartzites it occurs as normal quartzitic compositional bands. The sedimentary structures are preserved as cross-bedding, graded-bedding, ball and pillow structures. The whole sequence is strongly deformed into a tight regional fold (Glen and Laing, 1975).

The southwestern part of the area consists of a series of schists dipping to the west. The schists, as a result of differential weathering, show the original bedding planes. They are composed of muscovite, quartz, biotite, and sericite with varying amounts of magnetite. One of these schists contains quartz, muscovite, biotite, sericite, andalusite, sillimanite, chloritoid, magnetite, garnet, and tourmaline. It is well crystallised and well schistosed. The biotite is nearly changed to brownish-black opaque pseudomorphs. Andalusite (in small grains) is altering to sericite (Browne, 1922).

The central part of the area is occupied by the massive pegmatites (P & Pc). Mawson (1912) says: "In no other part of the world can pegmatite formations occur on a more extensive scale". The pegmatites are sill-like bodies filling and flanking the Mount Robe syncline. Their irregular length can be traced up to 6 miles. Many of the pegmatite bodies enclose the residual patches of the country rocks (e.g. schist and metaquartzite) and occur parallel to an earlier foliation in schist (Leslie & White, 1955).

The pegmatites are simple types, consisting of quartz and feldspar. They are generally coarse-grained, the larger feldspar grain being 4 inches. The average composition of pegmatites is 60% feldspar (both alkali and microcline) and 40% quartz (Leslie and White, 1955). Accessory minerals include muscovite, garnet and tourmaline. The garnet sometimes makes up about 10% of the rock. The pegmatites in the area are pegmatites with dominant potash feldspar (Browne, 1922). The potassium anomaly map (Overlay 3, Fig. 4.2) and the potassium contour map (Fig. 4.5) show the distribution of potassium in the area. The pegmatite along the Mundi Mundi Fault (P) seems to be more potassic than the central pegmatite body

(Pc) in which potassium seems to be distributed along the northern and southern margins only.

In the northeastern part of the area there is an outcrop of the Mundi Mundi type granite (G). The granite is a leucocratic rock in which ferromagnesium minerals do not exceed 4%, with a high percentage of muscovite. The grain size ranges between medium-grained and coarse-grained. According to Leslie and White (1955) this is per-aluminous sodi-potassic granite. The chemical composition is given in Table 2.2. Table 3.1 shows the general amounts of uranium, thorium and potassium present in common rocks.

In the area, the amphibolites can be seen encircling the central pegmatite (Pc) in a semi-circular fashion. Other exposures are found in the northwestern part of the area.

The amphibolites in this area belong to Zone A of Binns (Binns, 1964),consisting mainly of about two-thirds hornblende and one-third felsic minerals. A description of amphibolites has been given by Browne (1922) and Stillwell (1922), while Binns (1962) has presented a wealth of descriptive, optical and chemical data on these rocks. The amphibolites are hornblende-plagioclase-quartz amphibolites with green or blue-green hornblende (Binns, 1964).

4.3 Cainozoic Geology

Fig. 4.2 is a generalised geological map of the area and shows the distribution of the Cainozoic alluvial deposits. The northwestern (Mundi Mundi Plain) eastern and southeastern parts of the area are generally covered with the Cainozoic alluvial deposits. The thickness of these deposits exceeds tens of feet. In these alluvial deposits, the upper part of the soil profile consists of very fine to medium-grained subrounded clear to limonitic stained, occasionally opaque quartz, in a sparse white to yellow, silty, kaolinitic matrix. The clay is yellow, light brown, grey to dark grey, sandy in patches.

Thin alluvial and colluvial deposits are generally present adjacent to outcrops. Their thickness varies from 1 to 3 feet. They have greatly obscured the local rock units wherever they are present.

4.4 Spectrometric Studies

4.4.1 Processing and presentation of data

All digital data tapes (corrected) were merged and processed in the Department of Economic Geology, University of Adelaide, using Computing Centres CDC 6400 and CDC CYBER 173 computers. All profiles, flight path maps, and contour maps were drawn using Computing Centre's Calcomp plotter. Full use was made of the processing of the survey data done by the B.M.R., details of which are given in Appendix 2.

The geological map, profiles, flight path maps and contour maps were drawn at 1:25,000 scale for detailed interpretation of the spectrometric data in the Mount Robe area.

The anomaly maps for total count, potassium, uranium and thorium channels were prepared, plotting the anomalies along flight lines.

Suto (1977) developed a computer-drawn format for plotting the survey data in the form of contour maps.

In connection with the processing of the airborne survey data, the contour maps for channels and various ratios were drawn experimentally. Because of the nature of the computer program employing interpolation of data points, the contours along three flight lines on the top and bottom sides of all the contour maps, where the contours do not truly reflect the data and appear to be more or less straight, they should be ignored.

The contour maps for U/K and U/Th ratios were prepared on the basis of corrected data. All the contour maps are presented in Figs. 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 and 4.10.

4.4.2 Interpretation

All four spectrometer data channels were studied to delineate the zones of above-normal radioactivity in the Mount Robe area. In each channel, the radioactivity rarely exceeds the statistical noise level. The zones of activity, 2 x noise level, and more than 2 x noise level, are designated as moderate and high radioactive zones respectively. There are no particular zones in the area which really contains characteristic anomalies (except one uranium anomaly, EC, in the southwestern portion of the area) in any channel. Generally the anomalies are broad with low amplitudes. The anomaly maps for four channels were prepared on the basis of anomaly amplitude as said above. The anomalies were plotted along the flight lines from computer-drawn profiles on a scale of 1:25,000.

An inspection of overlays of Fig. 4.2 reveals that the tracts of moderate radioactivity are confined to the northeastern, northern and southwestern portions of the area. The areal distribution of anomalies (broad shape and medium amplitude) suggests that the radioactivity is associated with rock exposures and topography. The northeastern tract of moderate radioactivity (total count) overlies the outcrop of the Mundi Mundi granite (G); the northern moderate radioactivity is due to the exposures of the Willyama Complex mainly consisting of phyllites, slates and quartzites; and southwestern radioactivity is attributable to the well exposed rocks of Willyama Complex, comprising mainly of schists. The variation in amplitude within the moderate radiation zones is attributable to the bedrock covered by the varying thicknesses of overburden, 1 to more than 3 feet thick. The low radioactivity in the northwestern (Mundi Mundi Plain, Am) and southeastern parts of the area (A) is due to the Cainozoic alluvial deposits. Some sporadic anomalies in the southeastern portion follow the drainage.

The spectrometric studies, Fig. 4.2, (channel anomaly maps) show that the Mundi Mundi granite and the pegmatites are dominantly potassic. Uranium is more widely distributed than thorium, especially in the Mundi Mundi granite. Radiometrically the pegmatites seem to be uranium-barren.

The amphibolites encircling the pegmatitic bodies and spread in the northwestern part and south of the pegmatite show very low radiometric

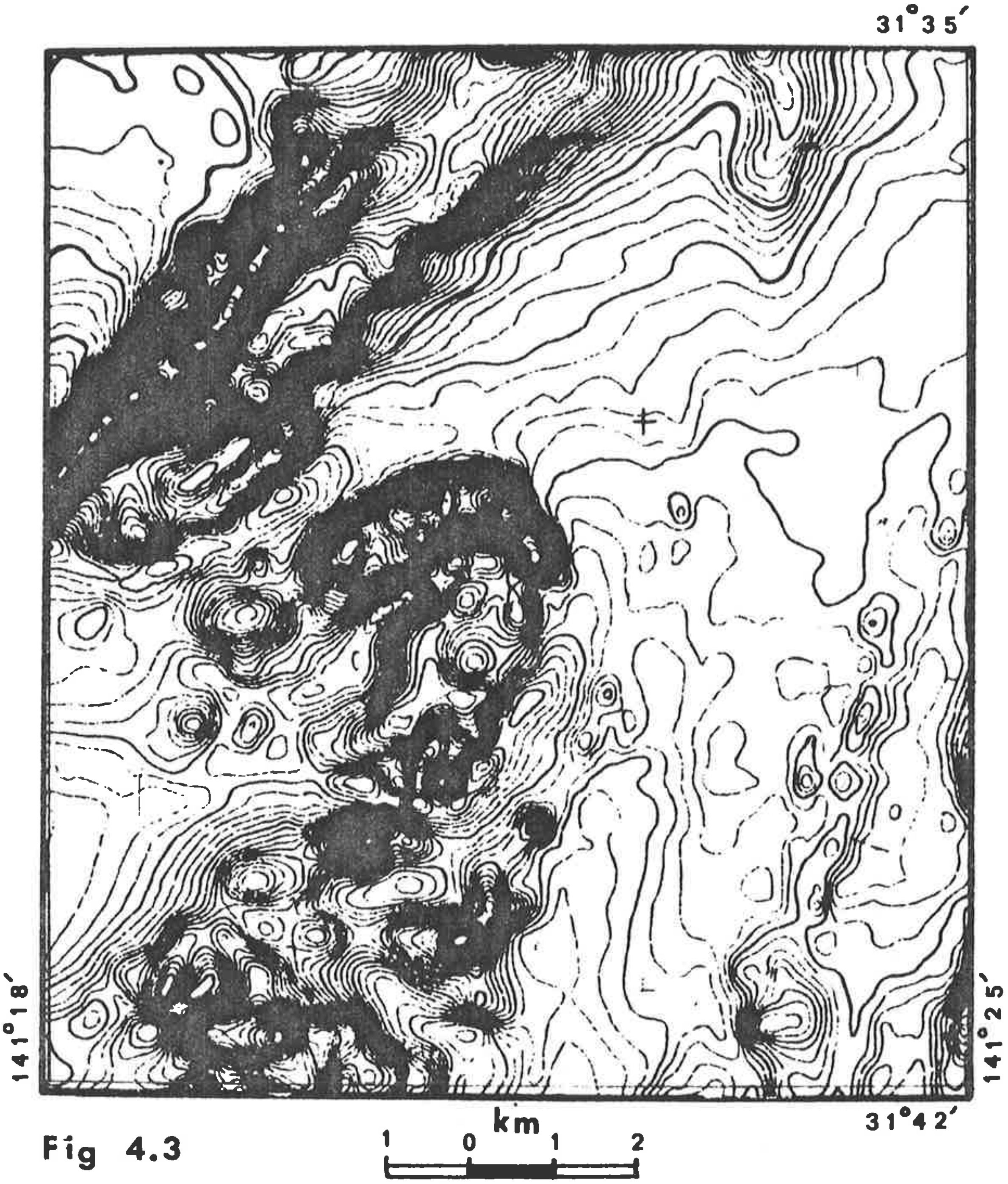


Fig 4.3

TOTAL MAGNETIC INTENSITY

OF THE

MOUNT ROBE AREA

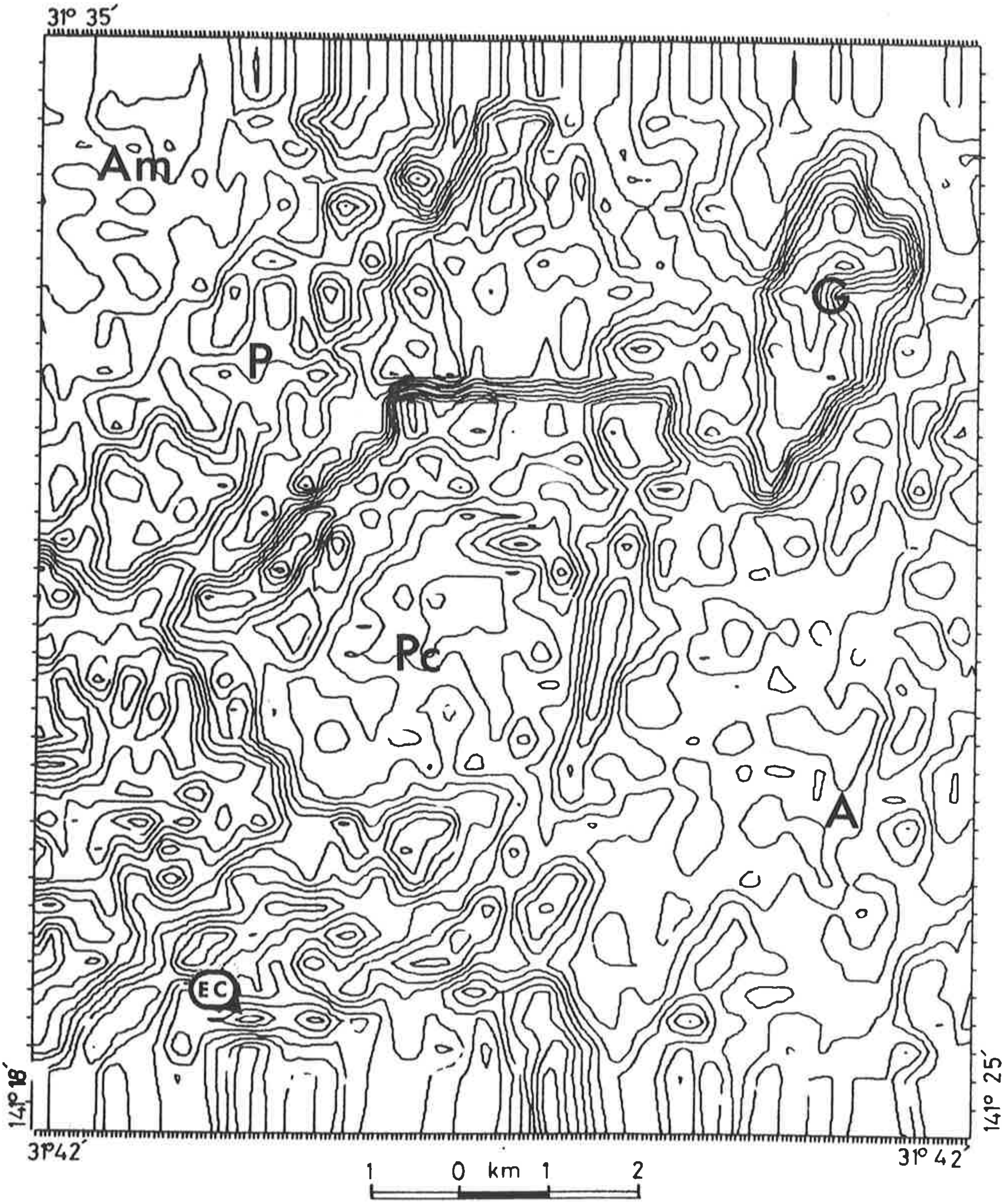


Fig. 4.4

MOUNT ROBE AREA

Total count, contour interval 10 counts per second.

Fig. 4.5

MOUNT ROBE AREA

Potassium, contour interval 2 counts per second.

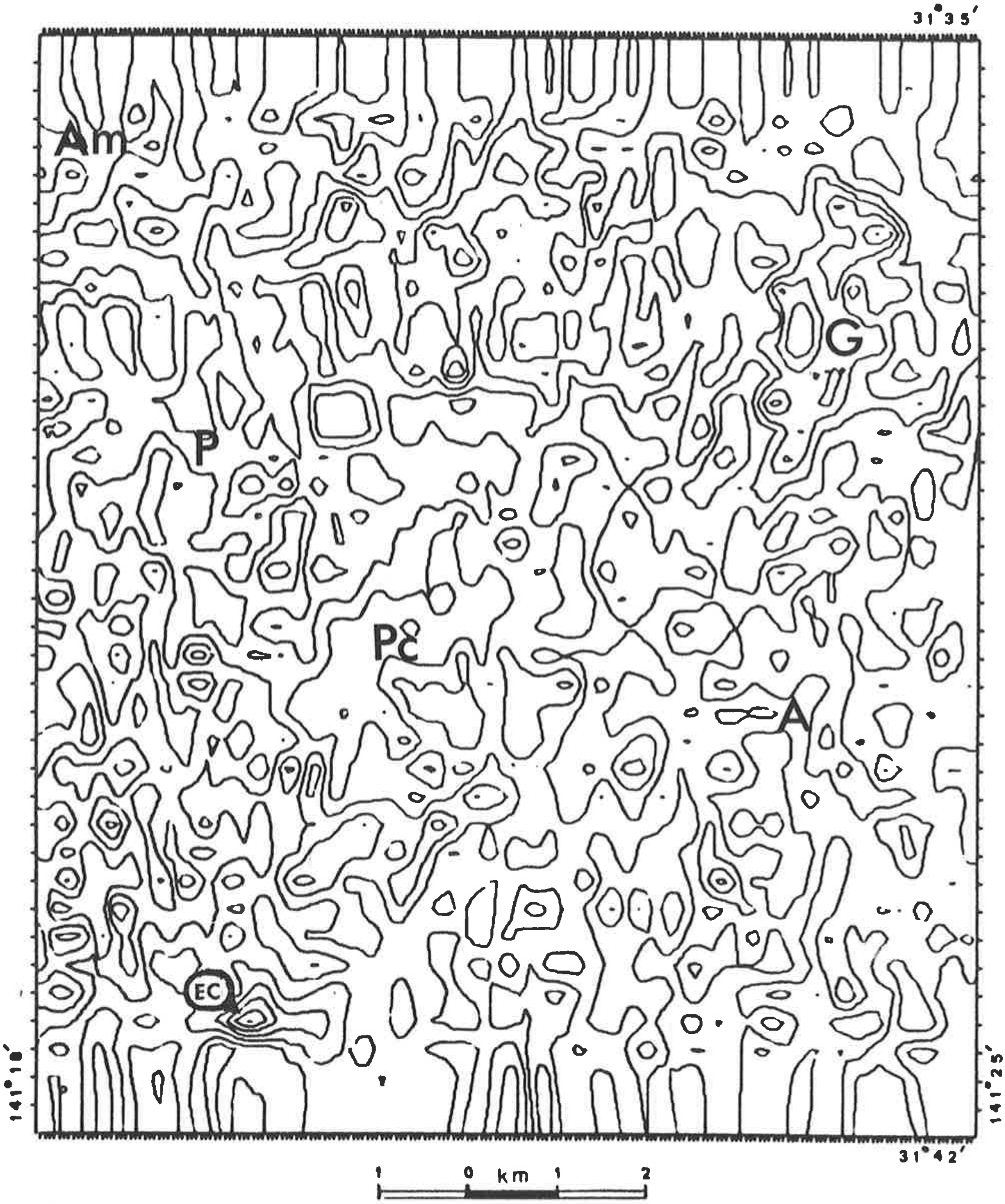


Fig. 4.6

MOUNT ROBE AREA

Uranium, contour interval 2 counts per second.

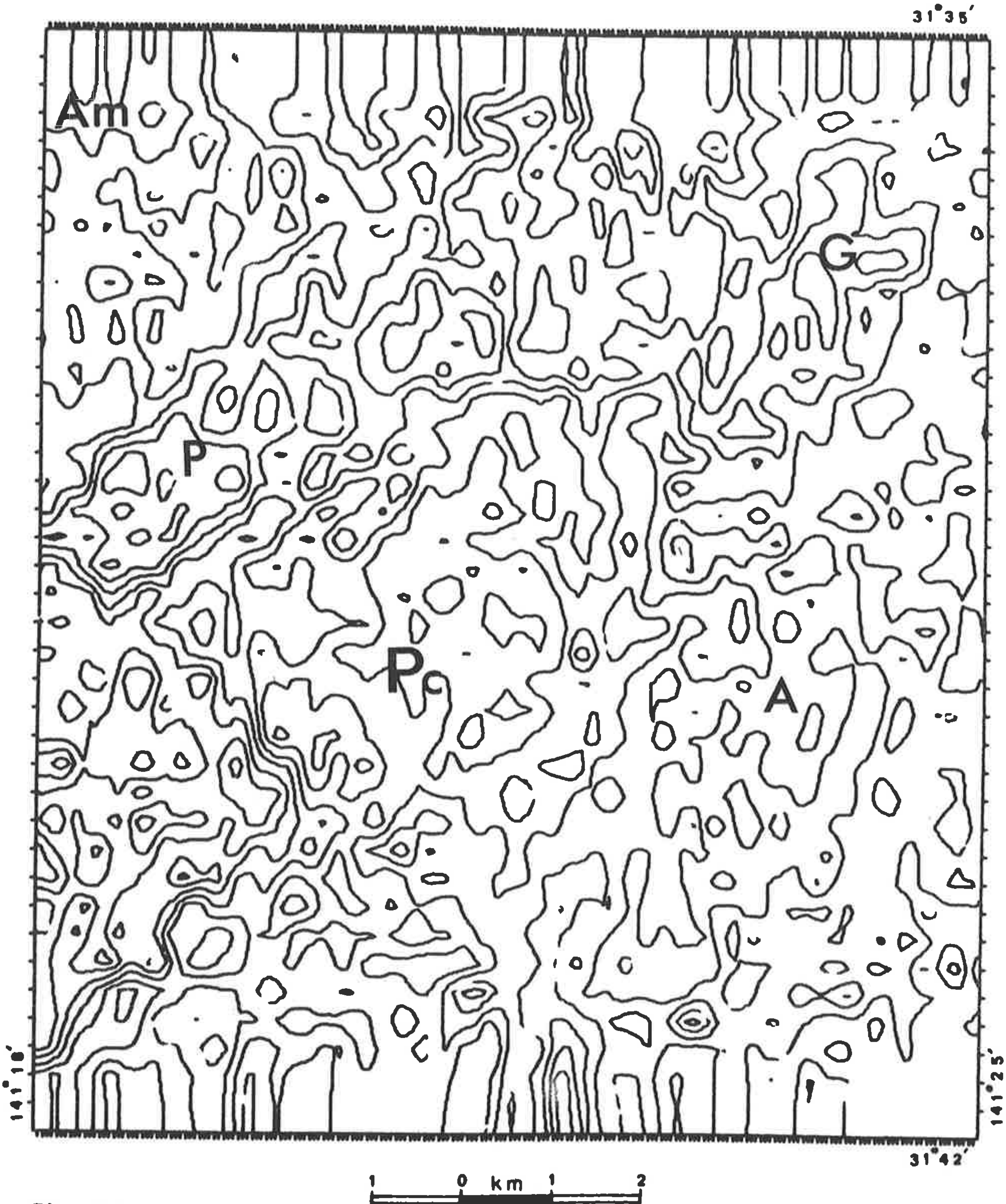


Fig. 4.7

MOUNT ROBE AREA

Thorium, contour interval 2 counts per second.

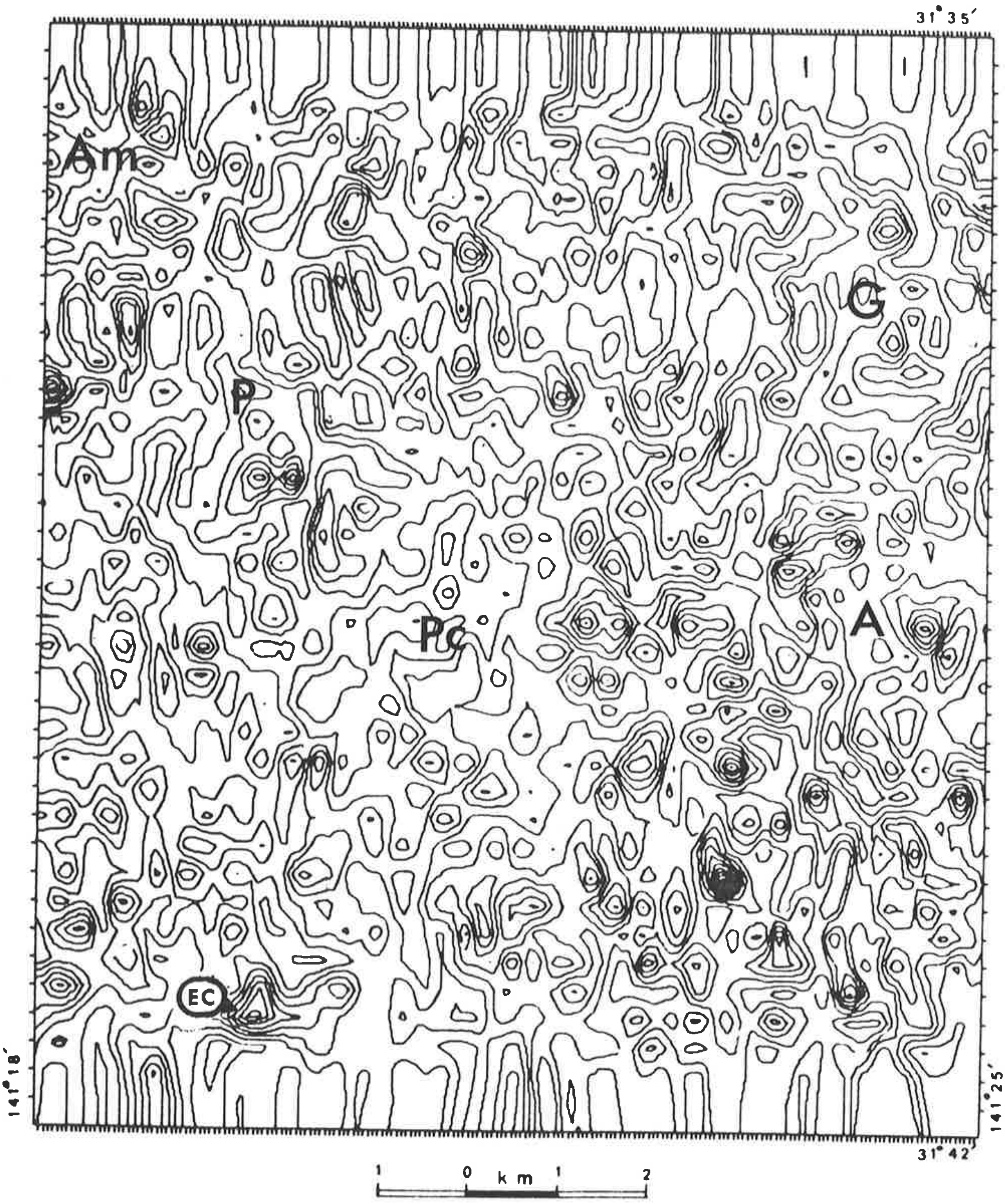


Fig. 4.8

MOUNT ROBE AREA

Uranium:Potassium ratio, contour interval 0.05

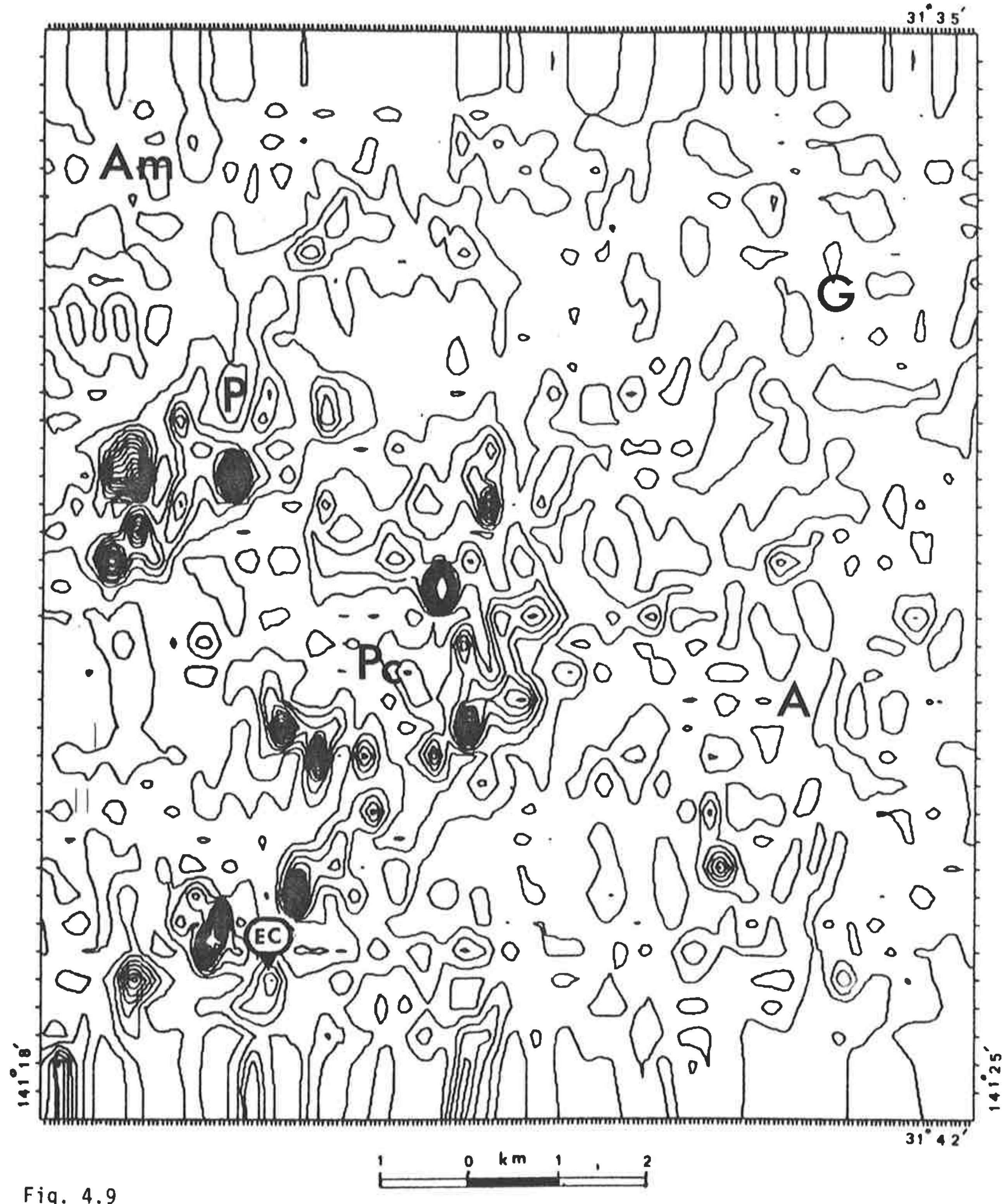


Fig. 4.9

MOUNT ROBE AREA

Uranium : Thorium ratio, contour interval 0.5

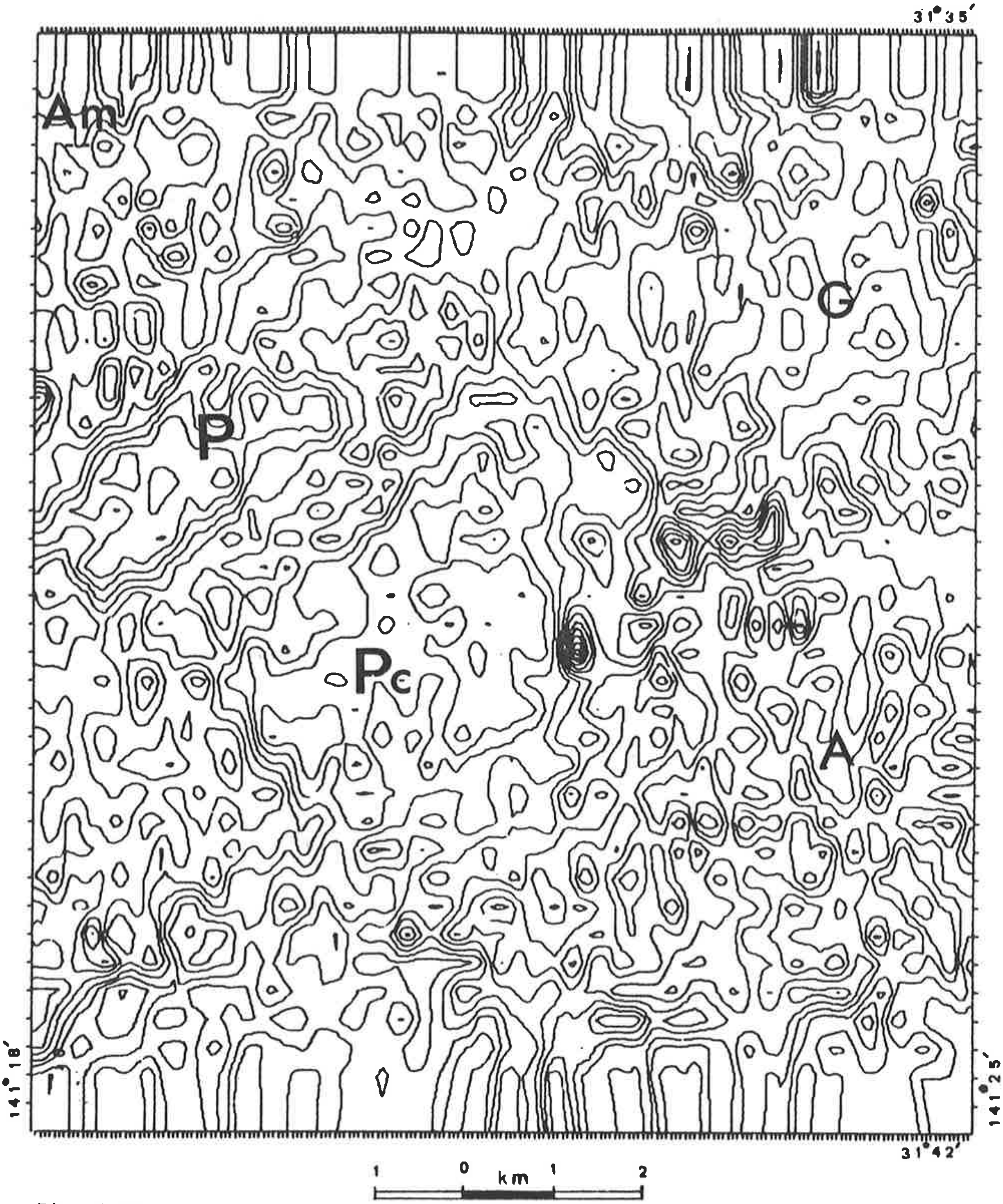


Fig. 4.10

MOUNT ROBE AREA

Thorium:Potassium ratio, contour interval 0.05

response. Markedly low radioactivity, associated with the amphibolites, is possibly due to their characteristic basic chemical composition (Table 2.1). The amphibolites in the area contain higher portions of ferromagnesium minerals, i.e. two-thirds hornblende and one-third felsic minerals. There is no definite correlation between the more magnetic lithologies and the zones of higher radioactivity. However, the trends defined by the radiometric zones do parallel some gross magnetic features.

Fig. 4.4 shows the contour map (total count) of the area. The correlations with the geology (Fig. 4.2) are fairly good. In particular, the limits of the Mundi Mundi granite (G), and to some extent, of pegmatites (P & Pc) are easily followed.

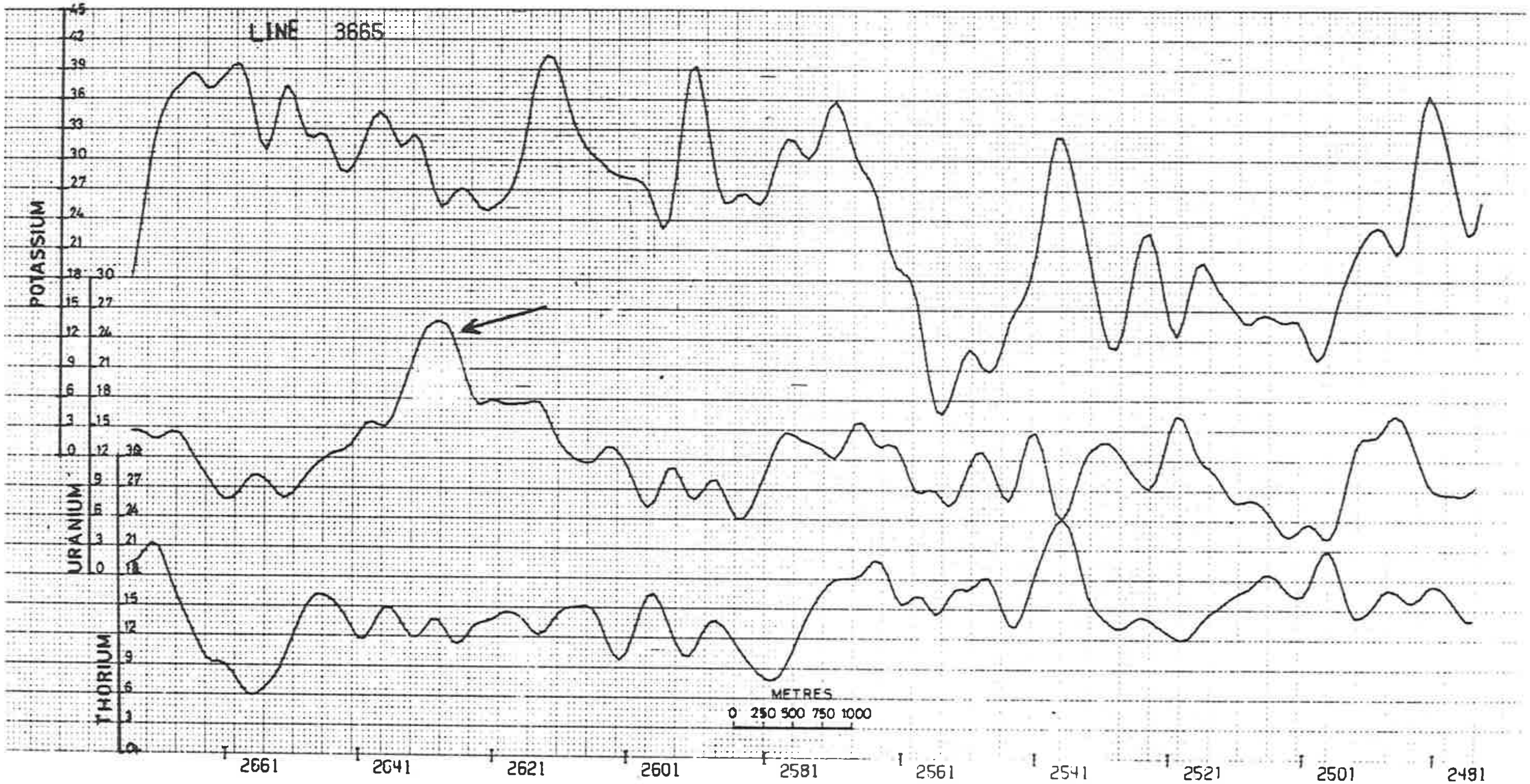
The magnetic map of the area is shown in Fig. 4.3. The magnetic map contains a flat area with strong anomalies in the northwestern and central parts of the area. The flat area coincides with moderate radiometric count. The magnetic and radiometric borders follow each other closely. The pegmatites, in parts, are magnetic.

The abundance ratio provides a means of filtering count-rate anomalies besides recognising unusual radioelement distribution where high-count rates may not occur. Uranium to thorium ratio (Darnley, 1973) is generally more specific for potentially economic uranium deposits than is the uranium to potassium, although the latter provides a wider target halo. Fig. 4.9 is a uranium to thorium ratio contour map of the Mount Robe area. The ratio anomalies appear to be uniform and relatively constant in their distribution in the northern and southwestern parts of the area occupied by the outcrops of the Mundi Mundi granite, and the Willyama Complex mainly consisting of phyllite, slate, quartzite and schist. No statistically significant above-average ratio anomalies are observed over the granite. Over other rock types, one anomaly (EC) which lies in the southwestern part of the map is caused by the uranium mineralisation in the Eldee Creek Shear Zone. Some small ratio anomalies in the northwestern and southwestern parts of the area may be due to similar causes. These anomalies overlie the drainage and are possibly due to the concentration of heavy minerals washed down from the nearby rocks, transported and deposited along the creeks. They are patchy and follow the creeks.

In the western, central and southwestern parts of the area, there are at least more than fifteen very strong above-average ratio (average ratio = 0.92) anomalies. When compared with uranium and thorium channel contour maps, it is observed that in fact uranium does not go up but thorium goes down. Another cause, possibly, is that the outcrops are very limited in these areas which could be responsible for higher uranium to thorium ratio. As said earlier in this section, the abundance of K, U and Th radioelements remain relatively constant over a wide range of rock types, it is rather an unusual situation.

An inspection of Fig. 4.8 (uranium to potassium ratio contour map) shows the distribution of ratio anomalies. The maximum, minimum and average ratios are 0.6, 0.03 and 0.2 respectively. The Mundi Mundi granite (G) shows slightly greater than above-average ratio anomalies in patches. The felsic rocks (granite, syenite) are more radioactive than mafic and ultrabasic rocks (Table 3.1). The primary reason is the greater abundance of potassium feldspar in felsic rocks. Also, increased mica (muscovite and biotite) content can increase the radioactivity of the rocks. As mentioned earlier in Section 4.2, the Mundi Mundi granite contains a higher percentage of muscovite, therefore it is more likely that these patchy anomalies are possibly related to the outcrops of the granite with local concentration of radioactive elements. The pegmatites exhibit less than average ratio which is flat but constant in distribution. The Eldee Creek uranium mineralisation (EC) stands out prominantly on the ratio map. The sporadic, strong and above-average ratio anomalies in the northwestern and southeastern parts overly the drainage. These ratio anomalies are perhaps due to the concentration of black sands (heavy minerals) derived from the adjacent outcrops and concentrated along the creek beds.

Fig. 4.11 Spectrometer stacked profiles for K, U and Th along flight line No. 3665 showing uranium anomaly over the Eldee Creek (EC) area.



LINE 3665
POTASSIUM
URANIUM
THORIUM
METRES
0 250 500 750 1000
2661
2641
2621
2601
2581
2561
2541
2521
2501
2481

Fig. 4.11

Spectrometric studies over the Mt. Robe area shows the variation in lithology. Although the complex structure and overburden present in the area do not allow to delineate the boundaries between various rock types, even then the results obtained represent a better picture of the area. There is a great remarkable similarity between the total count and potassium contour maps (Figs. 4.4 and 4.5). In both the maps the strong gradient around the boss of the Mundi Mundi granite (northeastern part, G) and encircling the central pegmatite body (Pc) shows their contact with the alluvium. Radiometric lows around the central pegmatites are related to the exposures of amphibolites. In the northern part of the map (Fig. 4.4) the anomalies generally trending N-S are possibly associated with the exposures of bands. Fig. 4.5 shows that the sillimanite schists in the southwestern part of the map are more potassic and lead to suggest that they were derived from sediments rich in kaolinitic matter as described by Glen (1978). An abrupt change in radiometric response in the northwestern part (Fig. 4.4) is related to the change in lithology and rock exposures. This radiometric change seems to follow the Mundi Mundi fault scarp (border between Am and P). The similar feature is also observed in the potassium channel (Fig. 4.5). A group of anomalies, in the figures just mentioned, present in the southwestern part of the maps are related to the outcrops of sillimanite schist which contain more K-feldspar than other schists present in the area.

An inspection of Fig. 4.10 shows a number of small anomalies around the central pegmatite (Pc). Although the anomalies are not distinctly sharp and strong, their presence shows that this pegmatite may have some bearing on the rare earth's mineralisation.

EVALUATION OF RADIOMETRIC ANOMALIES

The moderate radioactivity (less than 2 x stistical noise) generally overlies the northeastern, northern, western and southwestern parts of the Mount Robe area. The radioactivity is due to the outcrops and topography. Only one positive radiometric anomaly, due to uranium was established which lies in the southwestern corner of the area (Fig. 4.2). This uranium anomaly (EC) was picked from uranium profiles along flight line No. 3665 (Fig. 5.11), U/K ratio contour map (Fig. 4.8) and U/Th ratio contour map (Fig. 4.9). The anomaly did not show up in the total count anomaly map (Fig. 4.2, overlay 2) or the total count contour map (Fig. 4.4).

The only aerial significant uranium anomaly in the area is due to secondary uranium mineral, autunite, in schist confined to a shear zone as reported by Rayner (1957). Rayner also named the shear zone as the Eldee Creek Shear. The shear zone trends NE-SW and is of variable thickness from a few inches to 20 feet. The zone is occupied by grey biotite-quartz schist with iron-stained patches. The schist seems to be transgressive and cuts the surrounding rocks, amphibolites, quartz tourmaline rock and pegmatites. Quartz veins are common in the shear zone.

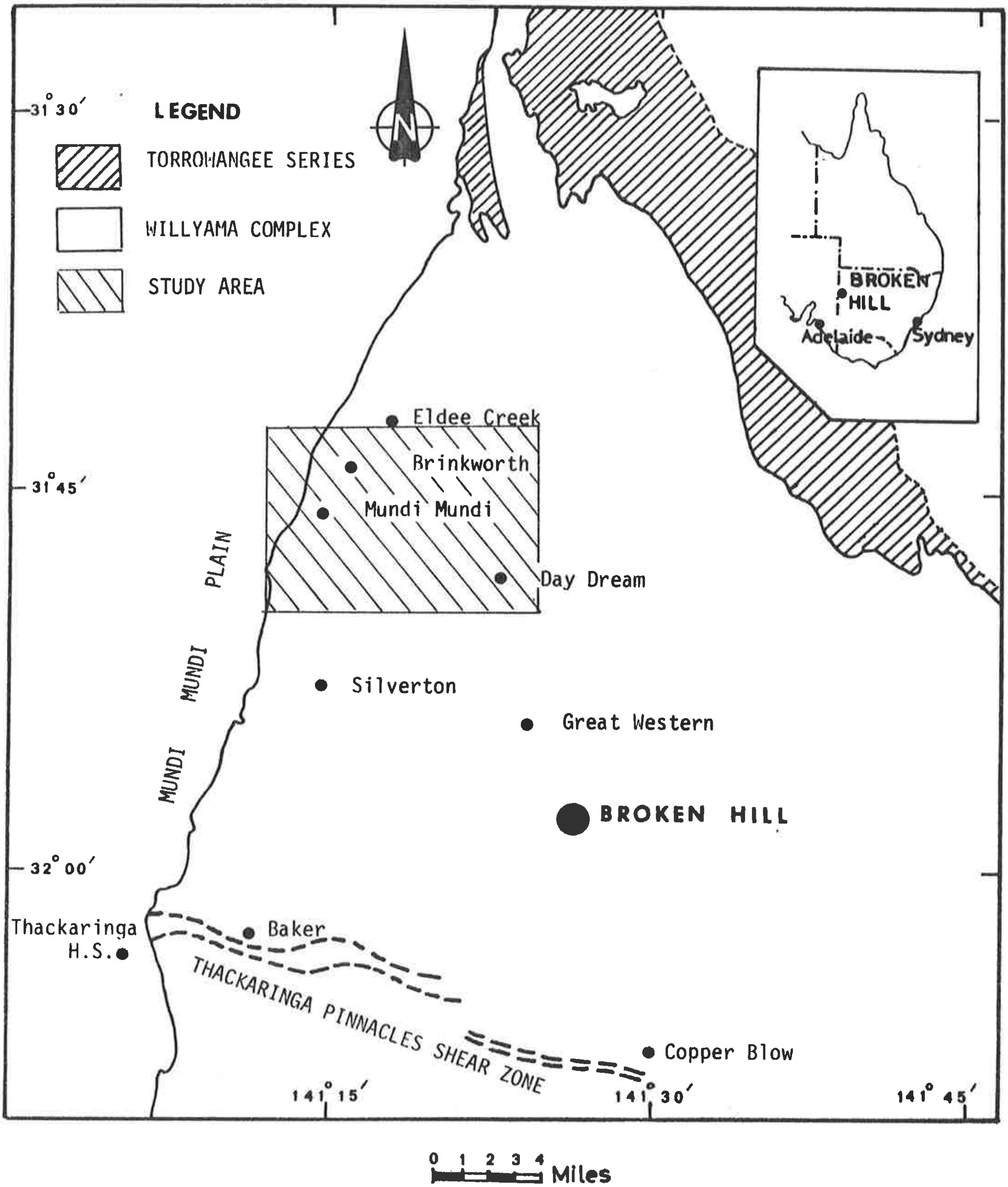
Edwards and McAndrew (1954) carried out the mineragraphic studies of the schist. According to them, "a slightly weathered biotite-quartz schist, the biotite partially bleached and discoloured by limonite, the quartz partly as grains showing strain and fracturing and partly as microcrystalline aggregates drawn out parallel to the schistosity as a result of recrystallisation during shearing. Limonite minerals have partially replaced quartz and form narrow sheets along the cleavage of biotite". The accessory minerals identified by them were mica, tourmaline, iron oxide, apatite, a titanium dioxide (anatase or brookite). The autunite occurs along ironstained cracks oblique to the schistosity. Assays of the autunite-bearing schist (Rayner, 1957) are in the order of 0.2 percent U_3O_8.

A radiometric ground survey could not delineate a continuation of the radioactive mineralisation due to increasing thickness of the overburden. Radioactivity higher than normal radioactivy, due to uranium in the schist, was recorded over the ironstained patches of the schist.

Secondary uranium mineralisation (autunite) in iron-stained patches within the schist could possibly be due to absorption of uranium by iron oxide as described by Lovering (1955) that uranium minerals in an oxidising sulphide environment, go into solution in acid sulphate waters as uranyl sulphate, in the presence of ferric sulphate. When these acid waters are neutralized, ferric sulphate hydrolises to form colloidal ferric oxide hydrate. This absorbs the uranyl ion and removes most of the uranium from the solution. As the colloidal ferric oxide hydrate ages, it crystallizes to form goethite, and in this process most of the uranium is expelled to form particles of secondary uranium minerals in the resulting limonite.
The occurrences of iron oxide containing small percentages of uranium are widespread (McKelvey, et al. 1956). Uranium-bearing iron oxides from the shear zone of Bihar, India, have been reported by Karkhanavala (1958) where rich deposits of copper sulphides, apatite-magnetite and uraniferous mineral veins occur along the Singhbhum Shear Zone, in Bihar, India and secondary uranium minerals associated with hematite have been observed.
As said earlier that the quartz veins are common throughout the Eldee Creek Shear Zone. The lowest radioactivity in all channels (Total count, potassium, uranium and thorium) was recorded over these quartz veins. No primary uranium minerals were observed to be associated with them.
The maximum radioactivity registered was slightly greater than three times the normal background radioactivity. The pegmatites in this area are barren as far as radioactivity is concerned.

CHAPTER 5

MUNDI MUNDI - MOUNT FRANKS AREA



LOCALITY MAP

Fig. 5.1

CHAPTER 5

DETAILED AIRBORNE SPECTROMETRIC STUDIES IN THE MUNDI MUNDI - MOUNT FRANKS AREA

5.1 Introduction

5.1.1 Location

Fig. 5.1 is a locality map of the study area comprising approximately about 115 square miles. It is situated 18 miles northwest of Broken Hill City and lies between longitudes 141°12' and 141°25' E and latitudes 31°42' and 31°50' S.

5.1.2 Physiography

The area represents varying physiographic features, from smooth plains through the rolling hills to highly rugged and rough hills. It typically shows semiarid vegetation comprising mulga, dead finish, beefwood and ever-present saltbush, whereas the creek beds support the vegetation of gum trees. Because of paucity of vegetation the good rock exposures are present in the central and western parts of the area.

The western part of the area across the Mundi Mundi Fault scarp is occupied by a smooth plain known as the Mundi Mundi Plain. The central part lying between the Mundi Mundi Fault scarp and the Mount Franks Shear Zone comprises highly rugged and rough ridges. The ridges generally run from south to north, i.e. from Umberumberka Dam through Mundi Mundi Trignometric Station and thence north. The eastern part across the Mount Franks Shear Zone is an area which consists of hills of low to moderate height with alluvial plains between them.

The country is well dissected by four major creeks; the Eldee Creek, the Mundi Mundi Creek, Stephens Creek and Lakes Grave Creek. These creeks are not permanent and flow only after heavy rain.

5.2 Geology

Fig. 5.2 is a geological map of the Mundi Mundi-Mount Franks area which shows the distribution of the Willyama rocks and the Cainozoic deposits.

In the Mundi Mundi area the rocks belong to the Mundi Mundi Group (Andrews, 1922). They form highly rugged and rough ridges passing from Umberumberka Dam through the Mundi Mundi Trignometric Station and thence north. The area has been mapped in detail by Glen and Laing (1975). The Willyama Complex, in the Mundi Mundi area (Glen, 1978), consists of a thick sequence of andalusite schists passing eastwards into quartzites with interbedded andalusite schists. These sequences are underlain by sillimanite schists to the west and to the east they are faulted against the sillimanite schists. Repetition of beds due to close folding is frequent. The rocks are excellently exposed.

In the Mount Franks and Apollyon Valley, to the east of the Mundi Mundi ruins, the rocks belong to the Great Western Basin of Andrews (Andrews, 1922; Glen, 1978; and Gustafson, et al. 1950). Here, the sediments are an alternating sequence of andalusite + biotite + muscovite + quartz schist (pelite) and quartz + muscovite + biotite + garnet + andalusite quartzite (psammite) (Glen and Laing, (1975)). Sillimanite is also common here. It is difficult to make the correlation due to recumbent folding. Sedimentary structures such as ripple marks, graded bedding, cross bedding, flame structures are well preserved. Bold and massive outcrops form rugged and rough ridges which run from north to south. The outcrops are fairly good in this area.

To the east of the Mount Franks Shear Zone there is a zone which comprises the thin alternating beds of schist and quartzite with rare sillimanite but in which mica, feldspar, and chloritoid minerals are well developed. Garnet is only developed along the contact zones of certain pegmatite sills. The rocks have been closely folded with the production of corrugated basins and arches which cause difficulty in mapping. The rocks have been affected by pronounced movements of crushing and faulting. Large sills of amphibolite, augen gneiss, pegmatite and granite are present throughout the zone. Cross-cutting dykes of granite and dolerite are also common. The whole zone represents a scene of an "igneous complex". The rock exposures are generally very poor in this zone.

In the central and western parts of the study area, numerous and large sills of amphibolites, pegmatites and granites, together with cross tongues of granite, are common associates of the Willyama metasediments. Pegmatites are in the form of discontinuous lenses and the amphibolite is of the spotted variety. The granite is leucocratic fine to medium-grained and is of Mundi Mundi type.

From a metamorphism viewpoint the whole area falls within the low-grade of metamorphic Zone A of Binns (Binns, 1964).

5.3 Cainozoic Geology

An inspection of Fig. 5.2 reveals that the western part of the area across the Mundi Mundi Fault is occupied by the Mundi Mundi Plain. The thickness of the Quaternary deposits in the Mundi Mundi Plain exceeds 500 feet as shown by drilling and the magnetic contour map. The sediments consist mainly of iron-stained fine to medium-grained subrounded clear to opaque quartz in a white to yellow silty kaolinitic matrix. The eastern portion of the map is filled with alluvium transported by the creeks flowing in that part. The alluvial cover consists of fine to medium-grained sediments, in places being silty to clayey. The colour varies from yellow to grey.

In the central part of the area the occurrence of outcrops of Willyama rocks is good. The residual overburden adjacent to the outcrops is a common feature in this area. The thickness of the overburden ranges between 1 and 5 feet. The presence of the overburden has not merely obscured the bedrocks but has also affected the radioactivity of the bedrocks. The radioactivity decreases with the increasing thickness of the soil cover.

Fig. 5.2 (cont'd)

Legend (cont'd)

17 Main road

18 Track

19 Creek

H.A.A. = High Amplitude Anomaly

M.A.A. = Medium Amplitude Anomaly

Overlay - 1 Flight line system

Overlay - 2 Total count anomaly map

Overlay - 3 Potassium anomaly map

Overlay - 4 Uranium anomaly map

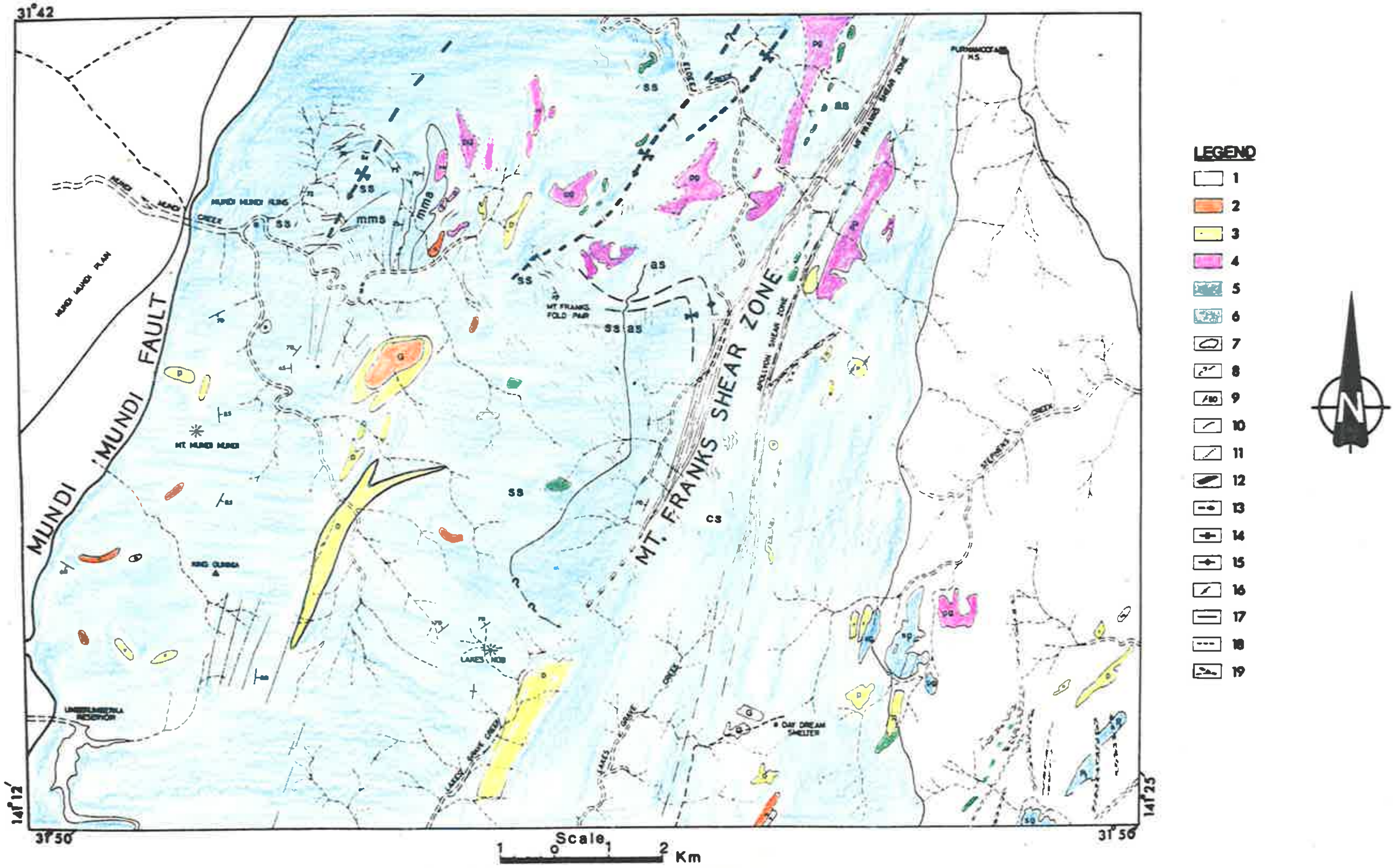
Overlay - 5 Thorium anomaly map

Source of data - geology simplified after Glen (1978).
Radiometrics compiled from a study of the original airborne spectrometer survey data digitally recorded on magnetic tapes. Aeromagnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W., B.M.R. survey, 1975.

Fig. 5.2 Geology of the Mundi Mundi-Mt. Franks area and aeroradiometric anomalies.

Legend

1 Alluvium
2 Granite
3 Pegmatite
4 Granitoid (pegmatite & granite)
5 Amphibolite
6 Willyama Complex consisting of:
  ss = sillimanite schist
  sg = sillimanite gneiss
  as = andalusite schist
  cs = chiastolite schist
  P_1 - potosi gneiss
7 Boundary of outcrop
8 Probable boundary of outcrop
9 Dip & strike of schistosity
10 Trend mapped
11 Trend, photo interpretation
12 Shear zone
13 Fold with plunge
14 Syncline
15 Anticline
16 Pegmatite dyke

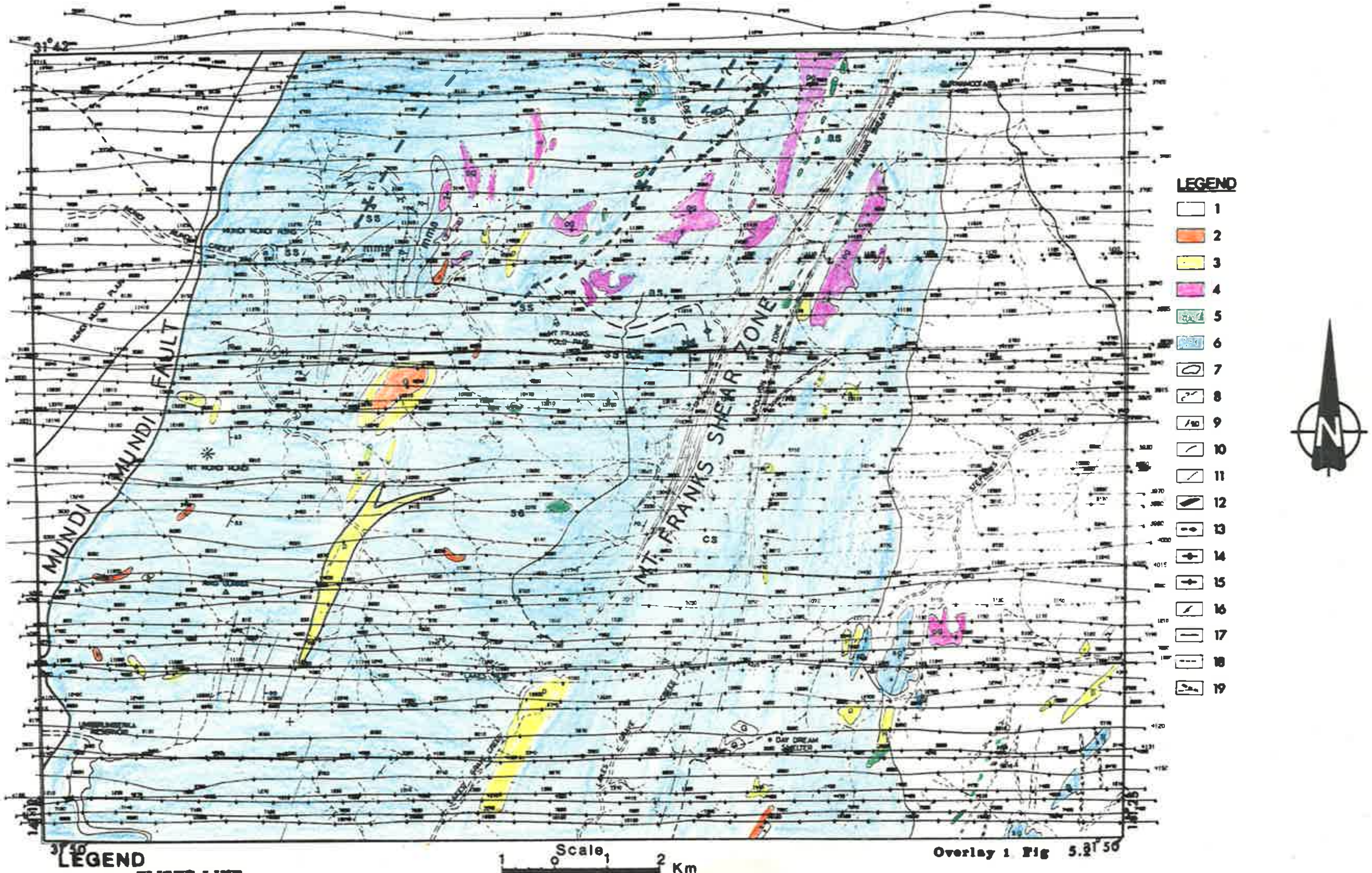


GENERALIZED GEOLOGY

OF THE

MUNDI MUNDI—MOUNT FRANKS AREA

Fig 5.2



LEGEND

4040 ______ FLIGHT LINE NUMBER

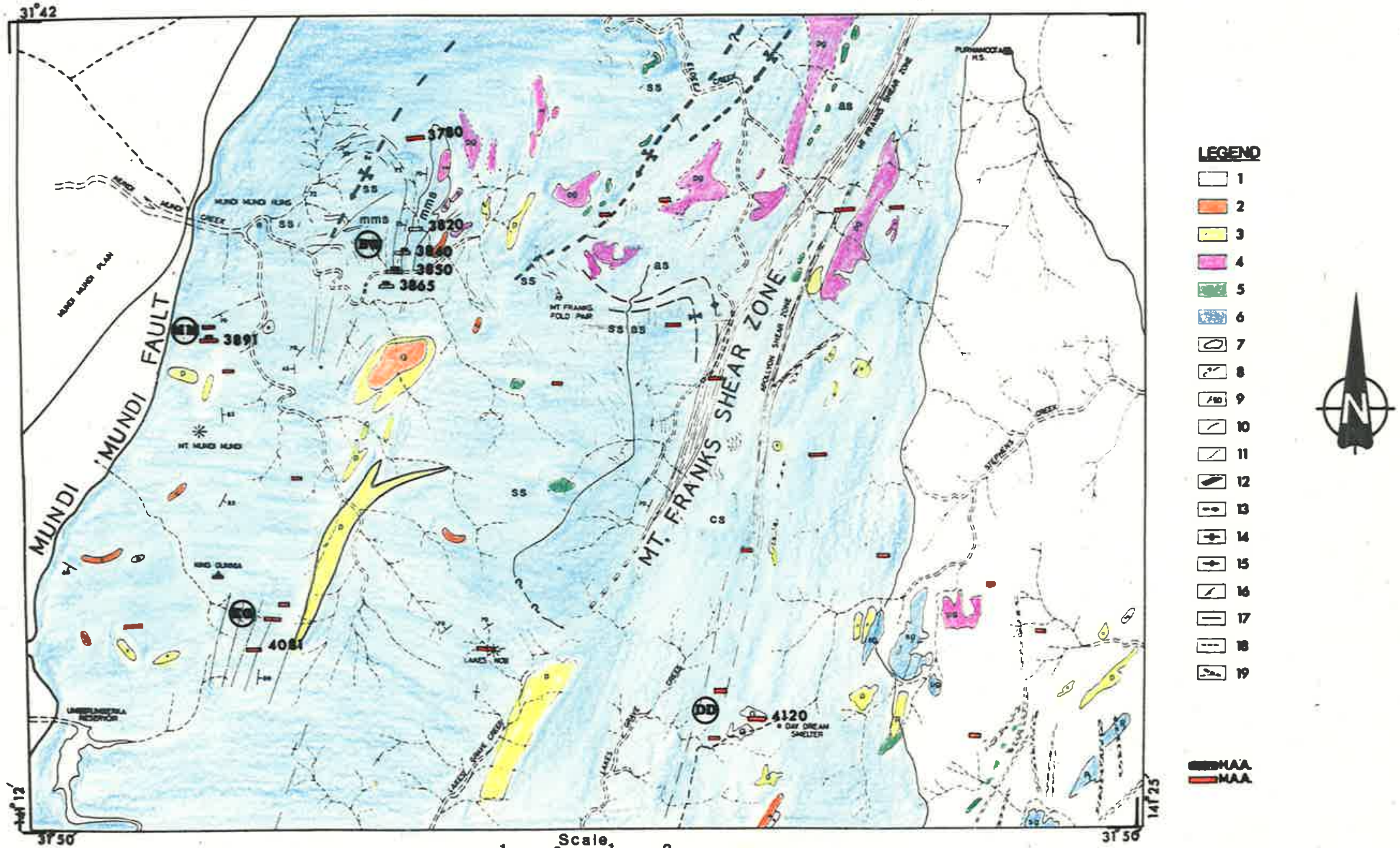
6850 ______ FIDUCIAL COUNT

GENERALIZED GEOLOGY

OF THE

MUNDI MUNDI—MOUNT FRANKS AREA

Fig 5.2



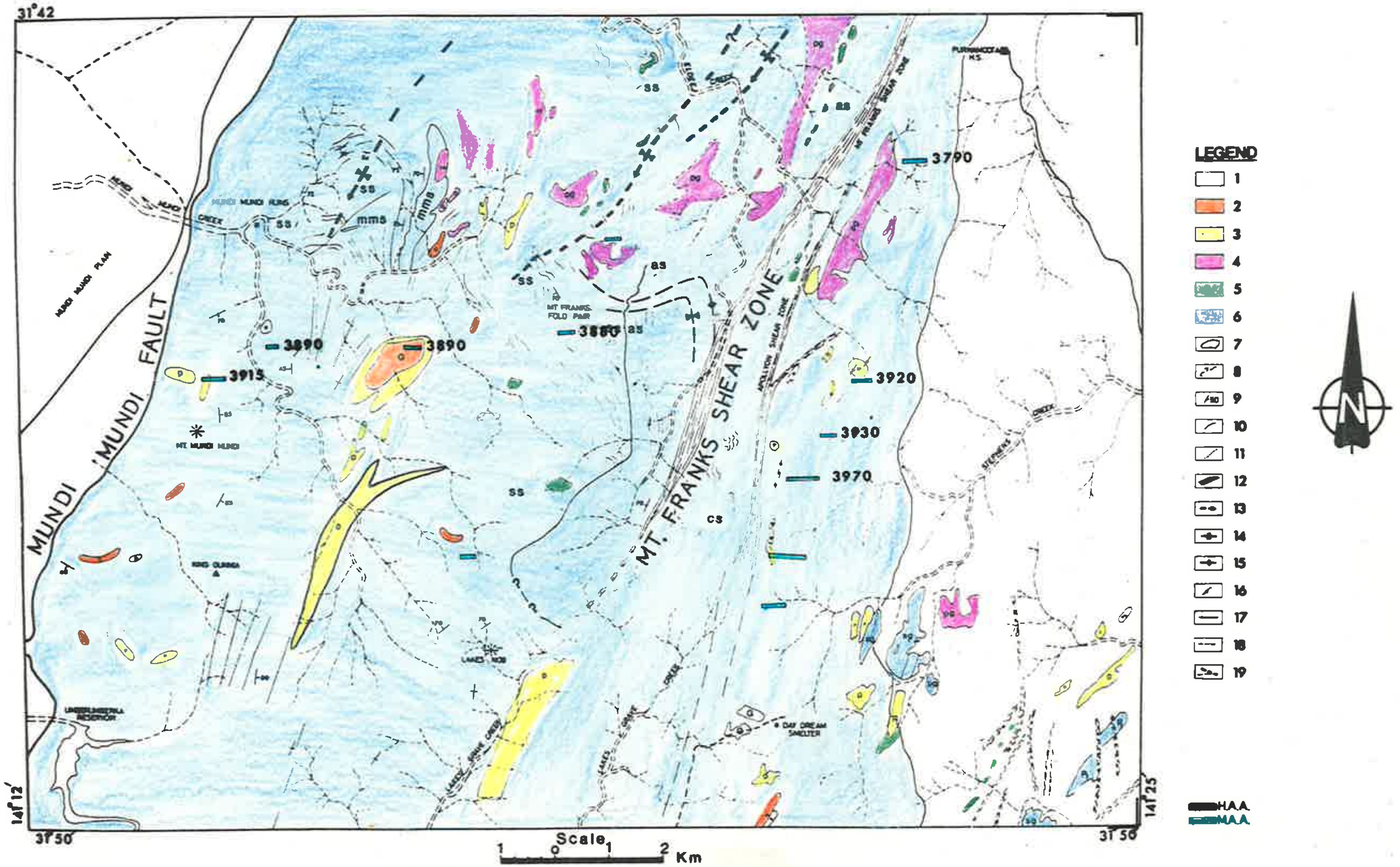
GENERALIZED GEOLOGY

OF THE

MUNDI MUNDI—MOUNT FRANKS AREA

Fig 5.2

Overlay 4 Fig 5.2 URANIUM



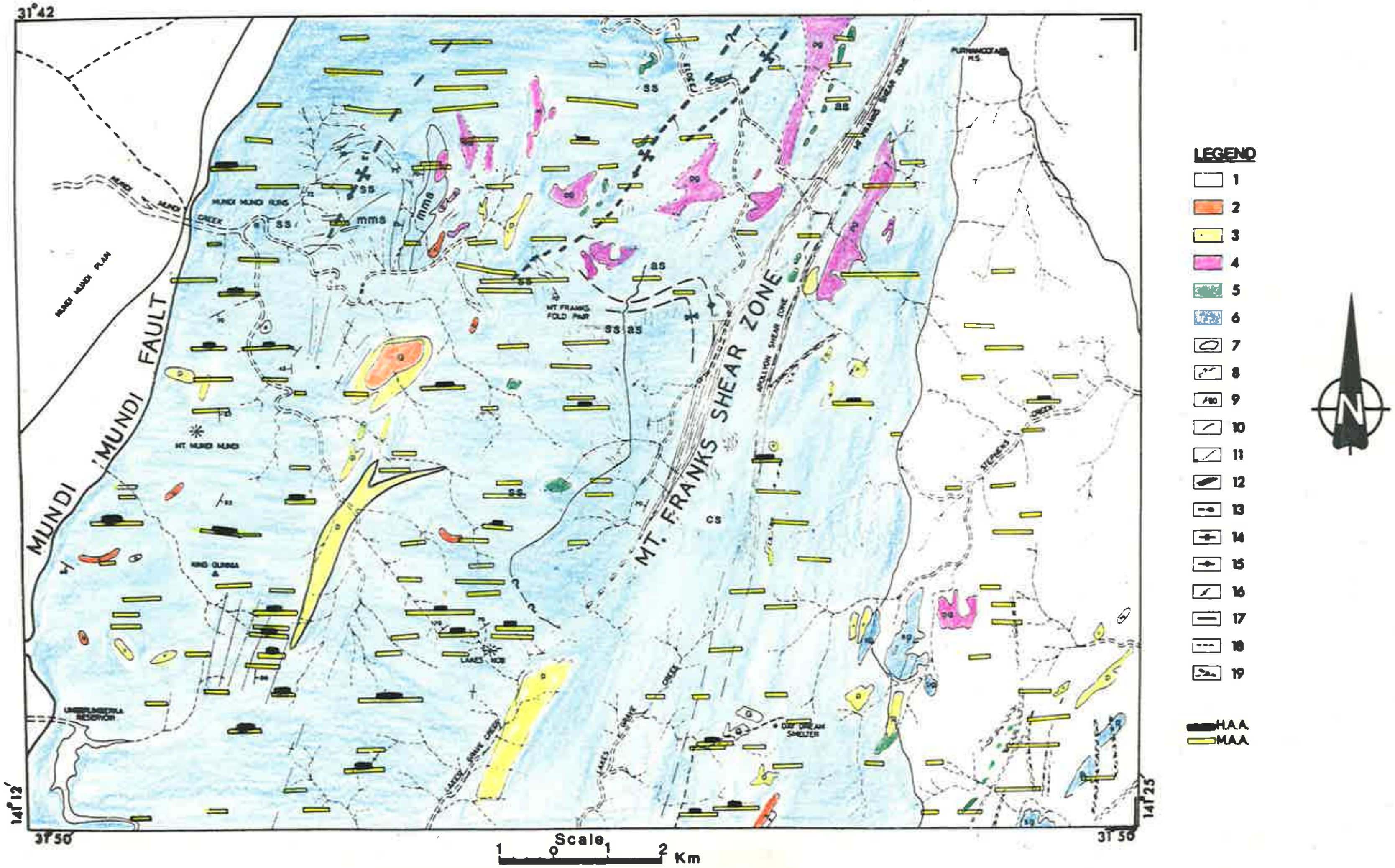
GENERALIZED GEOLOGY

OF THE

MUNDI MUNDI—MOUNT FRANKS AREA

Fig 5.2

Overlay 5 Fig 5.2 THORIUM



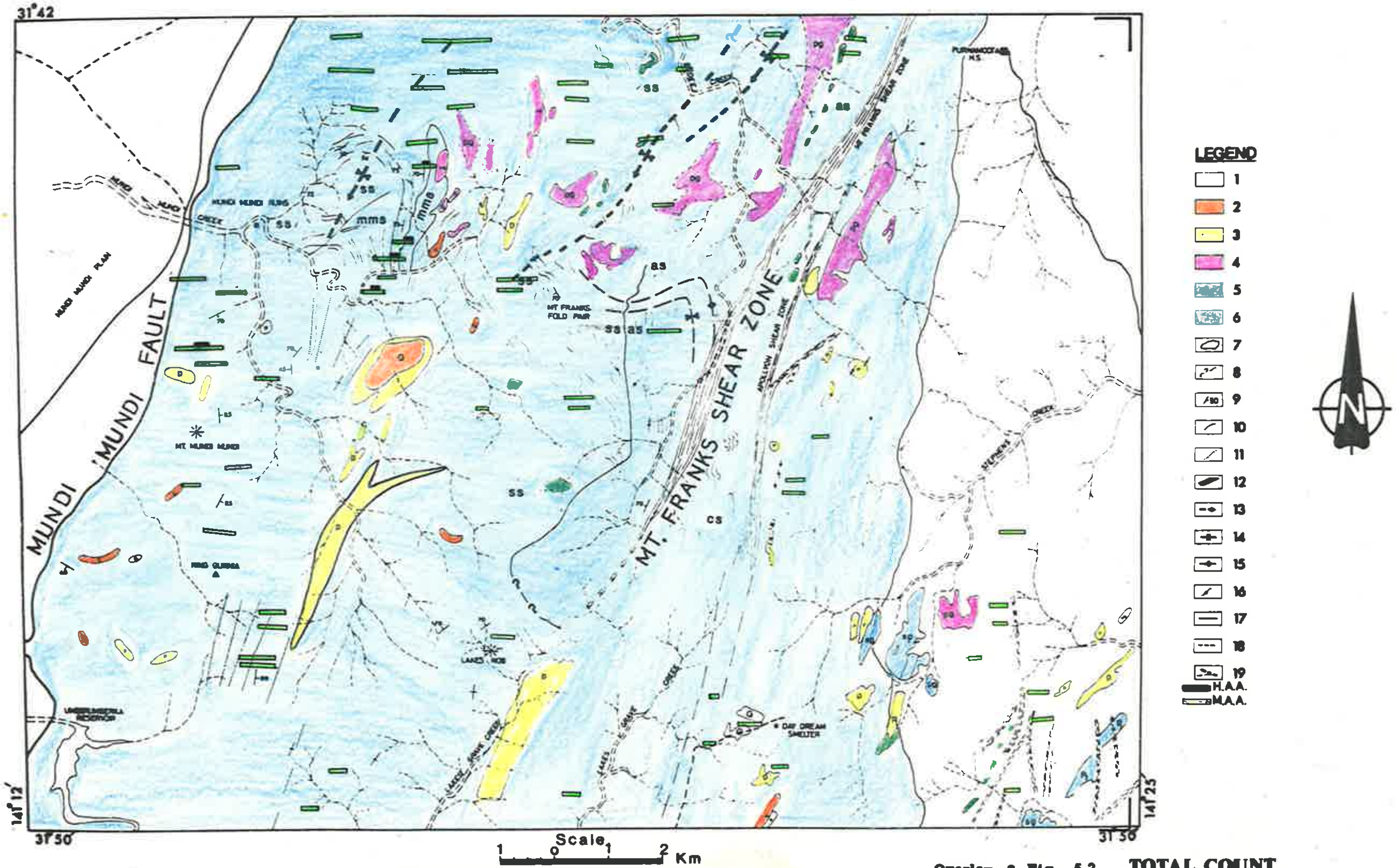
GENERALIZED GEOLOGY

OF THE

MUNDI MUNDI—MOUNT FRANKS AREA

Fig 5.2

Overlay 8 Fig 5.2 POTASSIUM



GENERALIZED GEOLOGY
OF THE
MUNDI MUNDI—MOUNT FRANKS AREA

Fig 5.2

Overlay 2 Fig 5.2 TOTAL COUNT

5.4 Spectrometric Studies

5.4.1 Processing and presentation of data

The processing of airborne spectrometer survey data related to the Mundi Mundi-Mount Franks area is similar to that which has been described in Chapter 4 and Appendix 2.

For detailed studies, the geological map, profiles along flight lines (for various channels and ratios) and flight path maps were drawn at 1:25,000 scale.

The anomaly maps for four channels were prepared by plotting the anomalies from the computer-drawn profiles along flight lines showing their widths (at half anomaly amplitude) and intensity of radioactivity as amplitude. The anomalies have been shown as high, medium or low amplitudes rather than counts per second, overlays (Fig. 5.2). The anomalies and levels of radioactivity were calculated against the noise level of normal radioactivity over the geologic units. The anomalies have been called the high amplitude, medium amplitude and low amplitude and were calculated as 3 or > 3 X noise level, 2 X noise level and 1 X noise level respectively.

Isles (1978) established a computer-drawn format for displaying airborne gamma-ray spectrometer, magnetometer and radio altimeter profiles of which Figs. 5.4, 5.5 and 5.6 are examples. This is fully corrected data. The corrections such as background subtraction, height correction, energy stripping and filtering were applied by the B.M.R. The corrected data were recorded on magnetic tapes which were acquired by the Department of Economic Geology, University of Adelaide in late 1977. The detail of processing of the airborne spectrometer survey data is given in Appendix 2. In these three examples three stacked profiles,each figure is shown all relating to the same flight line. The successive sampling intervals are shown as fiducial numbers along the flight line.

During the course of examination of the computer-drawn spectrometer profiles, it was observed that the high amplitude anomalies in all channels plotted along the flight lines (overlays, Fig. 5.2), are generally not quite sharp and hardly reach 3 X noise level of normal radioactivity in the study area. Low and moderate amplitude anomalies when compared with the geology of the area give a general idea about the distribution of radioactivity over various rock types. The low amplitude and less than moderate amplitude anomalies have been omitted in Fig. 5.2 to avoid congestion. The uranium anomalies were selected studying the spectrometer and ratio (U/K and U/Th) profiles along flight lines. The selected anomalies are shown after locality names (abbreviated) with their corresponding flight line numbers (overlay 4, Fig. 5.2).

5.4.2 Interpretation

The radiation to be recorded in airborne radiometric measurements comes from the layer consisting of the few uppermost inches of the overburden or bedrock exposures. Fig. 5.2 is a geological map of the study area. The area lying between the Mundi Mundi Fault and the Mt. Franks Shear Zone has a higher percentage of outcrop, 30% of the total area. The Mundi Mundi plain (north-western portion of the area) and the area south of Parnamoota Homestead are covered by the unconsolidated Cainozoic sediments. In the southeastern portion of the area the rock exposures are very limited.

The distribution of uranium, thorium and potassium in common rocks depends on several factors and can be described by criteria established by general rock types present in the area. Nearly all felsic rocks are more radioactive than mafic rocks. The primary reason is the greater abundance of potassium feldspar in felsic rocks. Two of the more common accessory minerals - monazite and zircon are radioactive and are generally confined to felsic rocks. Increased mica (muscovite and biotite) content can increase the radioactivity of the rock. While making the interpretation of radiometric response over the study area, the direct comparison of aeroradioactivity map patterns (all channels) with geologic map pattern was employed. Many geologic factors such as topography, lithology and soil were considered in evaluating the radiometric response. From an interpretative method viewpoint, the overlays for various channels were used for correlation with the areal geology which are shown in Fig. 5.2. The correlations with the geology are generally very good, particularly with the area lying between the Mundi Mundi Fault and Mt. Franks Shear Zone where the rocks are better exposed. Further, the rating of the anomalies was verified studying the ratio profiles plotted along the corresponding flight lines.

The overlays 2, 3, 4 and 5 of Fig. 5.2 show the radiometric response in the total count, potassium, uranium and thorium channels respectively. An inspection of overlays 2, 3 and 4 shows that the tract of higher radioactivity, due to total count, potassium and uranium generally occur over the Brinkworth (BW) and Mundi Mundi (MM) areas. In overlay 5 (thorium) the moderate radioactivity overlies a zone trending NE-SW in the eastern part of the map. During the examination of the channel overlays it was observed that the higher radiometric response, due to potassium and uranium was confined to different lithologies at different places. In the Brinkworth (BW) area the rock mainly consists of the Mundi Mundi carbonaceous subfacies as described by Glen (1978). This carbonaceous schist is of a dark, brownish-black, glossy and fine-grained schist, a good deal crumpled and with occasional crystals of chiastolite. The rock is well bedded in layers from half an inch to two inches thick, alternatively finer and coarser. The ground fabric is full of a black dusty material which is partly iron oxide, but partly carbonaceous matter. According to Browne (1922) the rock consists of 1.82 percent of carbon. Fine muscovite and biotite are also present as accessory minerals. The common associates of the carbonaceous schist are pegmatites, granitoids and granite. Other tract of higher radioactivity due to uranium and potassium, is related to the exposures of grey mica-quartz schist in the Mundi Mundi (MM) area. The radioactive schistose belt seems to be up to 100 feet wide and more than 1000 feet long. The schist is associated with gneisses, pegmatites and granite. A large granitic boss (central granite which cuts the pegmatite) crops out less than 2 miles to the east. The granites are of Mundi Mundi type described already in Chapter 2. Moderate levels of radioactivity due to total count, potassium and uranium were observed east of the King Gunnia copper mine, Lakes Nob and Day Dream areas. East of King Gunnia and in Lakes Nob areas, moderate radioactivity is related to the outcrops of a medium to fine-grained, light grey mica-quartz schist with some copper mineralisation (copper carbonate). Amphibolites and pegmatites (Na-feldspar) are the common associates of the schist. In the vicinity of Day Dream the moderate radioactivity is related to the rock exposures of the sulphide-rich (silver-lead sulphide) rocks and mine waste.

An examination of overlay 5, Fig. 5.2, shows that there is no statistically higher radioactivity due to thorium in the study area. Moderate radioactivity was observed only in the eastern part of the map. The tract of moderate radioactivity runs NE-SW. When compared with the areal geology it was observed that this tract generally follows the outcrops of the pegmatites. Similar radiometric response was also observed in potassium channel overlay. From a uranium mineralisation point of view, these pegmatites seem to be uranium-barren. The moderate radiometric response, due to thorium, suggests that these pegmatites might contain some amount of rare earths.

An inspection of potassium channels, leads to the suggestion that there are two types of pegmatites - potassic and sodic feldspar pegmatites. The K-feldspar pegmatites generally occupy the upper half of the area while the Na-feldspar pegmatites happen to be distributed in the lower half of the area.

In examining the ratio profiles for U/K, U/Th and Th/K it was observed that some of the granite outcrops showed higher U/K and U/Th ratios while some showed higher Th/K ratio. The granitic outcrops adjacent and east of MM anomaly showed higher U/K and U/Th ratio, Fig. 5.7. The central granitic body had a higher Th/K ratio. The specimens of Mundi Mundi type of granite collected from different places in the Willyama Complex gave similar chemical composition (Mawson, 1912; Brown, 1922 and Leslie and White, 1955). The only difference lies in their physical appearance such as colour and grain size, described in Chapter 2. The variation of U/Th ratio over various granite exposures suggests a vertical variation in the composition of pregranitic source rocks coupled with the formation of magma at different levels.

The radiometric response in all channels shows very low radioactivity over the outcrops of amphibolites (basic rocks). A small number of low to moderate radioactivity, due to uranium was observed over the Cainozoic cover over the Mundi Mundi plain and south of Purmamoota Homestead along the beds of creeks. Small and sporadic anomalies along the drainage might have been caused due to the concentration of heavy minerals.

Spectrometric studies carried out over the study area revealed that the Mundi Mundi carbonaceous subfacies and grey mica-quartz schists are higher in radioactivity due to potassium and uranium. The radioactivity, due to uranium, is higher in the carbonaceous schist (BW) along the carbon-rich bands and can be followed for a long distance (2 km) along the strike, overlay 4, Fig. 5.2. The grey mica-quartz schist shows higher radioactivity due to uranium over the iron-stained patches. Sillimanite schist and andalusite schist are moderately radioactive, due to potassium and uranium. Variable weak to moderate radiometric response, due to potassium and uranium was observed over the exposures of granite. The amphibolite gave very low radioactivity in all channels. The pegmatitic outcrops exhibited varying radioactivity (due to potassium), from moderate to high.

Moderate to high radioactivity (total count channel) when compared with the total magnetic intensity map of the area, it was observed that there was no direct correlation of magnetic highs to radiometric highs. In certain instances, especially in the Brinkworth, Mundi Mundi and King Gunnia areas the radiometric highs seem to overlie the magnetic lows and run parallel to each other.

Fig. 5.3 Total magnetic intensity contour map of the Mundi Mundi-Mount Franks area.

Source of data - taken from airborne magnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W. B.M.R. survey, 1975 (unpublished).

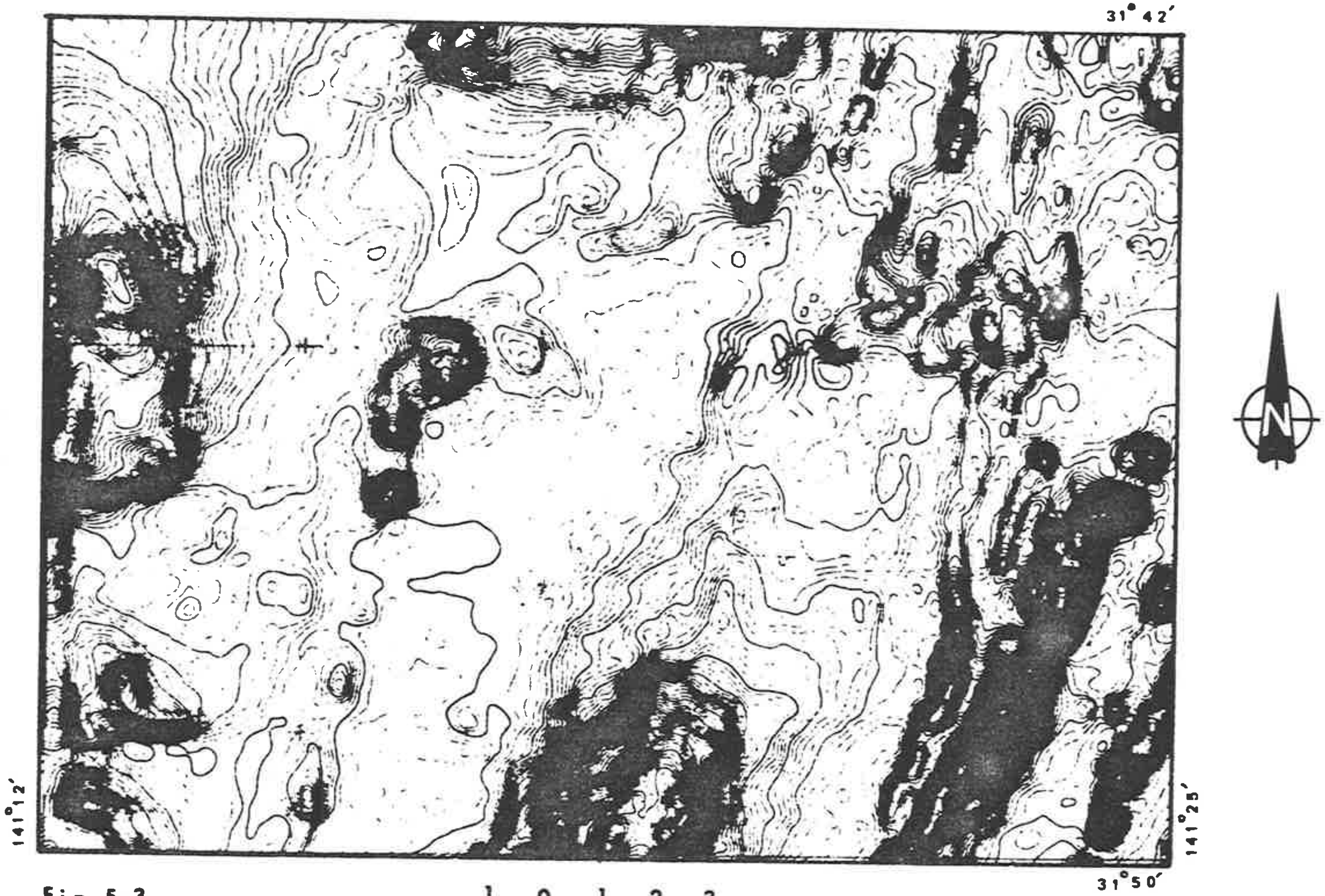


Fig 5.3

1 0 1 2 3 km

TOTAL MAGNETIC INTENSITY
OF THE
MUNDI MUNDI - MOUNT FRANKS AREA

Fig. 5.4 Stacked profiles of total magnetic intensity, total count and radio altimeter along flight line No. 3840.

Source of data - compiled from a study of the original airborne magnetic and radiometric survey data digitally recorded on magnetic tapes (detailed survey). Airborne magnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W., B.M.R. survey, 1975 (unpublished).

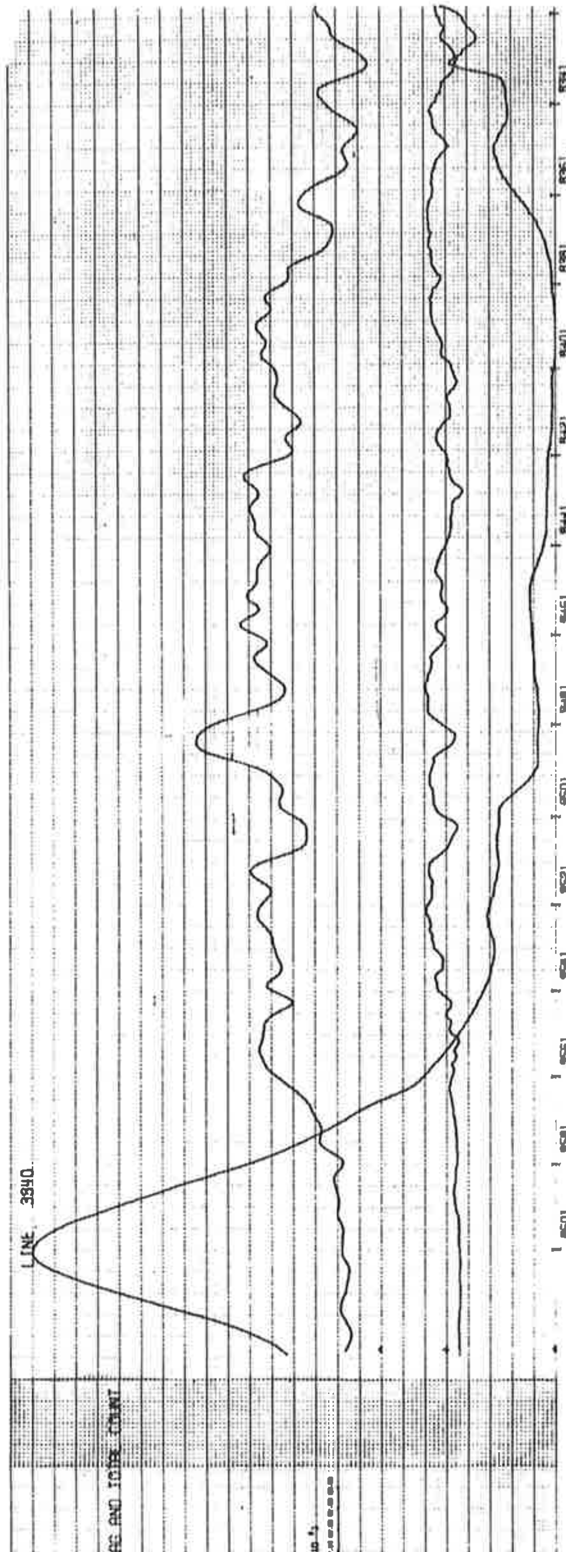


Fig. 5.4

Fig. 5.5 Stacked profiles of potassium, uranium and thorium along flight line No. 3840.

Source of data - compiled from a study of the original airborne spectrometer survey data digitally recorded on magnetic tapes (detailed survey).

Airborne magnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W., B.M.R. survey, 1975 (unpublished).

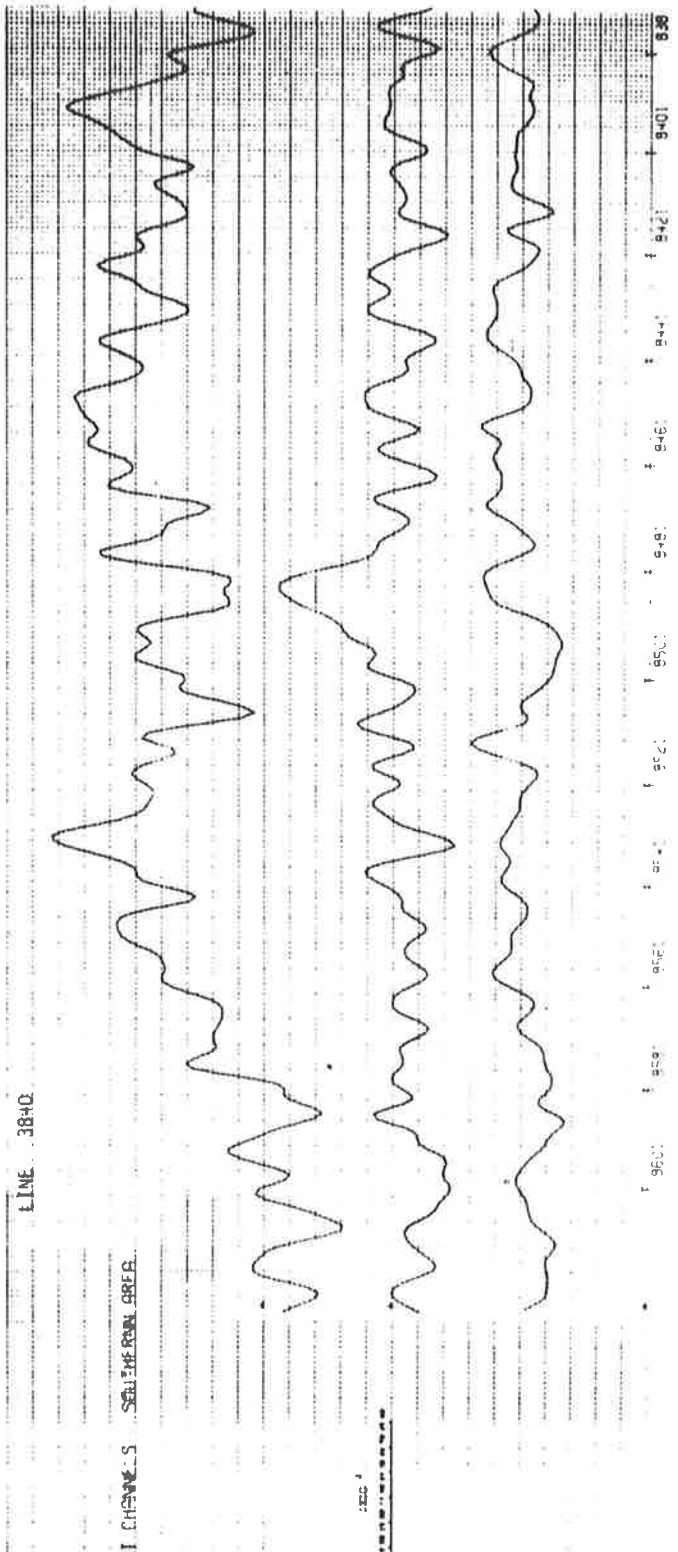


Fig. 5.5

Fig. 5.6 Stacked profiles of U/Th, U/K, and Th/K along flight line No. 3840.

Source of data - compiled from a study of original airborne spectrometer survey data digitally recorded on magnetic tapes (detailed survey). Airborne magnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W., B.M.R. survey, 1975 (unpublished).

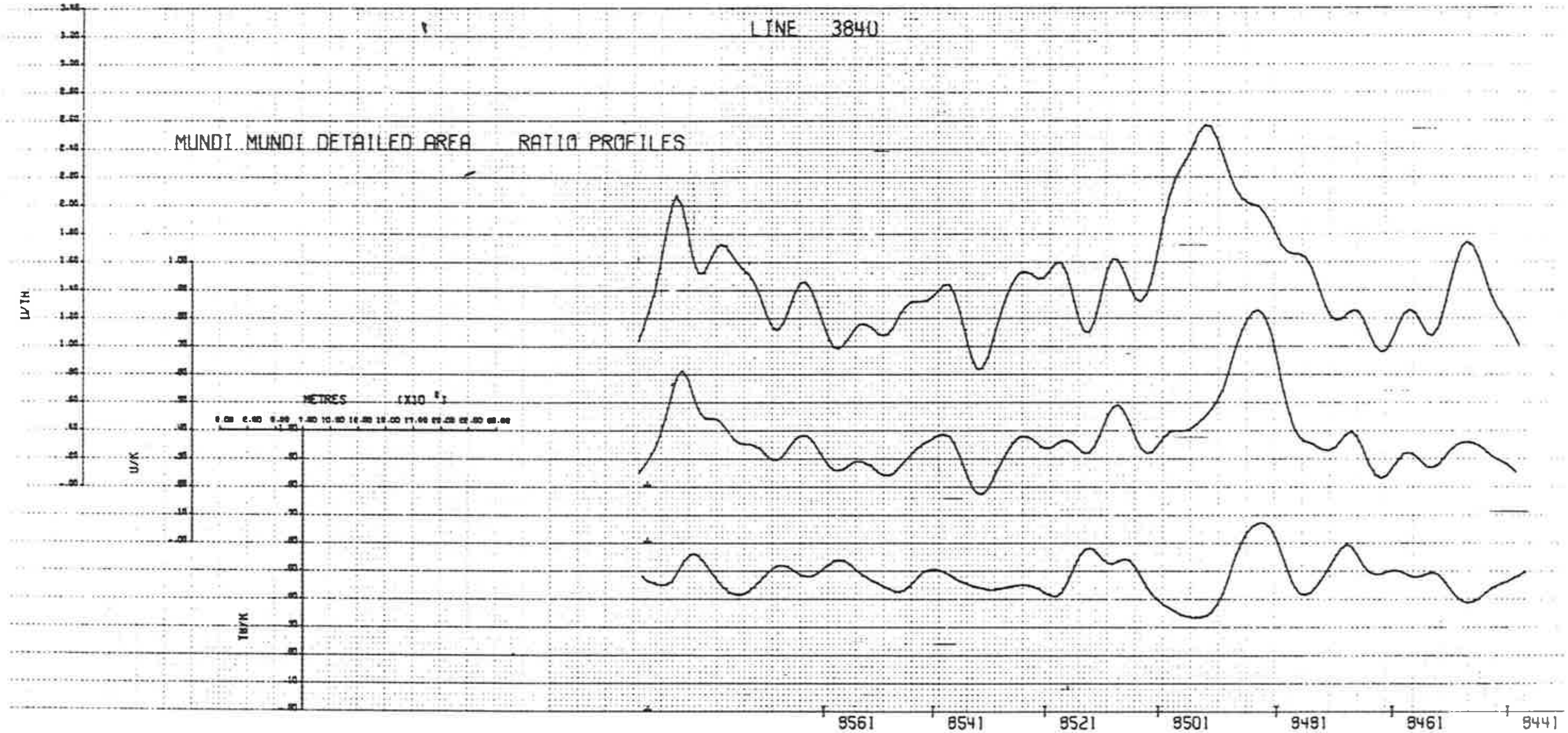

LINE 3840
MUNDI MUNDI DETAILED AREA RATIO PROFILES
U/TH
U/K
TH/K
METRES
8561
8541
8521
8501
8481
8461
8441

Fig. 5.6

Fig. 5.7 Stacked profiles of U/Th, U/K, & Th/K ratios in the Mundi Mundi area. Arrows show the various ratios over granite outcrop (Mundi Mundi type granite).

Source of data - compiled from a study of original airborne spectrometer survey data digitally recorded on the magnetic tapes (detailed survey).

Airborne magnetic and radiometric survey of Broken Hill 1:250,000 sheet area, N.S.W., B.M.R. survey, 1975 (unpublished).

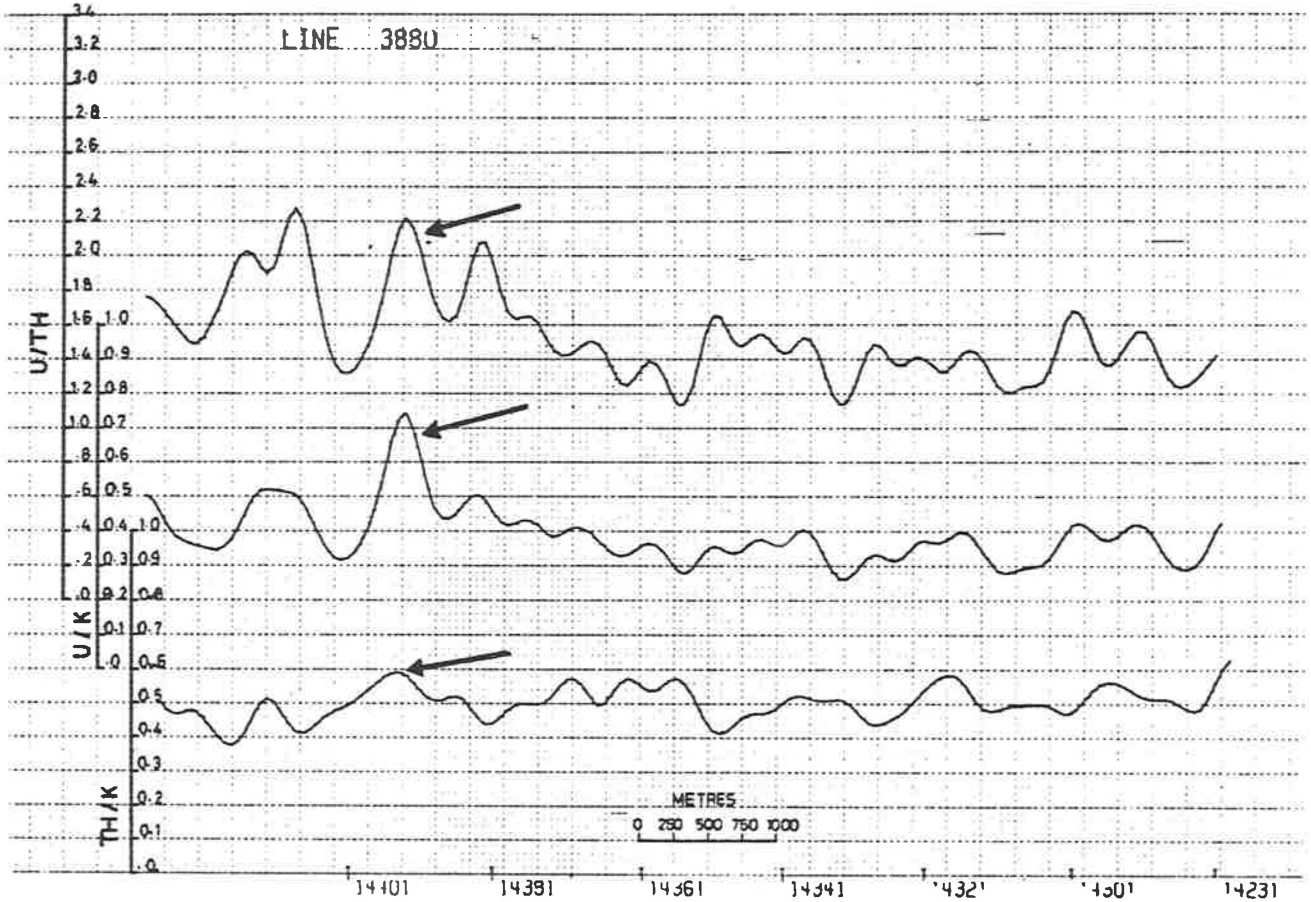


Fig. 5.7

EVALUATION OF RADIOMETRIC ANOMALIES

The uranium anomalies were selected studying the detailed airborne spectrometer survey data over the Mundi Mundi-Mt. Franks area. The anomalies were found to occur over Brinkworth, Mundi Mundi, King Gunnia and Day Dream areas which are shown in the uranium overlay as BW, MM, KG and DD respectively. Detailed ground geologic and radiometric investigations showed that invariably all the anomalies were found over the areas where the uranium mineralisation is known to occur, reported by Rayner (1957). During the ground spectrometer survey a portable four channel gamma-ray differential spectrometer was used and is described in Appendix 4.

Anomaly BW

Inspection of overlay 4, Fig. 5.2 shows that high amplitude airborne anomalies due to uranium were detected along three consecutive flight lines, 3840, 3850 and 3865 by the spectrometer. The anomalies are related to an outcrop of the Mundi Mundi Carbonaceous Subfacies which strikes nearly north to south and dips at an angle of 50-60 degrees to the west. The carbonaceous schist consists of two low hills deeply dissected by a creek. Ground radiometric observations showed that an increased radiation, three to five times that of the normal background count was recorded over an exposure of 150-250 feet wide and approximately 3000 feet north of an arm of the Mundi Mundi Creek. The highest radioactivity was registered over the carbon-rich bands in the schist. The radioactivity (2-3X normal background) was also recorded over the ironstained (dusty yellow) patches due to secondary uranium mineral autunite, as reported by Rayner (Rayner, 1957). The other hill further up north gave no statistically higher radiometric response, due to thick (2-4 feet) soil cover. Here, the rock exposures are extremely small and rare. Two pits measuring 2 x 3 feet were dug along the strike over this hill and the radiometric response recorded was 2-3 times that of the normal background count of the surface reading over the hill. In the absence of subsurface drilling data, it seems improper to assign any economic importance to the carbonaceous schist. It is probable that some time later it may prove to be a low-grade economic deposit.

Anomaly MM

The high amplitude anomaly due to uranium was picked up by the airborne spectrometer along the flight line 3891. This aerial anomaly was recorded over the Mundi Mundi uranium prospect as described by Rayner (1957). The radioactivity in the Mundi Mundi area was first discovered by A.J. Polkinghorne and G.W. Patterson in 1953. The prospect is situated in the highly rugged and rough hills, 2 miles north of the Mundi Mundi Trignometric Station. The prospect consists of two trenches along the slope of a hill. The upper trench is approximately 25 feet long, 6 feet wide and 5-6 feet deep. The lower trench, which lies at a distance of 400 feet down slope and nearly 200 feet west to the upper trench is 15 feet long, 5 feet wide and 4-6 feet deep and terminates abruptly in the creek against granite (Mundi Mundi type granite) body. Ground radiometric observations were made over these trenches and in the milieu of prospect. The radioactivity (10-15 X normal background count), due to uranium and potassium was observed in the trenches, particularly over the iron-stained patches. The radiometric readings, 2-4 times that of normal background count were recorded over a schistose belt of 250 feet wide and 900 feet long. Higher counts were confined to a belt of 35 feet wide and approximately 400 feet long which is sheared and stained with iron oxide (brown colour) in places. On the evidence of radiometric and fluorimetric analyses, Rayner suggested that the radioactivity which is highest in the ferruginous band, is caused by uranium mineralisation (probably secondary) is out of order. The radioactivity, due to uranium, occurs in grey mica-quartz schists and biotite-sillimanite schists in an undetermined form.

The schists were checked radiometrically in the Mundi Mundi area, especially the section along one of the arms of the Mundi Mundi Creek which flows approximately south to north. The radioactivity recorded over the schist exposures and the section along the Mundi Mundi Creek was of the order of 2-3 times that of normal background count in the uranium and potassium channels. The granite exposures in the immediate vicinity of the prospect and east of the MM anomaly, adjacent to the Mundi Mundi Creek, gave slightly higher than normal background radiometric response in all channels. Uranium counts were 2-3 times greater than thorium counts over the granite outcrops. The close spatial relationship of these granites to the prospect suggests that they might have been a source of uranium mineralisation in this area through a medium of ground water.

Anomaly KG

This weak to moderate amplitude aerial anomaly is associated with the outcrops of fine-grained grey mica-quartz schists with traces of copper mineralisation, and copper carbonate. The schist, in places, is traversed by numerous quartz veins and feldspar pegmatites. The thick overburden has obscured the local geology. The ground radiometric investigation showed only a moderate radioactivity due to uranium over the rock exposures. The radiometric response hardly reached twice that of the normal background radioactivity. The negative radiometric response over the pegmatites suggests that they are Na-feldspar pegmatites. Very low radioactivity was recorded over the quartz veins.

Anomaly DD

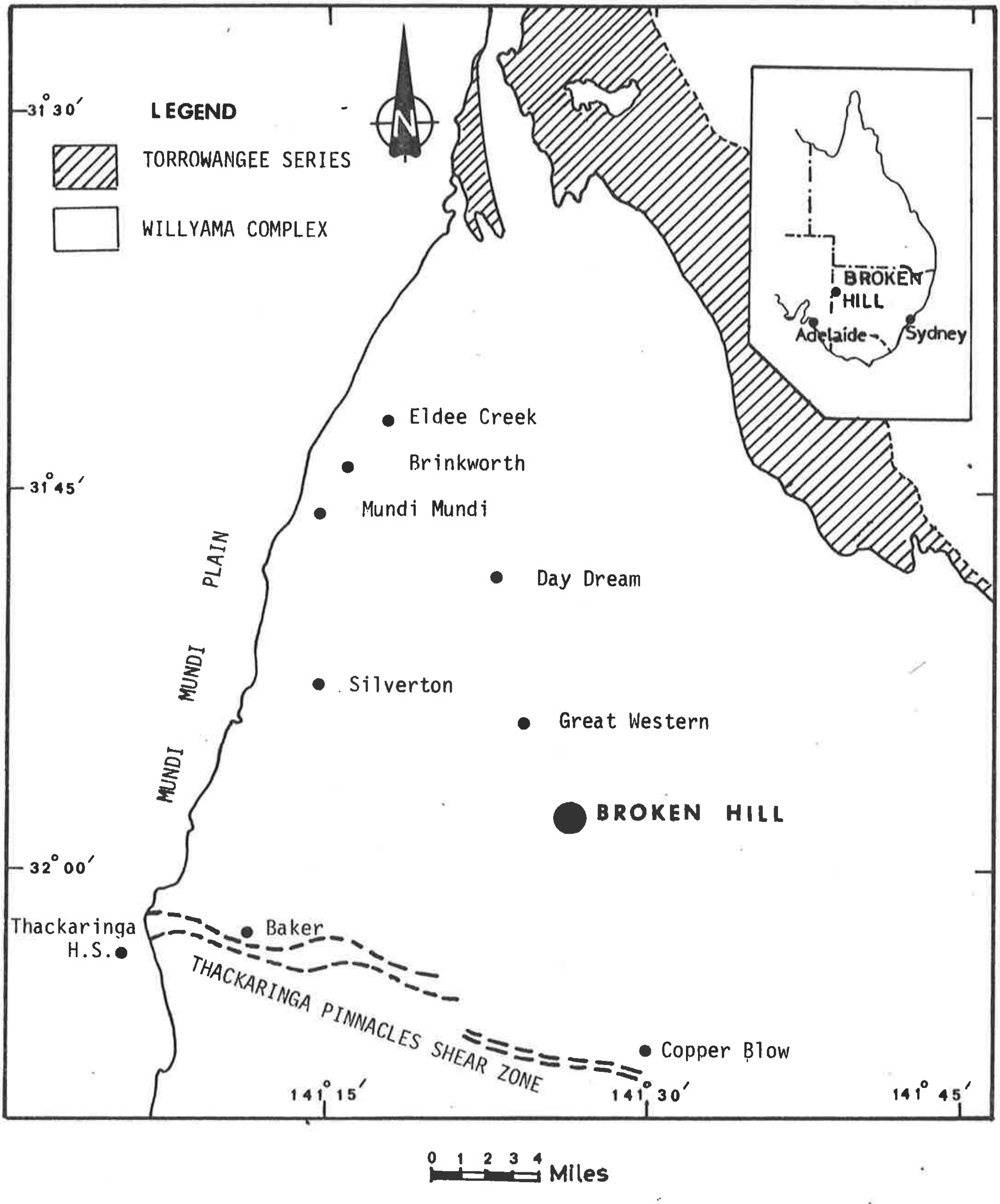
This aerial anomaly is associated with one of the mine dumps (silver-lead sulphide) close to the Day Dream Smelter, and is also known as Hen-and-Chickens. The outcrops are very rare in this area. The whole area is a flat alluvial covered plain. Ground radiometric checkings were carried out over the mine dumps. Only one mine dump gave higher readings, due to uranium. The readings were in the range of 2-3 times that of the normal background. A mine shaft next to the Day Dream Smelter was also checked. Day Dream lode system is an old silver-lead mine of Thackaringa type (vein type). The lode formation dips to the southeast at 30 degrees and is overlain and underlain by the Mundi Mundi type granite.

The highest radioactivity, due to uranium measured in the mine shaft was 10-15 times that of surface radioactivity. The higher count rate may be due to the solid angle effect. The higher readings were recorded over the limonitic bands in the oxidised zone. According to Rayner, the radioactivity results from uranium minerals of unknown composition, is commonly less than 0.1 percent U_3O_8 and is highest in the surface section of the oxidised zone, declining in intensity but persisting in some degree in deeper workings.

The uranium association with limonite seems to be similar as already mentioned. The close spatial relationship of the Mundi Mundi type granite is noteworthy from the point of view of uranium mineralisation.

CHAPTER 6

RADIOACTIVE MINERALISATION AND CLASSIFICATION OF DEPOSITS



LOCALITY MAP

Fig. 6.1

TABLE 6.1

SUMMARY OF RADIOACTIVE DEPOSITS

Deposits	Uranium minerals	Thorium minerals	Type of minerals	Associated rocks	Associated minerals	Associated base metals
Thackaringa	Davide	Brannerite	Primary	Pegmatites, aplites, granites, sillimanite- and mica-schists and granitic gneiss.	Rutile, hematite, magnetite, quartz, feldspar, muscovite and fluorite.	-
Copper Blow	Torbernite	-	Secondary	Quartz-biotite-sericite schist with magnetite.	1. Oxidised Zone. Hematite, limonite, magnetite, malachite, azurite & chrysocolla 2. Sulphide Zone. Magnetite, pyrite.	Copper Malachite, azurite, chrysocolla (Oxidized Zone). Chalcopyrite (Sulphide Zone).
Broken Hill	Uraninite (traces)	-	Primary	Pegmatised gneiss	Biotite and carbon-bearing mineral(?).	Silver, lead, zinc
Great Western	(?) unidentified	-	Secondary	Pegmatite, sillimanite-schist	Iron oxide	Silver, lead, zinc and copper.
Day Dream	(?) unidentified	-	Secondary	Schist, granite	Iron oxide	Silver, lead and copper (traces).
Mundi Mundi	(?) unidentified	-	Secondary	Mica-quartz-schist and biotite-sillimanite-schist	Iron oxide	Copper (traces)

TABLE 6.1 (cont'd)

SUMMARY OF RADIOACTIVE DEPOSITS

Deposits	Uranium minerals	Thorium minerals	Type of minerals	Associated rocks	Associated minerals	Associated base metals
Brinkworth	-	-	Secondary & primary (?)	Carbonaceous schist	Iron oxide and carbonaceous matter	-
Eldee Creek	Autunite	-	Secondary	Biotite-quartz schist	Limonite	Copper (malachite)
Centennial	-	monazite	Primary	biotite-quartz-gneiss	Biotite, quartz and feldspar	-

CHAPTER 6

RADIOACTIVE MINERALISATION AND CLASSIFICATION OF DEPOSITS

INTRODUCTION

A full account of the general characteristics and associations of radioactive mineralisation in the Lower Proterozoic Willyama Complex in the Broken Hill district, New South Wales, is described here. The uranium occurrences in various parts of the study area reported by Rayner (1957) have been classified as vein type and infillings in shear zones (Eldee Creek, Mundi Mundi, Copper Blow, Thackaringa). They all occur in the Lower Proterozoic Willyama Complex schists and may be genetically related to the Mundi Mundi type granite. The Thackaringa davidite belt may be related to end-phase granite activity. In the Mundi Mundi, Eldee Creek, Day Dream and Lake Nob areas there is a close spatial relationship to the Mundi Mundi type granite; and other minor occurrences are in pegmatites. The Mundi Mundi granite and pegmatite, with a few exceptions, show higher U/K, Th/K and U/Th ratios. It is therefore suggested that these Mundi Mundi granites and associated pegmatites are possibly the potential source for uranium and thorium mineralisation in this area. While uranium is associated with lesser or greater amounts of silver-lead-zinc mineralisation (Day Dream, Great Western, Gypsy Girl) not many silver-lead-zinc deposits carry significant uranium. A small amount of uranium has been recorded in the Broken Hill Lode. Uranium has been found with copper in the Copper Blow area, whereas its association with iron oxide is remarkably seen in the Eldee Creek, Mundi Mundi, Brinkworth, and Day Dream areas. Practically all the uranium mineralisation is of the epigenetic type except Brinkworth, Copper Blow and Great Western areas which are possibly syngenetic types. Table 6.1 shows a summary of the known deposits of the study area and Fig. 6.1 shows the location of the deposits described in this chapter.

URANIUM DEPOSITS

6.1 Thackaringa Deposit

Primary uranium mineralisation is found in veins and irregular lenses of pegmatite, in quartz veins of quartz-rich sections of pegmatite, in aplite, in red aplitic granite, in laminated quartz-feldspar rock, in sericitised and biotite schistose rock in the Thackaringa area within the Albert Shear Zone. Davidite, an iron-uranium titanate, is the primary uranium mineral. Within the uranium lodes, the davidite occurs as grains, small lenticular pods and veinlets. Irregular nests and bunches of davidite are also commonly seen in the lodes. In all these occurrences the mineralisation is sporadic and the davidite-bearing patches do not exceed 4-5 inches in length. Thorium minerals, thorite and monazite also occur, associated with davidite in places. All these radioactive mineralisations are confined within the Albert Shear Zone which is a curved shear zone considered by Rayner to have an important relationship to the uranium mineralisation. The belt to which the known davidite occurrences are confined is 6 miles in length and more than half a mile in width. The greater part of this belt has low relief and outcrops are rare, due to thick overburden. Rayner concluded that following early folding and metamorphism with some granitisation of the original sediments, there was cross-folding, faulting, crushing, and attenuation. Serpentine was introduced at this stage or at a later stage. Subsequently, there would appear to have been further tectonic movement, with faulting and shearing and the introduction of the Mundi Mundi type granite and associated pegmatites and aplites. The uranium mineralisation was probably introduced later in, or at the end of, this sequence of events. The deposit is classified as epigenetic in which pegmatites and hydrothermal solutions played an important role in introducing the primary radioactive minerals in the Willyama metasediments.

The surface expressions of these primary uranium mineralisation (as veins or disseminated) do not favour the idea of being economically important. It is probable that these sporadic and discontinuous showings and lack of subsurface geological information, were the main reasons which lead to the discouragement of a large number of prospectors working in that area. No exhaustive prospecting or exploratory work has been undertaken since 1955. For future exploration work the area should be investigated based on the ground geophysical surveys. There is a close similarity of uranium mineralisation in this area with the Radium Hill, uranium deposits (which are the potential economic uranium deposits of South Australia).

6.2 Copper Blow Deposit

Copper Blow is situated 12 miles south-south-east of Broken Hill City. Radioactivity, due to uranium mineralisation was first noted by Daly and White in 1952 as reported by Rayner (1957), and subsequently examined by geologists of the Zinc Corporation Ltd. Metatorbernite was found by E.O. Rayner and R.E. Ralph (Rayner, 1957).

Copper Blow is an old mine of iron and copper. Narrow lodes of hematite, with some magnetite, were formerly worked as a source of flux for smelters at Broken Hill. Copper mineralisation accompanies that of iron and narrow lodes were worked for copper down into the sulphide zone (the deepest working was about 300 feet, Rayner (1957)). The individual lodes are narrow but form a strong linear group about 1 mile in length along the strike and are contained within a shear zone which is up to 100 feet in width towards the southern end. The shear zone strikes parallel to the enclosing Willyama Complex rocks which consist of biotite-sillimanite-garnet schists, granitic gneiss, amphibolite and pegmatite. The host rock for the lode is, in part, a quartz-biotite-sericite with grains of magnetite.

The rocks and the lodes strike NE-SW and dip northeast at about 70 degrees. The rock exposures are very rare and poor. The whole Copper Blow area is a plain, covered with alluvium and saltbush.

During the ground follow-up program, radioactivity 2-5 times that of normal background was recorded along the open cut (about 1 mile along strike), the highest radioactivity was confined to the copper-bearing sections at the southern end. The maximum intensity (10X normal background) was recorded in the southern end known as Warren open cut and mine dump. In the oxidised zone, hematite, limonite, magnetite, malachite, azurite and chrysocolla were identified by Dr. I.R. Plimer who accompanied the writer. According to Rayner the uranium values from the oxide zone are from 0.1% to 0.3% U_3O_8. Sulphide dumps near the Warren shaft show radioactivity equivalent to be 0.05% U_3O_8, in association with chalcopyrite, pyrite and magnetite, and this suggests that some uranium mineralisation is present in the sulphide zone (Rayner, 1957). Penetration of the primary zone by the Zinc Corporation Ltd. drill holes showed slight radioactivity (higher than the wall and country rock) associated with the primary magnetite-pyrite-chalcopyrite lode, and Edwards and Baker (1953), (quoted in Rayner, 1957, p. 80) commented on the sulphide as examined in a specimen as follows:

> "The ore consists predominantly of fine-grained magnetite intersected by fine veinlets of chalcopyrite and pyrite. The chalcopyrite has corroded the pyrite and enclosed residuals of it. In addition, it contains a small number of ex-solution bodies of sphalerite and valleriite, and of pyrrhotite.
> A polished section of the specimen was left in contact with a nuclear research plate for three days. The resulting autoradiograph showed approximately 20 small scattered radial aggregates of alpha-particle tracts, indicating the presence of a radioactive mineral occurring as minute particles dispersed through the specimen. Some of the aggregates contained 5, some 15 and some 60 alpha-particle tracks. Some of the radioactive centres lay within areas of chalcopyrite and could possibly be attributed to minute inclusions in the chalcopyrite, but it was not possible to locate the radioactive mineral with certainty".

Rayner concluded that in the Copper Blow deposit the uranium mineralisation is essentially associated with that of copper in the primary zone, with secondary deposition and enrichment (including the copper-uranium phosphate, torbernite) in the oxidised zone.

Limited time and extremely poor rock exposures did not allow the writer to carry out the detailed ground geological and radiometric investigations in the Copper Blow area. However, no granite outcrops were observed within a radius of about 3 miles. Uranium mineralisation in the Copper Blow area seems to be similar to the mineralisation found in the Parabarana and Shamrock mines of the eastern Mt. Painter area, South Australia.
copper.

6.3 Broken Hill Deposit

The Broken Hill Lode is well known in geological and mining literature because of the size and grade of the deposit, and because of the continuing controversy over the origin of the ore since its discovery in 1883. The rocks enclosing the lode are highly deformed and lie within the high-grade metamorphic Zone C of Binns (Binns, 1964). Both & Rutland (1975) suggested that the Broken Hill Lode is a series of "lenses" or "layers" enclosed in, and separated by mica-sillimanite schists and gneisses and quartzite. There are six known ore-producing lenses. On the consensus of opinion of a number of workers, including Both & Rutland, they concluded that they were of a sedimentary origin, with the lode being regarded as a highly metamorphosed equivalent of stratiform lead-zinc ore bodies in Proterozoic sedimentary/ volcanic sequences elsewhere (e.g. Mount Isa, Queensland; Sullivan, B.C.), Both & Rutland (1975). The Broken Hill Lode has an unusually high length/ width ratio (approximately 8/1) compared to the more equidimensional shape of most stratiform deposits described in the literature.

According to Rayner (1957) the main line of lode at Broken Hill received early attention in the search for sources of uranium, since by virtue of the very considerable tonnages of ore mined and treated, any appreciable trace of uranium throughout the ore might mean that it could be economically concentrated and produced as a significant by-product. However, taken as a whole, the ore bodies are singularly lacking in radioactivity. The radiometric surveys at surface, underground and mill products carried out by him yielded negative results. Two occurrences of mineralogical interest quoted by Rayner (1957, p.78) are:

> "1. In a specimen of radioactive pegmatised gneiss occurring as wall rock on the eastern side of the lead lode on the No. 18 level of the Zinc Corporation Ltd's mine, uraninite was determined accompanying a hydrocarbon, as described by Edwards and McAndrew (1953). The gneiss is described as containing layers of biotite, with grains of a carbon-bearing mineral, in which were set particles of uraninite, in association with a few particles of pyrite and marcasite, and
>
> 2. Traces of uranium have been identified in some concentrate samples from the Broken Hill South mine".

The mineralisation was recorded in lens No. 2.

6.4 Great Western Deposit

The Great Western is an old silver-lead-zinc mine and is situated about 6 miles north-west of Broken Hill. The primary mineralisation (silver-lead-zinc) in the Great Western area is of the Broken Hill type, stratiform syngenetic, (Rayner, 1957).

The Silver-lead-zinc lode formation, 3-5 feet in width, strikes north-easterly in folded schists and pegmatites of the Willyama Complex. Higher radioactivity, due to secondary uranium mineralisation is confined to the iron-stained patches in the oxidised zone. Rayner (1957) reported the radio-activity in the order of 0.05% U_3O_8 in the dumps from the sulphide zone (primary mineralisation). In the oxide zone the uranium mineral (unidentified) was found associated with pegmatite (hanging wall) and sillimanite schist (foot wall). The oxidised lode material contains cerussite, carbonates of copper, quartz, fluorite, garnet, gahnite and iron oxide.

Low radioactivity and the small size of the deposit do not suggest that it could be a significant deposit from a uranium mineralisation stand-point. The interesting noteworthy feature is the association of uranium mineral with copper, lead, silver and zinc in the primary zone. As said above that the silver-lead-zinc mineralisation is of the Broken Hill type (i.e. sedimentary syngenetic), it seems probable that the secondary uranium mineral in the oxidised zone was possibly derived from the Willyama Complex metasediments.

6.5 Day Dream Deposit

The Day Dream Mine is also an old silver-lead mine and lies at a distance of about 13 miles northwest of Broken Hill. The silver-lead mineralisation is of Thackaringa type (vein type). The lode formation (silver-lead) is overlain and underlain by leucocratic granite (Mundi Mundi type granite) of fine and even grain size. The Willyama Complex forms the country rocks which consist of schists, pegmatites and amphibolites.

The radioactivity results from uranium minerals of unknown composition are commonly less than 0.1% U_3O_8 (Rayner, 1957). There is a paucity of outcrops as the whole area is covered with alluvium. During the ground geologic and radiometric survey the mine dumps, shafts and open cuts were checked. The higher radioactivity (2-3X normal background) was observed over one of the dumps, particularly iron-stained rock pieces. The highest radioactivity (8-10X normal background) was recorded in a shaft, close to Day Dream Smelter, at a depth of about 20 feet in the oxidised zone. It was noticed that the intense radioactivity was along the bands of dark brown limonitic material. The lode formation contains cerussite, cerargyrite, a little galena, bindheimite, azurite and coarsely crystalline siderite gangue (Rayner, 1957). The higher radioactivity observed in the shaft was possibly due to solid angle effect. The dump from the same shaft was also checked radiometrically and the radioactivity measured hardly reached twice that of normal background level. Traces of copper mineral were also found in this dump. Neither the primary uranium mineral was found nor is it reported in the literature. The secondary uranium mineralisation was possibly derived by leaching from the enclosing granite rocks and enriched in the oxidised zone.

The low concentration of uranium mineralisation in the oxidised zone (<0.1% U_3O_3) and the small size of the deposit do not suggest that it could be an economic uranium deposit.

6.6 Mundi Mundi Deposit

The Mundi Mundi deposit is situated approximately 20 miles north-west of Broken Hill and lies in the highly rugged and rough hills, two miles north of the Mundi Mundi Trignometric Station. The deposit was first discovered by A.J. Polkinghorn and G.W. Patterson in 1953, as reported by Rayner (Rayner, 1957).

The radioactivity occurs in undetermined mineral form, in grey mica-quartz schist and biotite-sillimanite, and, in particular, in iron oxide-rich bands. The Willyama Complex (schists and gneisses with pegmatite and granite) forms the country rocks. They strike approximately NE-SW and dip towards the west.

During the ground follow-up program the schists, gneisses, granite and pegmatites were checked radiometrically in the vicinity of the Mundi Mundi prospect and the section exposed along one of the arms of the Mundi Mundi Creek which flows approximately south to north (Fig. 5.2). The radioactivity measured over the rock exposures (schist and gneiss) and the section along the arm of the Mundi Mundi Creek (as mentioned) was of the order of 2-3 times that of the normal background count in the uranium and potassium channels. The granite outcrops in the immediate vicinity of the prospect (north of the prospect) and east of the prospect (adjacent to the arm of the Mundi Mundi Creek) gave slightly higher than normal background radioactivity response due to uranium.

The uranium prospect in the Mundi Mundi area consists of two trenches and were dug (most probably by Rayner) along the strike on the slope of one of the hills. The upper trench is approximately 25 feet long, 6 feet wide and 5-6 feet deep. The lower trench which lies at a distance of about 400 feet down slope and nearly 200 feet west to the upper trench is 15 feet long, 5 feet wide and 4-6 feet deep and terminates abruptly in the creek against granite (Mundi Mundi type granite) body towards the north. Ground radiometric observations were carried out over these trenches and in the milieu of the prospect. The radioactivity (10-15X normal background count) due to uranium was recorded in the trenches, particularly over the iron-stained patches. The radioactivity response, 2-4 times that of the normal background count was observed over a schistose belt of 250 feet wide and 900 feet long. Higher counts (>5X normal background count) were confined to a belt of 35 feet wide and approximately 400 feet long which is sheared and stained with iron oxide in places. Traces of malachite were also found in the shear zone. The uranium oxide content of schist as reported by Rayner (Rayner, 1957) is between 0.01% and 0.04% U_3O_8. On the evidence of radiometric and fluorimetric analyses, Rayner suggested that the radioactivity which is highest in the ferruginous band, and is caused by uranium mineralisation (probably secondary) is out of equilibrium. The radioactivity, due to uranium, occurs in grey mica-quartz schist and biotite-sillimanite schist in an undetermined form (Rayner, 1957, p.77).

The association of uranium mineralisation with iron oxide is noteworthy in the Mundi Mundi area and appears to be due to fixation of secondary uranium mineral by absorption with ferric oxide hydrate following neutralisation of acid sulphate waters which had carried the uranium in solution. The process seems to be similar as explained by Lovering.

Lovering (1955) concluded that uranium minerals dissolve in acid sulphate waters. When these waters become neutralised, iron hydrolyses to form colloidal ferric hydrate, which together with any colloidal silica, coagulates; the uranyl ions are absorbed on the colloidal particles and removed from the solution. As the colloidal ferric oxide hydrate ages, it crystallises to form goethite, and uranium is excluded from the structure and forms secondary uranium minerals scattered through the limonite. According to Lovering, uranium or uranium minerals are rarely associated with secondary hematite.

The Mundi Mundi deposit is classified as epigenetic in which the ground waters played an important role for the secondary uranium mineralisation and the shear zone was responsible for localising the mineralisation. It is probable that the uranium minerals were carried in solution by the ground waters derived from the nearby intrusive granite bodies. The small intrusions and boss of granite (Mundi Mundi granite) lie within a radius of 3 miles. The occurrences of iron oxide containing small percentages of uranium are wide-spread (McKelveg, Everhart and Garrels, 1955). The low concentration of uranium minerals and limited extent of mineralisation do not suggest that it could be an economic deposit.

6.7 Brinkworth Deposit

The Brinkworth deposit is situated about 3 miles northeast of the Mundi Mundi deposit and lies along an arm of the Mundi Mundi Creek which flows approximately east to west. In this area the rocks mainly consist of the Mundi Mundi carbonaceous subfacies as described by Glen (Glen, 1978). The carbonaceous schist is of a dark, brownish-black glossy and fine-grained schist and contains mica, quartz, feldspars, graphite, with occasional crystals of chiastolite. The rock is well bedded in layers from half an inch to two inches thick, alternatively finer and coarser. The ground fabric is full of a black dusty material which is partly iron oxide, but is partly of a carbonaceous matter. According to Browne (1922) the rock contains 1.82 percent of carbon. The rock is greatly crumpled due to tight folding. The common associates of the schist are pegmatites, granitoids, and granite. The whole area consists of a series of low hills deeply dissected by creeks. The overburden has obscured the geology and rock exposures are limited and rare.

During the ground geologic and radiometric investigations, the higher radioactivity (3-5X normal background count) was observed over an exposed schistose belt of 150-250 feet and approximately 3000 feet long along the strike, NE-SW. The belt is covered with overburden in places. The higher radioactivity was recorded over the carbon-rich bands particularly iron-stained patches. The adjacent hill further north gave no statistically higher radiometric response, due to thick (2-4 or even more feet) overburden. Here, the rock exposures are extremely small and rare. Two pits measuring 2 x 3 feet were dug along the strike over this hill and the radiometric response recorded was 2-3 times that of the normal background count of the surface reading over the hill.

Autunite, secondary uranium mineral was identified by Rayner (Rayner, 1957) and the uranium content of iron oxide patches in the schist reported by him is of the order of 0.14% U_3O_8. Due to the limited time and paucity of outcrops it is not possible to say that the secondary uranium mineral, autunite, was derived from the nearby intrusive granite (Mundi Mundi type granite). During the ground radiometric measurement the highest radioactivity (5X normal background count) was observed over the iron-stained patches whereas non-iron-stained carbon-rich bands of the schist gave the radiometric response up to two times that of the normal background count. Therefore, it appears that the secondary uranium mineral might have derived from the nearby intrusive granite or from the carbonaceous material of the schist itself or from both.

The association of uranium mineral with carbonaceous matter is widespread in literature (Heinrich, 1958) and extensive low-grade uranium mineralisation is known to occur in alum shales in Sweden and Chattanooga shales in the United States (Ruzicka, 1975) and Dictyonema shales of the Leningrad district, U.S.S.R. (Heinrich, 1958). In the absence of drilling data, it seems improper to assign any economic importance to these carbonaceous schists.

6.8 Eldee Creek Deposit

The Eldee Creek uranium prospect is situated approximately 25 miles north-west of Broken Hill City. The radioactivity, due to uranium mineralisation, is confined to the narrow shear zone (the Eldee Creek Shear Zone, as named by Rayner, 1957). The shear zone is about 1 mile long, varying from a few inches to 20 feet. The shear zone which trends northeasterly is occupied by grey biotite-quartz schists with small amounts of sillimanite (Glen, 1978). The schistose belt is transgressive in part, cutting other schists, pegmatites, quartz-tourmaline rock, amphibolites and passes through the massive pegmatites.

Uranium mineralisation, due to a secondary mineral, autunite, occurs along iron-stained cracks oblique to the schistosity. Assays of the autunite-bearing schist are in the order of 0.2% U_3O_8 (Rayner, 1957). The higher radioactivity is confined to the ironstained (limonitic) portions of the schist. Copper mineralisation (malachite) is found in limonitic sections in traces. The deposit is classified as epigenetic in which the secondary uranium mineral, autunite, in limonite (goethite) appears due to fixation of autunite by absorption with ferric oxide hydrate following neutralisation of acid sulphate waters which had carried the uranium in solution. The process seems to be similar as explained by Lovering.

The Eldee Creek prospect is classified as epigenetic in which the ground waters played an important role for the secondary uranium mineralisation and the shear zone was responsible for localising the mineralisation. During the ground geological and radiometric investigations, no primary uranium minerals were found in the Willyama metasediments nor have they been reported in the literature. It is probable that the uranium minerals were carried in solution by the ground waters derived from the nearby intrusive granite bodies. The small intrusions of granite (Mundi Mundi type granite) lie within a radius of 2 miles. The low concentration of secondary uranium minerals and limited extent of mineralisation do not suggest that it could be an economic deposit.

6.9 Thorium Mineralisation

Thorium mineralisation has been reported by Rayner (Rayner, 1957) in the Thackaringa and Centennial areas.

In the Thackaringa area the thorium mineralisation was found by Rayner in a small group of transverse shears at the north-eastern end of the Albert Shear Zone, but is presumably of no economic significance. The thorium mineral described by him is a variety of thorite which occurs as grains and nodules in a partly decomposed and iron-stained veinlets of platy bronze biotite with small amounts of zircon, quartz and feldspar.

In the Centennial area radioactivity due to thorium, is associated with a gneissic biotite-quartz rock within areas of granitic gneiss and amphibolite at a locality 4 miles southwest of Centennial. On evidences of microscopic and chemical examination, electromagnetic and mechanical concentrating tests, Rayner (1957) confirmed that most of the radioactivity resulted from the presence of monazite and established this area as a potential source of thorium.

Due to the tight schedule this particular locality could not be visited by the writer.

6.10 Airborne Response

As mentioned earlier, the use of two B.M.R. survey data has been made. In 1959, the area was surveyed using a single NaI (Tl) crystal in which the radioactivity (total count) was recorded continuously by the airborne scintillograph along flight lines. In the absence of height correction, a good correlation of aeroradioactivity with the areal geology could not be achieved. In 1975 the area was resurveyed by the B.M.R., using airborne spectrometer. The results of this survey proved that the airborne radiometric measurements made with advanced instrumentation and the quality of processing the survey data could yield useful information for uranium exploration and mapping. The advantages of spectrometry became clear when the results were examined. Channel maps have made it possible to classify anomalies (i.e. due to uranium, thorium or potassium).

On the evidence of the airborne radiometric response, it has been possible to differentiate between the older Precambrian (Willyama Complex) rocks and the younger Precambrian rocks (Torrowangee Series), and the various geologic units within the Willyama Complex have been differentiated as well. The results of the spectrometer survey (1975) revealed that the highest radiometric response was seen to have been associated with the outcrops of sillimanite gneiss, carbonaceous schist, mica-quartz schist and davidite-bearing veins. Variable moderate radioactivity is observed over the exposures of granitic gneiss, granitoid, granite, whereas amphibolite, dolerite, serpentine and the thick Cainozoic deposits show low radiometric response. The spectrometry has further allowed the recognition of two types of pegmatites, Na-feldspar and K-feldspar in the area. Variable radiometric response and ratio (U/Th) are observed over granite (Mundi Mundi type granite). On the evidence of radiometric response (overlays - Fig. 3.7) over outcrops of granite (No. 1 in potassium and uranium channel maps) it reveals that the granite is potassic and contains higher amounts of uranium than thorium.

6.11 Control of Mineralisation

Most of the deposits in the region can be assigned to the structural features which have been important in localising the uranium and thorium mineralisation. These favourable structures range from large shear zones, faults and fissures, down to minor joint and bedding planes, microfractures and interstitial openings.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Airborne radiometric surveys and particularly the spectrometric survey, 1975, have identified areas of above-average radioactivity and provided an indication of the predominant sources of the radioactivity, i.e. whether due to uranium, thorium, or potassium. Within the area of Precambrian outcrops itself, the Younger Torrowangee Series of meta-sediments are characterised by areas of very low radioactivity. Within the Willyama rock assemblages, moderate to high radioactivity has been observed over the outcrops of rocks such as sillimanite gneiss, carbonaceous schist, mica-quartz schist, pegmatites (K-feldspar) granite gneiss, granitoids, and granite; and low radiometric response is found to be associated with the outcrops of andalusite schist, chiastolite schist, pegmatite (Na-feldspar), amphibolite, dolerite, and serpentine. All granite masses are slightly radioactive, potassium and uranium being the major sources. The radiometric anomalies of the highest amplitude were recorded over the areas of known radioactive mineralisation (Brinkworth, Mundi Mundi and Thackaringa) due mainly to uranium and potassium. Among the medium amplitude anomalies the only noteworthy anomaly is from Copper Blow.

All known mineralisation has been identified by the airborne survey and the spectrometer information has permitted results of uranium mineralisation from other sources of radioactivity. This shows that the airborne spectrometer is a reliable, efficient method of exploration for uranium, thorium and potassium in areas similar to Broken Hill. Two of the anomalies, i.e. Brinkworth and Thackaringa are considered to require furtner investigation based on ground magnetic and radiometric surveys. For ground radiometric the gamma logging, emanation surveys and gridded foot surveys should be employed.

REFERENCES

Adams, J.A.S., (1954): Uranium and thorium contents of volcanic rocks; in: Nuclear Geology, ed. H. Faul, John Wiley & Sons, New York, pp. 89-98.

Agoes, W.B., (1955): Airborne Scintillation Counter Surveys. *Trans. Can. Inst. Min. Metall., v. 58,* pp. 59-61.

Anderson, D.E., (1966): The structural metamorphic petrology of the Mount Robe District, Broken Hill, N.S.W. Ph.D. thesis, Univ. Sydney, unpublished.

Andrews, E.C., (1922): The geology of the Broken Hill District. *Mem. Geol. Surv. N.S.W. v. 8.*

Bates, R.G., (1966): Airborne radioactivity surveys, an aid to geologic mapping. *Mining Geophysics, v.1,* pp. 67-76.

Bell, K.G., (1954): Uranium and thorium in sedimentary rocks; in: Nuclear Geology, ed. H. Faul, John Wiley and Sons, New York, pp. 98-114.

Binns, R.A., (1962): Metamorphic proxenes from the Broken Hill district, N.S.W. *Mineralog. Mag. 33,* pp. 320-38.

Binns, R.A., (1963): Some observations on metamorphism at Broken Hill, N.S.W. *Proc. Australas. Inst. Min. Metall., 207,* pp. 239-259.

Binns, R.A., (1964): Zones of progressive regional metamorphism in the Willyama Complex, Broken Hill district, N.S.W. *J. Geol. Soc. Aust., 11(2),* pp. 283-325.

Both, R.A. and Rutland, R.W.R., (1976): The problem of identifying and interpreting stratiform ore bodies in highly metamorphosed terrains: The Broken Hill Example. Elsevier Scientific Publishing Company, Amsterdam, Chapter 6, pp. 261-325.

Browne, W.R., (1922): Report on the Petrology of the Broken Hill Region, excluding the Great Lode and its immediate vicinity. *Mem. Geol. Surv. N.S.W., 8,* pp. 295-353.

Campbell, K., (1974): Bibliography of the Geology of Broken Hill and District. Geological Research Library, Broken Hill Mining Managers' Association. Univ. N.S.W., W.S.&.L.B. Robinson University College, Broken Hill, N.S.W. March, 1973 and April, 1974.

REFERENCES (cont'd)

Campana, B. and King, D., (1958): Regional geology and mineral resources of the Olary Province. *Bull. Geol. Surv. S. Aust., 34.*

Charbonneau, B.W. and Darnley, A.G., (1970): A test strip for calibration of airborne gamma-ray spectrometers; in report of Activities. *Geol. Surv. Can., Paper 70-1, Pt. B,* pp. 27-32.

Charbonnea, B.W., Richardson, K.A. and Grasty, R.L., (1973): Airborne gamma-ray spectrometry as an aid to geological mapping, Township No. 155, Elliott Lake area, Ontario; in Report of Activities, Pt. B., Geol. Surv. Can., Paper 73-1, pp. 39-47.

Cooper, P.F., (1975): Explanatory Notes Broken Hill Geological Sheet (1:250,000). *Geol. Surv. N.S.W., 1975.* pp. 1-56.

Darnley, A.G.,(1970): Airborne gamma-ray spectrometry; *Can. Min. Mettal., Trans., v. 73,* pp. 20-29.

Darnley, A.G., (1973): Airborne gamma-ray survey techniques present and future; in Uranium Exploration Methods, IAEA Vienna, pp. 67-105.

Darnley, A.G., (1975): Uranium exploration '75. Geol. Surv. Can., Paper 75-26, pp. 21-31.

Darnley, A.G., Bristow, Q. and Donhoffer, D.K., (1969): Airborne gamma-ray spectrometer experiments over the Canadian Shield; in Nuclear Techniques and Mineral Resources, IAEA Vienna, pp. 163-186.

Darnley, A.G. and Grasty, R.L., (1971): Mapping from the air by gamma-ray spectrometry, Can. Inst. Min. Metall., Special Volume 11, Proc. 3rd. International Geochemical Exploration Symposium, Toronto, pp. 485-500.

Demnati, A. and Naudy, H., (1975): Gamma-ray spectrometry in Central Morocco, Geophysics, v.40, No. 2, pp. 331-343.

Dury, G.H., (1966): Duricrusted residuals on the Barrier and Cobar pediplains of New South Wales. *J. Geol. Soc. Aust. 13(1),* pp. 299-307.

Duval, J.S. et al. (1971): Circle of investigation of an airborne gamma-roy spectrometer: *J. Geophys. Res., v.76,* pp. 8466-8470.

Foote, R.S., (1967): Radioactive methods in mineral exploration. Mining and Groundwater Geophysics, Rep. No. 26, Geol. Surv. Can., pp. 177-190.

Glen, R.A., (1978): Structural and metamorphic relations between low, medium and high grade rocks, Mt. Franks-Mundi Mundi Area, Broken Hill, N.S.W. Ph.D. Thesis (unpublished), University of Adelaide, South Australia.

Glen, R.A. and Laing, W.P., (1975): The significance of sedimentary structures in the Willyama Complex, N.S.W. Proc. Australas. Inst. Min. Metall., No. 256, pp. 15-20.

Glen, R.A., Laing, W.P., Parker, A.J. and Rutland, R.W.R., (1977): Tectonic relationship between the Proterozoic Gawler and Willyama Orogenic Domains, Australia. *J. Geol. Soc. Aust. v.24(3)*, pp. 125-150.

Grasty, R.L., (1975): Uranium measurement by airborne gamma-ray spectrometry. *Geophysics, v.40*, pp. 503-519.

Grasty, R.L., (1976): A calibration procedure for an airborne gamma-ray spectrometer. Geol. Surv. Can., Paper 76-16, pp. 1-9.

Gregory, A.F., (1955): Aerial detection of radioactive mineral deposits. *Trans. Canadian Inst. Min. Metall. v. 58*, pp. 261-267.

Gregory, A.F., (1956): Analysis of radioactive sources in aeroradiometric surveys over oil fields. *Amer. Assoc. Petrol. Geol. Bull., v. 40, No. 10*, pp. 2457-2474.

Gregory, A.F., and Horwood, J.L., (1961): A laboratory study of gamma-ray spectra at the surface of rocks; Mines Branch Res. Rep. R85, Ottawa.

Gustafson, J.K., Burrel, H.C. and Garretty, M.D., (1950): Geology of the Broken Hill Ore Deposits, N.S.W., Australia. *Bull. Geol. Soc. Am. 61*, pp. 1374-1378.

Heinrich, E.W., (1958): Mineralogy and geology of radioactive raw materials. McGraw-Hill Book Co., New York, pp. 483-493.

Heir, K.S. and Carter, J.L., (1964): Uranium thorium and potassium in basic rocks and their bearing on the nature of the upper mantle; in: The Natural Radiation Environment, The University of Chicago Press, pp. 63-85.

Hobbs, B.E., (1966): The structural environment of the northern part of the Broken Hill ore body. *J. Geol. Soc. Aust., 13;* pp. 315-338.

REFERENCES (cont'd)

Hobbs, B.E. and Vernon, R.H., (1968): The structural and metamorphic history of the area around the northern half of the Broken Hill Lode. *Proc. 8th Commonw. Min. Metall. Congr. 6,* pp. 1419-28.

Hobbs, B.E., Ransom, D.M., Vernon, R.H. and Williams, P.F., (1968): The Broken Hill ore body, Australia. A review of recent work. *Miner. Deposita, 3,* pp. 293-316.

Horsfall, K.R. and Wilkes, P.G., (1972): Aeromagnetic and radiometric survey of Cobourg Peninsula, Alligator River and Mount Evelyn (Part) 1:250,000 Sheet Areas. Bur. Min. Res., Rep. 1975/89.

Isles, D.J., (1977a): Notes on the Bouguer Anomaly Map of the Broken Hill Region. Report, Dept. of Econ. Geol., Univ. Adel. S.A. (unpublished).

Isles, D.J., (1977b): Programs for processing magnetic and radiometric data on BMR computer tapes. Dept. of Econ. Geol., Univ. Adel. (unpublished report).

Isles, D.J., (1978): Fortran programs for manipulating magnetic tapes in BMR standard data format. Dept. of Economic Geology, University of Adelaide (unpublished report).

Jaquet, J.B., (1894): Geology of the Broken Hill Lode and Barrier Ranges Mineral Field, N.S.W., Mem. Geol. Surv. N.S.W., Geol. 5, 149pp.

Johannsen, A., (1932): A descriptive petrography of the igneous rocks.

Karkhanavala, M.D., (1958): On radioactive uraniferous iron oxides. *Geochi. et Cosmochi. Acta, v.15,* pp. 229-236.

Kellogg, W.C., (1968): Aerial radioactivity surveying: Techniques of successful application. Airborne Geophysics Division, Lockwood, Kessler and Bartlett, Inc. Consulting Engineer, Pasadena, California.

Ketola, M., Piiroinen, E. and Sarikkola, R., (1975): On feasibility of airborne radiometric surveys for uranium exploration in Finland. Fin. Geol. Surv., Rep. No. 7, 43p.

King, H.F. and Thomson, B.P., (1953): Geology of the Broken Hill district: In: A.B. Edwards (Editor), Geology of Australian Ore Deposits, *Emp. Min. Metall. Congr., 5th,* pp. 578-600.

REFERENCES (cont'd)

Langford-Smith, J. and Dury, G.H., (1964): A pediment survey of Middle Pinnacle, near Broken Hill, New South Wales. *J. Geol. Soc. Aust., 11(1),* pp. 79-88.

Lewis, B.R., Forward, P.S. and Roberts, J.B., (1965): Geology of the Broken Hill Lode, Reinterpreted, Geology of Australian Ore Deposits, 2nd ed. (Ed. J. McAndrew), pp. 319-332 (8th Empire Min. Met. Congr: Melbourne).

Lovering, T.C., (1955): Progress in radioactive iron oxides investigation. *Econ. Geol., 50, No. 2,* p. 186.

Mawson, D.M., (1912): Geological investigations in the Broken Hill area, *Roy. Soc. S. Aust., Mem. Vol. 2, part 4,* pp. 211-319.

McKelvey, V.E., Everhart, D.L.E. and Garrels, R.M., (1955): Proc. Int. Conf. Peaceful Uses of Atomic Energy, Geneva, V. VI. p. 551. United Nations.

McSharry, P.J., (1973): Reducing errors in airborne gamma-ray spectrometry. *Aust. Soc. Explor. Geophys., Bull. v.4, No. 1,* pp. 31-41.

Pidgeon, R.T., (1967): A Rubidium-Strontium Geochronological Study of the Willyama Complex, Broken Hill, Australia. *J. Petrology, 8,* pp. 283-324.

Pitkin, J.A., (1968): Airborne measurements of terrestial radioactivity as an aid to geologic mapping. U.S. Geol. Surv. Prof. Paper, 516F, pp. 1-29.

Ransom, D.M., (1968): The relationship of lode shape to wall-rock structure in the southern half of the Broken Hill ore body. *J. Geol. Soc. Aust., 15,* pp. 57-64.

Rayner, E.O., (1955): Davidite and other radioactive occurrences in the Thackaringa area. N.S.W. Tech. Rep. Dept. Mines, N.S.W., v.3, pp. 62-72.

Rayner, E.O., (1957): The nature and distribution of uranium deposits in New South Wales. Tech. Rep. Dep. Mines, N.S.W. vol. 5 for 1957, pp. 63-101.

Richards, S.M., (1966): The banded iron formations at Broken Hill, Australia, and their relationship to the lead-zinc orebodies. *Econ. Geol., 6,* pp. 72-92.

Rutland, R.W.R., (1973): A note on major structures in the Willyama Complex, Broken Hill, N.S.W. *Trans. R. Soc. S. Aust. 97*, pp. 77-90.

Rutland, R.W.R. and Etheridge, M.A., (1975): Two high grade schistosities at Broken Hill and their relation to major and minor structures. *J. Geol. Soc. Aust., 22*.

Ruzicka, V., (1975): New sources of uranium? Types of uranium deposits presently unknown in Canada. Uranium Exploration '75. *Geol. Surv. Can., Paper 75-26*, pp. 13-19.

Stillwell, F.L., (1922): The Rocks in the Immediate Neighbourhood of the Broken Hill Lode and their Bearing on its Origin. *Mem. Geol. Surv. N.S.W., 8*, pp. 354-396.

Stillwell, F.L., (1953): Mineralogy of the Broken Hill Lode. In: A.B. Edwards, (Editor), Geology of Australian Ore Deposits. *Emp. Min. Metall. Congr., 5th*, pp. 601-626.

Suto, K., (1978): Explanatory notes of GEOROUTINES. Report, Dept. of Econ. Geology, Univ. Adel. (unpublished).

Thomas, W.N., (1961): Environmental aspects of ore occurrence at Broken Hill, in: "Syngenesis in ore Deposition". Symposium Aust. N.Z. Ass. Advmt. Sci., Brisbane, Roneoed Sheet.

Thomson, B.P., (1956): Tectonics and Archaean Sedimentation of Barrier Ranges, N.S.W. Univ. Adel. M.Sc. Thesis (unpublished).

Thomson, B.P., (1973): Ore deposits in relation to the tectonic development of Eastern Australia. *Bull. Bur. Miner. Res., 141*, pp. 95-105.

Turner, F.J. and Verhoogen, J., (1960): Igneous and Metamorphic Petrology. McGraw Hill, New York, N.Y., 2nd ed., 694pp.

Vernon, R.H., (1969): The Willyama Complex, Broken Hill Area. In: G.H. Packham (Editor). The Geology of New South Wales, *Geol. Soc. Aust., 16*, pp. 20-55.

Vernon, R.H. and Ransom, D.M., (1971): Retrograde schists of the amphibolite facies at Broken Hill, N.S.W. *J. Geol. Soc. Aust., 18*, pp. 267-277.

Williams, P.F., (1967): Structural analyses of the Little Broken Hill area, N.S.W. *J. Geol. Soc. Aust. 14*, pp. 317-331.

REFERENCES (cont'd)

Wyatt, B.W., (1977): (pers. comm.) Geophysicist, Bur. Miner. Res., Canberra, A.C.T., Australia.

LIST OF APPENDICES

APPENDIX 1A

AIRBORNE TOTAL COUNT AND MAGNETIC SURVEY, 1959

Operator	Bureau of Mineral Resources, Geology & Geophysics, Canberra, A.C.T.
Aircraft	DC-3.
Altitude	500 feet above ground level, controlled through the Radio Altimeter.
Line spacing	One quarter of a mile.
Line orientation	East-west.
Tie system	3 north-south single tie lines.
Navigation	Aerial photographs.
Background	Measured at 2000 feet above ground level.
Calibration	Applied.
Time constant	1 second.
Mode of recording survey data	Analogue.
Gamma radiation	Recorded by Scintillometer, single NaI(Tl) crystal of 6x4 in.
Magnetic intensity	Recorded by Magnetometer.

APPENDIX 1B

AIRBORNE SPECTROMETER AND MAGNETIC SURVEY, 1975

Aircraft	Twin Otter VH-BMG
Ground speed	55 m/sec.
Altitude	100 metres above ground level
Line spacing	300 metres (Detailed) 1.5 km (Regional)
Line orientation	east-west
Tie system	5 north-south double tie pairs
Doppler	Marconi AD-560 system
Camera	BMR 35 mm strip camera
Altimeter	Collins ALT 50
Spectrometer	Hamner Harshaw
Detector	3700 cc Sodium Iodide (226 cu in.) (2 crystals each 15.24 cm diameter, 10.16 cm thick = 6 x 4 in.)

Energy Levels Recorded

CHANNEL	WINDOW WIDTH
Total count	0.84 - 3.0 MeV
Potassium	1.3 - 1.6 MeV
Uranium	1.6 - 1.9 MeV
Thorium	2.4 - 2.8 MeV
Timer	BMR NZA1
Magnetometers	Fluxgate MFS-7 (airborne) Proton MNS-2 (ground)
Acquisition system	Hewlett Packard 2114 B computer
Sampling period	Magnetic field.......0.2 sec. Altimeter............1.0 sec. Spectrometer.........1.0 sec. Doppler.............10.0 sec.
Chart recorder	Geometrics MARS-6 H.P. Mosley 2100 B

APPENDIX 2

DATA PROCESSING AND PRESENTATION BY THE B.M.R.*

All digital data tapes were merged and processed in Canberra using the B.M.R's Hewlett Packard 2100 and CSIRO's CDC CYBER 76 computers. All profiles, flight path maps and contour maps were drawn using the B.M.R's Calcomp drum and flatbed plotters.

Flight Path Recovery

Four control points on each flight line were plotted on air photos, transferred to 1:25,000 scale planimetric maps, digitised and then used to position absolutely the doppler coordinates recorded digitally during flight.

Flight line plots were produced at scales of 1:100,000 for use with all stacked profiles and at 1:50,000 for superposition with magnetic contour at that scale (maps published and released).

The baseline for each profile in the abovementioned stacked profiles is the straight line being the best least squares fit to the actual flight path.

Magnetic Data

Total magnetic intensity was recorded every 0.2 seconds but all the processing used one second averages of this. The 0.2 second data has been achieved in an unedited form.

The edited magnetic data was levelled to the Broken Hill regional survey using the five common double tie pairs. No subtraction of recorded diurnal changes was attempted. Drift, as approximately by third order polynomials, was removed from each flight.

The regional gradient was removed using the IGRF model for 1965.0 at 300 metres above sea level and a constant of 5000 nT was added for presentation purposes.

The magnetic field was contoured using one data point every three seconds along flight lines and using a grid of 60 metres in the east-west direction and 50 metres in the north-south direction. Preliminary total magnetic intensity contours have been produced as ten sheets at 1:25,000 scale and as a composite at 1:100,000 scale. Final contours are to be published at 1:50,000 scale with superimposed flight path and topographic information.

The magnetic field has also been displayed as a set of stacked profiles expanded four times in the north-south direction for clarity.

Gamma-ray Spectrometer Data

Background variation was assumed to be linear throughout the flight and was subtracted using measurements made at 660 metres above ground level at the start and end of each flight.

The data set was normalised to 100 metres above ground level using the formula:

$$C_{100} = C_h \exp{-\mu(100-h)}$$

where C_{100}, C_h are the count rates at heights of 100 and h metres respectively and μ is the attenuation coefficient. μ = 0.00656, 0.00755, 0.00557, 0.00557 for Total count, Potassium, Uranium and Thorium respectively.

Compton scattering corrections were applied using the formulae:

$$U_{stripped} = U - \alpha . Th$$

$$K_{stripped} = K - \beta . Th - \gamma . U_{stripped}$$

where $\alpha = 0.7$, $\beta = 0.75$, $\gamma = 1.1$

The values of α, β, and γ have not been properly established and may be in error.

The four spectrometer channels were filtered using a low pass filter with the following coefficients:

0.03512, 0.1236, 0.2148, 0.2531, 0.2148, 0.1236, 0.3512

Ratios of the corrected and filtered data were taken as follows:

U/Th, U/K, Th/K, U.U/Th, U.Total/Th

and the same low pass filter was applied to the U/Th, U/K, Th/K data.

The Total count data for the regional survey have been contoured but not yet released, using one observation every five seconds along flight lines and using a surface grid of dimension 100 metres in the east-west direction and 85 metres in the north-south direction.

Total count, Potassium, Uranium, Thorium, Altimeter channels (published) and U/Th ratio (unpublished) have been presented as stacked profiles expanded four times in the north-south direction.

PROGRAM GAMADJ

The program corrects for deviations from mean terrain clearance in all channels and/or for Compton Scattering contributions to the observed K_{40}, (channel 2) and Bi_{214} (channel 3) counts. The program also has facilities to subtract constant from the data and/or multiply all data by a constant.

The program assumes exponential attenuation of intensity with ground clearance up to a maximum of 250 m. The equations used for height correction are:

$$C_1 = C_1(h)\exp(-\mu_1 \Delta h)$$
$$C_2 = C_2(h)\exp(-\mu_2 \Delta h)$$
$$C_3 = C_3(h)\exp(-\mu_3 \Delta h)$$
$$C_4 = C_4(h)\exp(-\mu_4 \Delta h)$$

C_1, C_2, C_3, and C_4 are the height corrected counts and $C_1(h)$, $C_2(h)$, $C_3(h)$, and $C_4(h)$ are the measured counts in channels 1-4 respectively, after background correction.

μ_1, μ_2, μ_3, μ_4 are the attenuation coefficients for each channel.

h = h - hs, whereas hs is the ground clearance datum.

The spectral interaction corrections are made using the equations:

$$K_2 = C_2 - \gamma\, U_3 - \beta Th$$
$$U_3 = C_3 - \alpha Th$$
$$Th_4 = C_4$$

Values of attenuation coefficients and correction factors are input to the programs by the user. If ground clearance is greater than 250 m or if data are missing for any one spectrometer channel, then all of the corresponding spectrometer data are deleted.

---

*Notes were kindly provided by Bruce Wyatt, Geophysicist at the B.M.R., during the writer's visit to the B.M.R. in October, 1977.

The published account of the survey data may be available by the end of 1978.

APPENDIX 3

DATA PROCESSING

All data, including magnetic, radiometric, altitude and navigational data from the B.M.R's 1975 survey of the Broken Hill area was recorded on magnetic tape. In 1976, the B.M.R. kindly made available a complete copy of the survey data to the University of Adelaide for use in its research related to the Broken Hill region. A full account of the organisation of the information is given by Isles (1977). Briefly, the data is stored in binary form on tapes with each flight line representing a definite entity, a file, on the tape. All of the information required to identify the numbers in each file is also written at the beginning of each file. The data has been grouped to allow rapid processing into Regional and Detailed survey lines and also within these classifications radiometric and magnetic data exist on separate tapes, both with included geographic coordinates. In addition for both the Regional and the Detailed surveys a 'back up' tape is available with a skeleton of navigation data and the magnetic and radiometric data written together.

The data presentation is of high quality and so the tapes are generally easy to process, reading time is not excessive and small sections of the data may be readily assessed.

DATA PROCESSING SYSTEM

Three routines were developed by Isles (1977) to process the BMR data from the magnetic tapes. The routines were designed to apply to small sections of data corresponding to particular areas of interest rather than the complete data set or a data set comprising whole lines.

The routines perform the following tasks:

1. Flight line traces are plotted for a given scale or a selected area.

2. Required data on the selected area is written onto a disc file for easy repeated access in further processing.

3. Profiles from the data set produced in (2) are plotted at user defined scales.

Brief descriptions of the programs mentioned above are given with details of input parameters and resulting output.

PROGRAM BMRLINES

A flight path map is produced from the 'back up' tape containing the processed Doppler navigation data which is in the form of geographic coordinates at the Doppler recording points (intervals of 10 fiducials or approximately 500 m). Line numbers and fiducials are labelled on the plot which may be drawn on transparent film if required. Two versions of BMRLINES exist. One plots lines along the plotting drum allowing indefinite line length and a limited number of lines, whilst the complimentary program plots across the plotting drum giving a restricted line length, but an indefinite number of lines. The program simply reads the required lines, one at a time, selects the chosen range from the line then draws and labels the line. The coordinates of each control point are printed on the program output.

INPUT PARAMETERS

1. Number of lines preceding first required line.
2. Number of lines to be plotted.
3. Heading (80 characters to be drawn on the plot).
4. Origin and scale values for X (along line) and Y (across line) axes.
5. Coordinates for border to be drawn around the plot.
6. Range of X values to be selected from each line.
7. Any reference points to be included on plot.

OUTPUT

1. Flight line plot.
2. Print of control point coordinates.

PROGRAM BMREX

Extracts a set of data from a specified area and writes the data set to a disc file for later processing*.

INPUT.

1. Number of lines preceding first required line.
2. Number of lines required.
3. Range of X (along line) values required.
4. Number of data values required from each sample.

   e.g. a sample may consist of X, Y, T, U, Th, K and Alt values from which only X, U, Th and K values are required.
5. Location of required values within sample, e.g. in above, 1st, 4th, 5th and 6th value from sample are selected.

OUTPUT

Print of line details, X values of limits of selected data set, corresponding fiducials and print of all requested data values.

Note: Because of varying sizes of data sets the program may need to have the number of arrays and the dimensions of arrays changed to minimise storage during execution of the program and hence increase the efficiency of the program.

PROGRAM PLOTSECT

Produces a profile of up to three different data types on each plot. The program operates on a data set produced by BMREX, plotting the complete X-range chosen by BMREX for each line.

INPUT

1. Number of lines preceding first required line.
2. Number of lines required to be plotted.
3. X-origin value and X-scale (common to all profiles).
4. For each data type required (i.e. 1→3). Type (e.g. thorium), location within sample, scaling factor, origin position on plot, origin value, height of plot for this data, type of line or symbol required on plot.

*For very large data sets (25 complete lines or more) which are not being repeatedly used, the disc storage costs make the use of this program uneconomical, and it is advisable to read the data directly from the tape when required.

OUTPUT

Profiles with fiducials marked and labelled on X-axis. Examples can be seen in Figs. 5.5, 5.6 and 5.7.

A scaling diagram is drawn prior to plotting the profiles and since the scales are common to all profiles, the scaling information is not repeated with each profile. Minimum information is printed since the program has entirely a graphic function.

APPENDIX 4

DESCRIPTION OF PORTABLE SPECTROMETER, DISA 400*

The sensor consists of one 3" diameter x 3" thick Sodium Iodide crystals, hermatically sealed. Power is supplied from a fully regulated electric high tension (EHT) supply which is itself supplied from a low voltage regulated supply.

Sensor output is taken to a preamplifier consisting of a charge amplifier which takes care of signal degredation due to varying cable lengths.

The amplified signal passes to the Pulse Height Discriminator (PHD's) where 4 separate PHD's are set at varying window widths to process the incoming signal. The windows allow only that signal which is above and below a certain level to pass to the adjustable rate meter circuits.

The threshold stabilizer circuit uses the cesium peak to correct window width variation due to temperature or power supply fluctuations. This must be performed manually during the duration of the survey.

One rate meter is used, being switched to each window to give individual readings on each window.

One frequency counter is used to count and store the pulses from each window for the specified time, in this case 1 second to 30 minutes. The data is latched to a buffer within the counter and displayed for about four seconds in a sequence from T_o to T_3.

---

*Notes were provided by John Willoughby, Department of Economic Geology, University of Adelaide, South Australia.

APPENDIX 5

EXPLANATION OF BLOCK DIAGRAM*

The sensor consists of two 6" diameter x 4" thick Sodium Iodide crystals, thermally insulated against sudden temperature variations. Power is supplied from a fully regulated electric high tension (EHT) supply which is itself supplied from a low voltage regulated supply.

Sensor output is taken to a preamplifier consisting of a charge amplifier which takes care of signal degredation due to varying cable lengths.

The amplified signal passes to the Pulse Height Discriminator (PHD's) and Automatic Threshold Stabilizer where 4 separate PHD's are set at varying window widths to process the incoming signal. The windows allow only that signal which is above and below a certain level to pass to the adjustable rate meter circuits.

The automatic threshold stabilizer circuit uses the cesium peak to correct window width variation due to temperature or power supply fluctuations.

Four adjustable rate meters are used, one for each window and are set to give the best readings on each window, the readings are monitored on the count rate monitor meter during flight.

Four frequency counters are used to count and store the pulses from each window for the specified time, in this case 1 second. The data is latched to a buffer within the counter ready for the digital recorder to store the data or tape while the next sample is being accumulated.

---

*Notes were kindly provided by John Willoughby, Department of Economic Geology, University of Adelaide, South Australia.

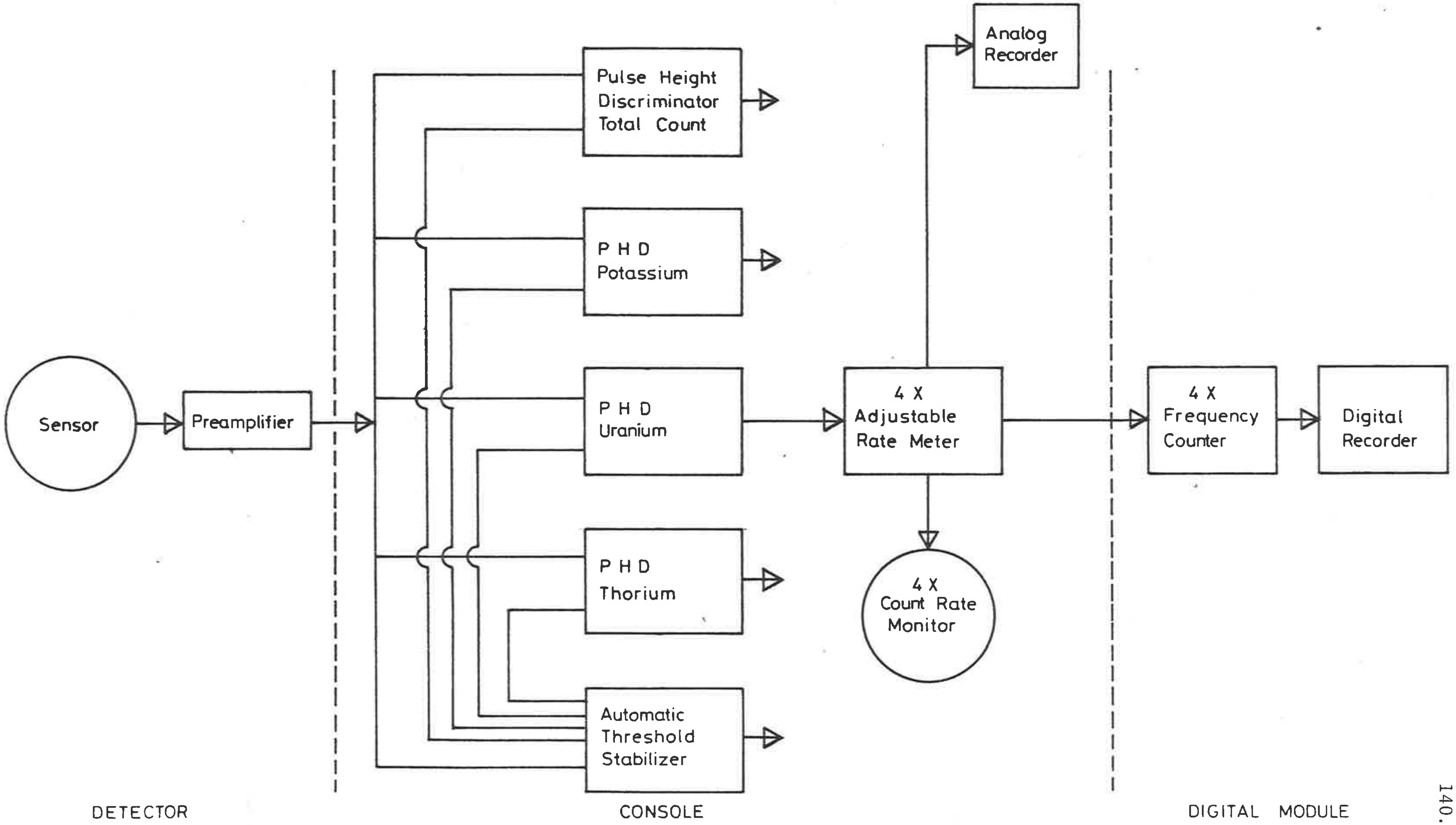


Fig.:5.1, BLOCK DIAGRAM OF AIRBORNE FOUR CHANNEL GAMMA-RAY DIFFERENTIAL SPECTROMETER

APPENDIX 6

SPECIFICATION FOR GAMMA-RAY SPECTROMETER SURVEY*

OPERATIONAL PARAMETERS

Mean flying height	:	400 ft. ± 25 ft.
Local height deviations	:	+400 ft.-200 ft.
Airspeed	:	To be held ± 5 mph in range 60 to 120 mph; detector size and counting interval to be determined according to speed of aircraft to be used.

DETECTOR SYSTEM

Crystal size : Minimum diameter of individual crystals 5"
Minimum thickness of individual crystals 4"

Detector volume: The number of crystals employed must provide: a total of approximately 1500 in^3 of NaI(Tl) at 60 mph or approximately 3000 in^3 of NaI(Tl) at 120 mph. or pro rata at intermediate speeds.

Detector stabilization: Maintain at constant temperature and if single channel analysers are used in spectrometer system, a radioisotope calibration-source spectrum stabilizer is necessary. This calibration source must not interfere with the specified window widths.

1. Sampling time: Counts to be accumulated over sampling times in the range 0.5 to 5.0 secs; to be pre-selected according to operational requirements.

2. Terrain clearance: A suitable means of continuously monitoring terrain clearance, e.g. radar altimeter, must be used in conjunction with the spectrometer, and mean terrain clearance during each sampling period must be determined and recorded with the data from the spectrometer.

3. Line spacing: Detailed survey: 0.25 mile (or 0.5 km)

Reconnaissance survey: 2.5 or 5.0 km; to be determined by scientist in charge.

---

*Abstracted from Airborne Gamma-Ray Survey Techniques, Darnley, 1971.

<u>Fig. 3.7</u> Geological map of Broken Hill (Australia, Geological Series Sheet SH 54-14, 1:250,000).

Overlay 1 = Flight-line system
Overlay 2 = Uranium, above average response
Overlay 3 = Thorium " " "
Overlay 4 = Potassium " " "
Overlay 5 = Total count" " "

Source of data - geology base from Australia, Geological Series Sheet SH 54-14 (1:250,000), Department of Mines, N.S.W. First Edition, 1970.

Radiometrics compiled from a study of original airborne spectrometer survey data presented in the form of stacked profiles (at 1:250,000 scale), B.M.R. survey, 1975.

FIG 3.7

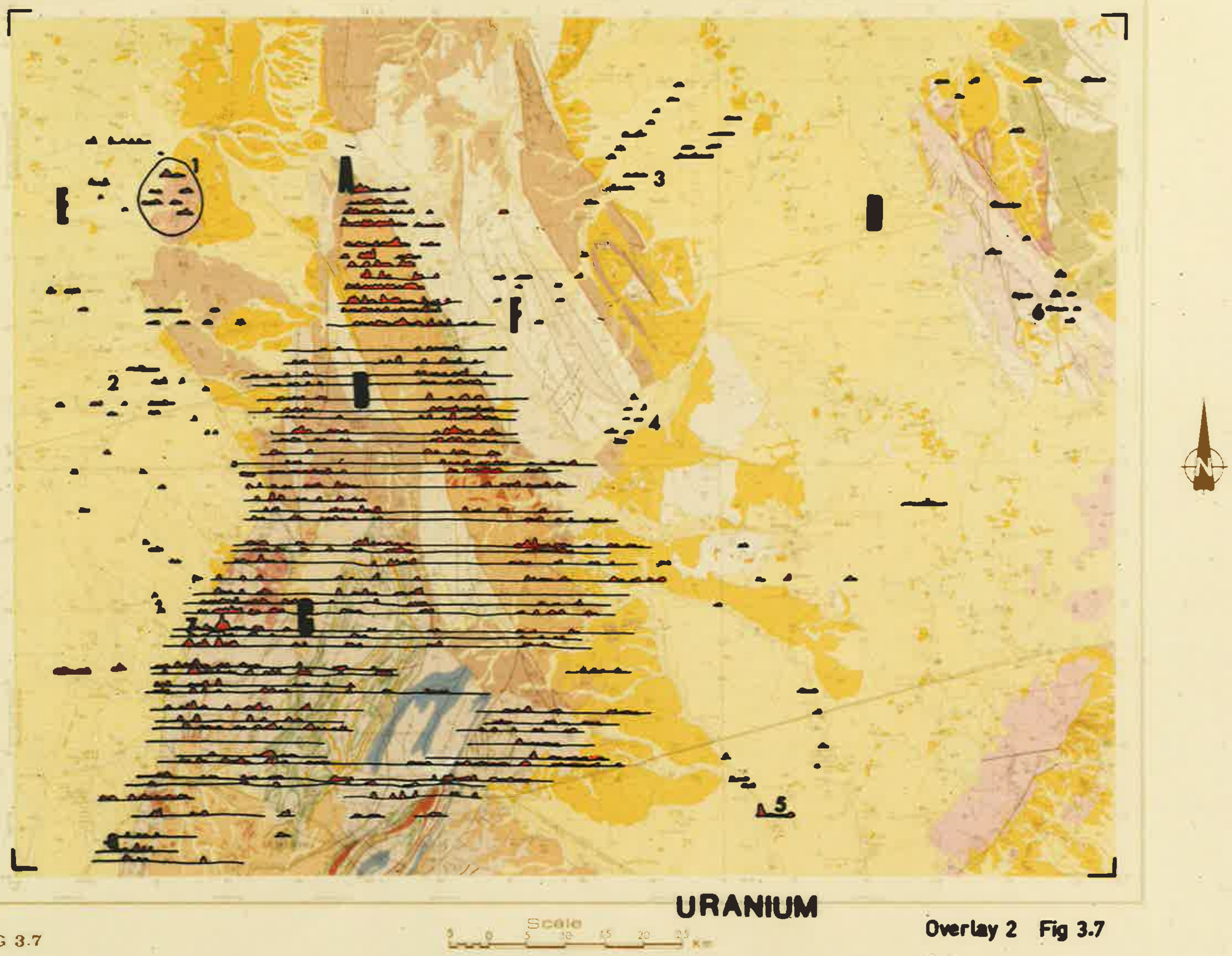
GENERALIZED GEOLOGY

FIG 3.7
FLIGHT-LINE SYSTEM
GENERALIZED GEOLOGY

AUSTRALIA 1:250 000

BROKEN HILL

1:250 000 GEOLOGICAL SERIES SHEET SH 54-14



URANIUM

Overlay 2 Fig 3.7

FIG 3.7

GENERALIZED GEOLOGY

AUSTRALIA 1:250 000 BROKEN HILL 1:250 000 GEOLOGICAL SERIES SHEET SH 54-14

THORIUM

FIG 3.7

Scale
5 0 5 10 15 20 25 Km

Overlay 3 Fig 3.7

GENERALIZED GEOLOGY

FIG 3.7

GENERALIZED GEOLOGY

POTASSIUM

Overlay 4 Fig 3.7

FIG 3.7

GENERALIZED GEOLOGY

TOTAL COUNT

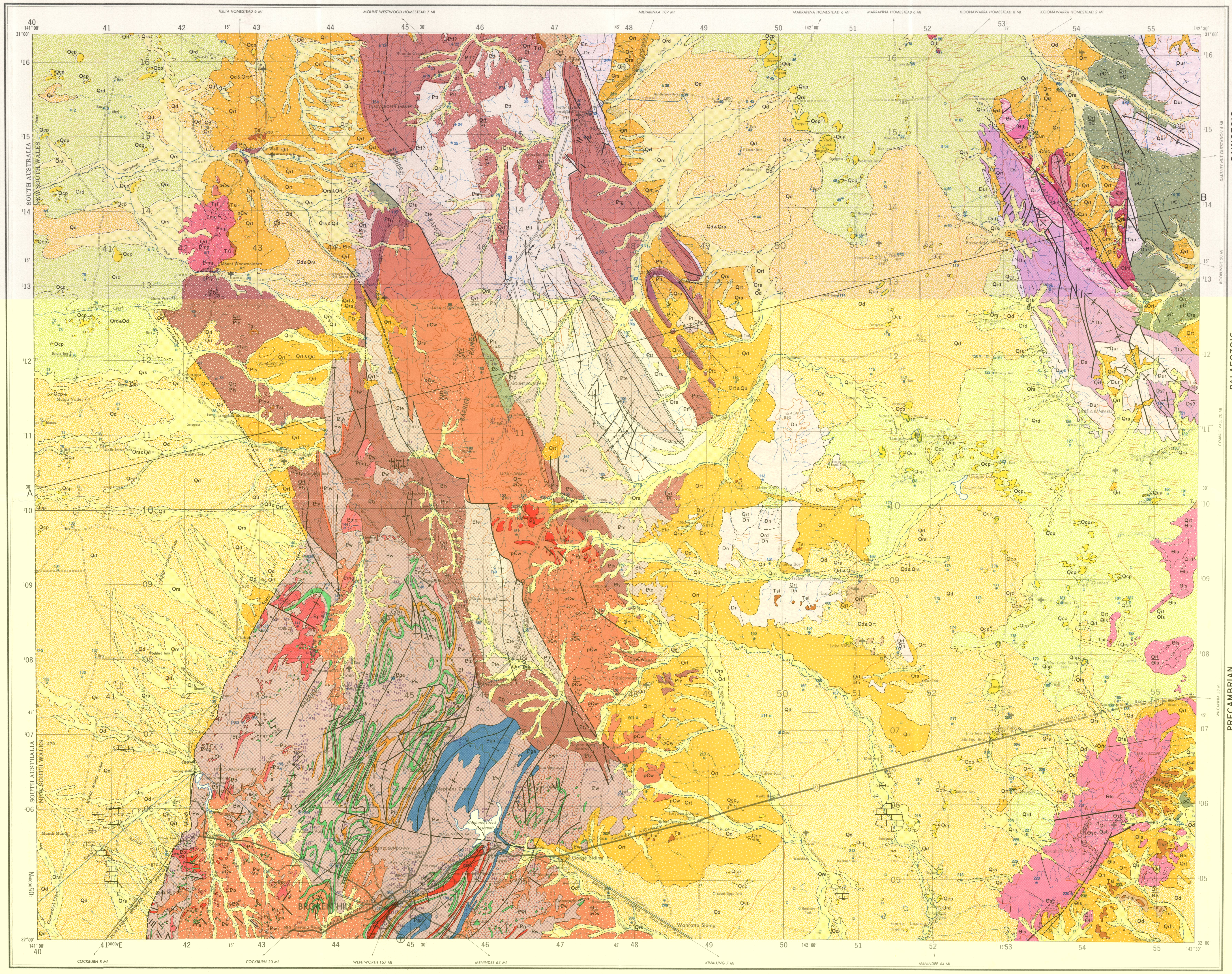
Overlay 5 Fig 3.7

AUSTRALIA 1:250,000

BROKEN HILL

1:250,000 GEOLOGICAL SERIES SHEET SH 54-14

FIRST EDITION, 1970



Reference

- Built-up area
- Road sealed surface first class; route marker
- Road sealed surface second class; mileage
- Road loose surface dry weather
- Road unimproved earth, gate
- Railway, single track
- Siding, station with siding
- Telephone line, power transmission line
- Windpump; yard; building(s); church
- Wireless transceiver; cemetery
- Airport or airfield; landing ground
- Control point major; minor; astronomical
- Spot elevation in feet
- Contours with value
- Sand ridges
- Water tank; dry lake, water pipeline
- Lake; perennial
- Lake, river or stream intermittent

Geological Boundaries
- Established boundary—position accurate (includes interpreted boundaries in central Willyama Complex)
- Established boundary—position approximate
- Inferred or probable boundary

Strike and Dip of Foliation (dominately bedding)
- Measured
- Inclined showing prevailing dip
- Vertical
- Trend from aerial photographs

Faults
- Established fault—position accurate
- Established fault—position approximate
- Concealed fault
- Inferred or probable fault
- Inferred or probable fault—concealed
- Lineament
- Basic Dykes

Folds
- Anticline—position accurate
- Anticline—position approximate
- Syncline—position accurate
- Syncline—position approximate
- Plunge of fold

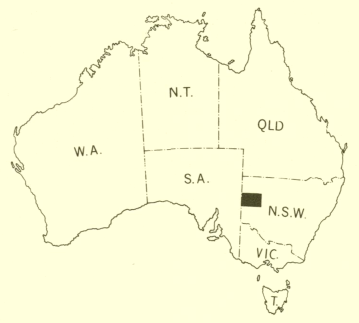
Bores
- Number refers to list in text
- Water bores positioned by R.A.S.C.
- Water bore positioned by Water Conservation and Irrigation Commission
- Radiometric age sample showing age in million years
- Fossil Locality
- Mineral Deposits

Reference

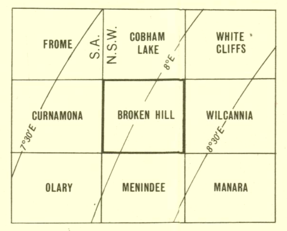
CAINOZOIC	QUATERNARY		Qrs	Floodplains, outwash areas and drainage flats of black and red clayey silt and sand
			Qcp	Playas, lakes and "claypans" of black and grey silty clay and silt
			Qd	Flat to gently undulating plains of red and brown clayey sand, loam and lateritic soils
			Qrd	Dune deposits of red and brown clayey sand, loam and lateritic soils, irregular deposits of aeolian sand
			Qrt	Residual and colluvial deposits of angular poorly sorted sand and gravel
				Infilled "mud cracks" up to twelve feet wide
	TERTIARY?		Tsi	Silicified conglomerate, quartzite and porcellanite, diagenetic siliceous cement, includes "greybilly" and "Duricrust"
			T	Undifferentiated Tertiary sediments including Tsi ferruginous and poorly consolidated sandstone, siltstone and claystone
			Qrt/T	Tertiary sediments largely obscured by Qrt
			Cza	Undifferentiated Cainozoic sediments; may include some Mesozoic sediments. (Sections only)
PALAEOZOIC	CARBONIFEROUS? TO UPPER DEVONIAN?	Ravendale Formation	Dur	Flaggy quartz sandstones
		Nundooka Sandstone	Dn	Quartz sandstone
		Coco Range Beds	Dc	Quartz sandstone, siltstone and conglomerate
			Qrt/Dn	Nundooka Sandstone largely obscured by Qrt
	DEVONIAN	Snake Cave Sandstone	Ds	Sandstone, conglomerate, siltstone
	LOWER ORDOVICIAN	Scopes Range Beds	Ols	Quartz sandstone and conglomerate, white claystone and siltstone
			Osc	Red conglomerate, sandstone and siltstone. Time equivalent of Bynguano Quartzite
			Osb	Poorly sorted, semiconsolidated "scree" breccia
			Qrt/Ols	Scopes Range Beds largely obscured by Qrt
	ORDOVICIAN	Mootwingee Group: Rowena Formation	Or	Shale, siltstone, limestone
	LOWER ORDOVICIAN	Mootwingee Group: Bynguano Quartzite	Olb	Quartzite, sandstone
	UPPER UPPER CAMBRIAN	Mootwingee Group: Nootumbulla Sandstone	Cun	Sandstone, shale, siltstone
	LOWER MIDDLE CAMBRIAN	Gnalta Group: Coonigan Formation	Cmc	Shale, limestone, sandstone
	LOWER CAMBRIAN	Gnalta Group: Cymbric Vale Formation	Clc	Shale, siltstone
		Gnalta Group: Mt. Wright Volcanics	Clm	Volcanics with limestone, shale and chert interbeds
	LOWER CAMBRIAN?	Acacia Downs Formation	Clw	Quartzite, shale, siltstone
PRECAMBRIAN	UPPER PROTEROZOIC (Probable Adelaide System Equivalents) — Marinoan	Torrowangee Group: Lintiss Vale Beds	Ptl	Quartzite shale and limestone
		Camels Hump Quartzite	Ptc	Quartzite and shale
		Fowlers Gap Beds	Ptg	Quartzite, shale and limestone; Quartzite markers
		Far-Away-Hills Quartzite	Ptf	Quartzite
		Teamsters Creek Beds	Ptt	Shale, quartzite, tillitic sandstone, limestone; Dolomite; Horizon of erratic boulders and tillitic sandstone
	Sturtian	Euriowie Beds	Pte	Laminated tillitic shales, limestone, sandstone and conglomerate
			Qrt/Pte	Euriowie Beds largely obscured by Qrt
		Yancowinna Beds	Pty	Conglomerate, sandstone, numerous erratic pebbles and boulders of possible glacial origin; Limestone
			Qrt/Pty	Yancowinna Beds largely obscured by Qrt
	Torrensian	Pintapah Quartzite	Ptp	Quartzite, sandstone, pebbly quartzite
	Willouran	Wilangee Volcanics	Ptw	Basalt, epidotised basalt
			Qrt/Pt	Torrowangee Group largely obscured by Qrt
	MIDDLE PROTEROZOIC	Mundi Mundi Granite	Pmg	Granite, includes similar age granites of Broken Hill area Radioactive age 1307–1466 m.y.
			Qrt/Pmg	Mundi Mundi Granite largely obscured by Qrt
	LOWER TO MIDDLE PROTEROZOIC (Age by Radiometric dating)	Bijerkerno Beds	Pb	Sandstone, siltstone, chert, black shale
		Wonominta Beds	pC	Schist phyllite, quartzite. Includes probable Precambrian of Scopes Range area
			Qrt/pC	pC largely obscured by Qrt
		Willyama Complex	Pp	Pegmatite
			Pg	Granite gneiss
			Pw	Sillimanite gneiss, andalusite-, chiastolite-, mica-, schist, phyllite, quartzite, sandstone, slate
			a	Amphibolite
			Pf	Potossi-footwall gneiss, includes Parnell Gneiss of Corruga-Allendale area
			Pga	Augen granite gneiss, intrusive amphibolite
		Thorndale Gneiss	Pwt	Feldspathic gneiss, intrusive amphibolite
			pCw	Undifferentiated Willyama Complex
			Qrt/pCw	Willyama Complex largely obscured by Qrt

Note:—The interpretation of the Willyama Complex in the Allendale–Acacia Vale–Broken Hill–Yanco Glen area was prepared by K. S. Cordwell, K. R. Glasson and I. R. Williams for New Consolidated Goldfields (A/sia) Pty. Ltd.

Compiled by Division of Regional Geology Geological Survey of New South Wales. Base map compiled and drawn by the Royal Australian Survey Corps in 1963 from National Mapping compilation and 1954 and 1961 aerial photography. Photogeology by Geophoto Resources Consultants for Planet Exploration Co. Pty. Ltd. and G. Rose—Geological Survey of New South Wales. Published by New South Wales Department of Mines.



INDEX TO ADJOINING SHEETS
Showing Magnetic Declination as at 1965



Scale 1:250,000

Statute Miles 5 0 5 10 15 20 25
Nautical Miles 5 0 5 10 15 20
Yards 10,000 0 10,000 20,000 30,000
Kilometres 5 0 5 10 15 20 25

CONTOUR INTERVAL 250 FEET
VERTICAL DATUM IS BASED ON MEAN SEA LEVEL, PORT ADELAIDE

TRANSVERSE MERCATOR PROJECTION
HORIZONTAL DATUM IS BASED ON SYDNEY OBSERVATORY, LATITUDE 33°51'41.10"S LONGITUDE 151°12'17.85"E

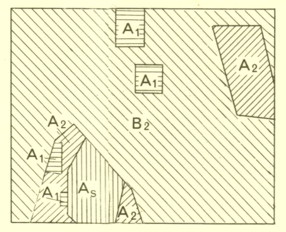
BLACK NUMBERED LINES INDICATE THE 10,000 YARD TRANSVERSE MERCATOR GRID, ZONE 6 (AUSTRALIA SERIES), CLARKE 1858 SPHEROID
THE LAST FOUR DIGITS OF THE GRID NUMBERS ARE OMITTED

1960 MAGNETIC DECLINATION FOR THIS SHEET VARIES FROM 7°30' EASTERLY FOR THE CENTRE OF THE WEST EDGE TO 8°00' EASTERLY FOR THE CENTRE OF THE EAST EDGE. MEAN ANNUAL CHANGE IS 03' EASTERLY.

Geology by:—D. E. Anderson, K. S. Cordwell, K. R. Glasson, W. H. Jones, E. J. Kenny, P. S. Lavers, G. Rose, N. F. Taylor, B. P. Thomson, C. R. Ward, K. R. Warne, R. A. Warner, I. R. Williams, B. Warris, C. N. Wright Smith, Enterprise Exploration Co. Pty. Ltd., North Broken Hill Ltd., New Consolidated Goldfields (A/sia) Pty. Ltd., Zinc Corporation Ltd.

Compiled by: G. Rose 1968
Drawn by: Mercury Press Pty. Ltd., Hobart

GEOLOGICAL RELIABILITY DIAGRAM

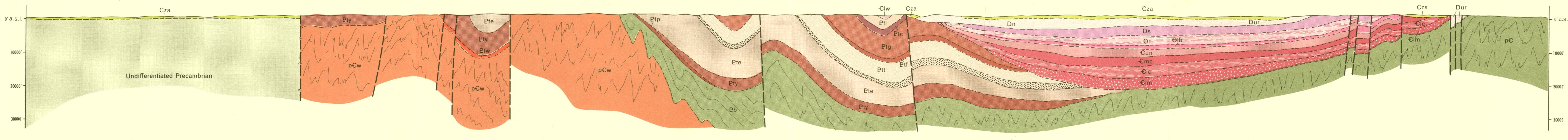


- A1 Detailed Mapping
- A2 Detailed Mapping with airphoto interpretation
- A3 Detailed Mapping with Stratigraphic interpretation
- B2 Airphoto interpretation with several ground traverses

Plate 2A

Section A B

Folding of pCw Pb pC Diagrammatic



BROKEN HILL
NEW SOUTH WALES
SHEET SH 54-14

Copies of this map may be obtained from the Department of Mines, Sydney, N.S.W.

Printed in Australia by V. C. N. Blight, Government Printer. New South Wales.

AUSTRALIA 1:250,000

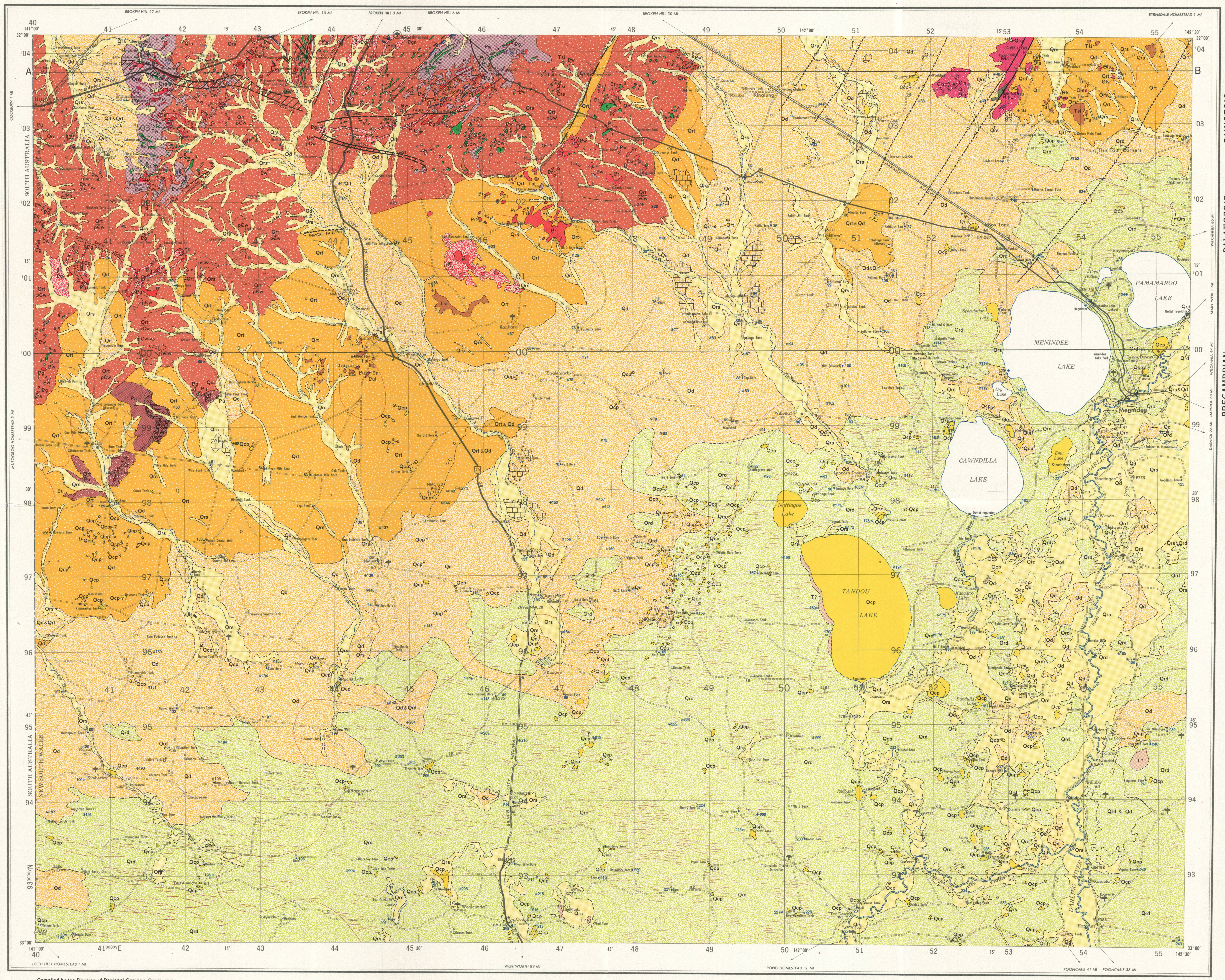
MENINDEE

1:250,000 GEOLOGICAL SERIES SHEET SI 54-3

FIRST EDITION, 1969

Reference

- Built-up area
- Road sealed surface first class; route marker
- Road sealed surface second class; mileage
- Road loose surface all weather
- Road loose surface dry weather
- Road unimproved earth
- Bridge road; bridge railway
- Railway Single track
- Station; Station with siding
- Telephone line; power transmission line
- Levee
- Mine; windpump; yard
- Building; post office; wireless transceiver
- Airport or airfield; landing ground
- Control point minor; astronomical
- Bench mark; spot elevation in feet
- Contours with value; sand ridges
- Lake; river or stream perennial
- Lake; river or stream intermittent
- Drain or ditch perennial; water tank
- Bores
- Number refers to list in text
- Water bore positioned by R.A.S.C.
- Water bore positioned from Water Conservation & Irrigation Commission Graticules



67 • *Mineral deposits*

1.	—	Cu, Pb, Zn.
2.	Pioneer Extended	—
3.	Lady Beryl	Be, Fs, Mi.
4.	Exhibition Lode	Pb, Ag.
5.	Pioneer	Ag, Pb, Cu.
6.	McGrath and Kingston	—
7.	—	—
8.	Gipsy Queen	Pb.
9.	—	—
10.	Alberta	Pb.
11.	Maggies Secret	—
12.	Bakers M.L. 33	Fs, Be, Mi.
13.	Gipsy Girl	Ag, Pb, Cu.
14.	Gipsy Boy	Pb.
15.	Hercules	Pb.
16.	Devlins	Pb.
17.	Lady Brassey	Ag, Pb, Zn, As.
18.	Viney	Be.
19.	Tripple Chance	Be, Fs, Mi.
20.	Carnes	Mi.
21.	Pearces M.L. 28	Fs.
22.	Bald Hill	—
23.	Goat Hill Extended	Pb, Ag, Zn.
24.	Goat Hill	Pb, Cu, Py.
25.	Outward Bound	Ag, Au, Pb.
26.	Pearces M.L. 31	Be, Fs, Mi.
27.	Bakers M.L. 39	Be, Fs, Mi.
28.	McKenzie	Be.
29.	Pearces M.L. 27	Be, Fs.
30.	Egebek	Be, Fs, Mi.
31.	Bonanza	Pb.
32.	Comstock	Pb.
33.	Dan O'Connell	Pb, Ag, Zn.
34.	Homeward Bound	Pb, Ag, Zn.
35.	Pearces No. 2	Be, Fs.
36.	Great Vugh	—
37.	Spar Ridge	Be, Fs, Mi.
38.	Lily	Cu, Ag, Pb.
39.	Thackaringa Sillimanite	Sm.
40.	Cues	—
41.	Pearces M.L. 36	Fs, Be, Mi.
42.	Angus	Pb, Ag.
43.	—	Ky.
44.	Big Hill	Ag, Pb.
45.	Irelands Garnet	Gn.
46.	Himalaya	Pb, Ag.
47.	South Kinchega	—
48.	*Several Shafts*	—
49.	Kinchega	Pb, Ag.
50.	Pinnacles	Pb, Ag, Zn.
51.	Consols	Pb, Ag, Zn.
52.	Berwick Moreing	Pb, Ag, Zn.
53.	Lady Bevys	Zn, Pb.
54.	Marshalls Monarch	—
55.	Balaclava	Ag.
56.	Dunlop	—
57.	Rising Sun	Pb, Ag, Zn.
58.	White Leeds	Pb, Ag, Zn.
59.	Radford Limestone	Ls.
60.	Bakers or Laurel	Pb, Ag.
61.	South Boulder	Pb, Ag.
62.	Amalgamated Rockwell	Pb, Ag.
63.	Copper Blow	Cu.
64.	Sydney Rockwell Extended	As.
65.	Eureka Rockwell	Pb, Ag.
66.	North Sydney Rockwell	Pb, Ag.
67.	Sydney Rockwell	Pb, Ag.
68.	Bendigo Rockwell	Pb, Ag.
69.	Block 48	Pb, Ag.
70.	Kinchega Rockwell	Pb, Ag.
71.	Great Central Rockwell	Pb, Ag.
72.	Central Rockwell	Pb, Ag.
73.	Rockwell Silver Mining Co.	Pb, Ag.
74.	Melbourne Rockwell	Cu, Pb, Ag.
75.	Great Consols	—
76.	Maiden Rockwell	Pb, Ag.
77.	Murrays	—
78.	Dora	—
79.	Ironclad	—
80.	Red Hill	Ac.
81.	Panama Hat	Au.
82.	Block 56	—
83.	Davies and Meadows	Au.
84.	Rockwell Consolodated	—
85.	Rockwell Hope	—
86.	Blazing Stump	Ac.

Ac – Asbestos
Ag – Silver
As – Arsenic
Au – Gold
Be – Beryllium
Cu – Copper
Fs – Felspar
Gn – Garnet
Ky – Kyanite
Ls – Limestone
Mi – Mica
Pb – Lead
Py – Pyrite
Sm – Sillimanite
Zn – Zinc

Reference

CAINOZOIC

QUATERNARY
- Qrs — *Floodplains, outwash areas and drainage flats of black and red clayey silt and sand*
- Qcp — *Playas, lakes and "claypans" of black and grey silty clay and silt*
- Qd — *Flat to gently undulating plains of red and brown clayey sand, loam and lateritic soils*
- Qrd — *Dune deposits of red and brown clayey sand, loam and lateritic soils; irregular deposits of aeolian sand*
- Qrt — *Residual and colluvial deposits of angular, poorly sorted sand and gravel*
- *Infilled "mud cracks" up to twelve feet wide*

TERTIARY?
- Tsi — *Silicified conglomerate, quartzite and porcellanite, diagenetic siliceous cement, includes 'Greybilly', 'Duricrust' and lateratised Ordovician? sandstone.*
- T? — *Poorly consolidated sandstone and shale, kunkarised sand and clay*

- Cza — *Undifferentiated Cainozoic sediments (Section only)*

PALAEOZOIC

LOWER ORDOVICIAN — Scopes Range Beds
- Ols — *Quartz sandstone and conglomerate, white claystone and red sandstone*
- Qrt/Ols — *Scopes Range Beds largely obscured by Qrt.*

PRECAMBRIAN — PROTEROZOIC

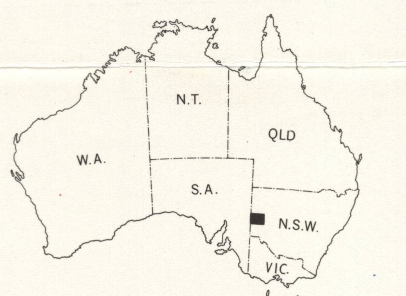
- p€ — *Phyllite, cleaved claystone, siltstone and sandstone of Scopes Range Area*

UPPER? — Possible equivalent of Torrowangee Group
- Pu — *Quartzite, sandstone, siltstone, claystone, iron rich sandstone, limestone (Pul)*
  - *Dominantly quartzite and sandstone*
  - *Dominantly siltstone and claystone*
  - *Ironstone overlying Upper Proterozoic sediments*
- Qrt/Pu — *Upper Proterozoic largely obscured by Qrt.*

?LOWER TO MIDDLE (Radiometric Age) — Willyama Complex; Redan Gneiss
- Pi — *"Bedded Iron Formation", quartz-magnetite rocks*
- Pr — *Gneiss and granulite*
- Pf — *Potosi-footwall gniess*
- Pg — *Granite gneiss*
- Pga — *Granite gneiss with felspar augen*
- *Interpreted sub-crop areas of gniesses*
- Pp — *Pegmatite*
- Pa — *Aplite*
- a — *Amphibolite, serpentine and hornblendite*
- Pw — *Sillimanite gneiss, andalusite, chiastalite, mica, schist, phyllite, quartzite, sandstone, slate.*
- p€w — *Undifferentiated Willyama Complex*
- Qrt/p€w — *Willyama Complex, largely obscured by Qrt.*

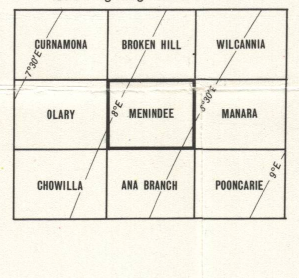
- Geological boundaries
  - Established boundary—position accurate
  - Established boundary—position approximate
- Strike and dip of foliation (dominantly bedding)
  - Inclined, showing prevailing dip
  - Measured
  - Strike
- Faults
  - Established fault—position accurate
  - Established fault—position approximate
  - Established fault—concealed
  - Inferred or probable fault
  - Inferred or probable fault—concealed
- Lineament
- Folds
  - Plunge of minor folds
  - Syncline, position concealed

Compiled by the Division of Regional Geology, Geological Survey of New South Wales. Topographic base and contours compiled and drawn by the Royal Australian Survey Corps in 1965 from 1961 and 1952 aerial photography. Photogeology by G. Rose, Geological Survey of New South Wales. Published by the New South Wales, Department of Mines.



INDEX TO ADJOINING SHEETS

Showing Magnetic Declination



Scale 1:250,000

Statute Miles / Nautical Miles / Yards / Kilometres

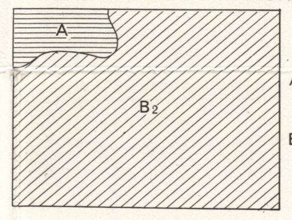
CONTOUR INTERVAL 250 FEET
VERTICAL DATUM IS BASED ON MEAN SEA LEVEL, SYDNEY

TRANSVERSE MERCATOR PROJECTION
HORIZONTAL DATUM IS BASED ON SYDNEY OBSERVATORY, LATITUDE 33°51'41.10"S LONGITUDE 151°12'17.85"E

BLACK NUMBERED LINES INDICATE THE 10,000 YARD TRANSVERSE MERCATOR GRID, ZONE 6 (AUSTRALIA SERIES), CLARKE 1858 SPHEROID
THE LAST FOUR DIGITS OF THE GRID NUMBERS ARE OMITTED

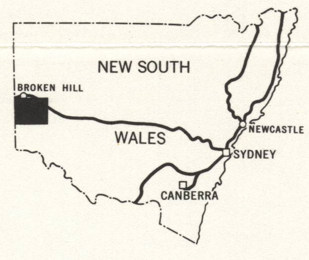
1965 MAGNETIC DECLINATION FOR THIS SHEET VARIES FROM 8°00' EASTERLY FOR THE CENTRE OF THE WEST EDGE TO 8°30' EASTERLY FOR THE CENTRE OF THE EAST EDGE. MEAN ANNUAL CHANGE IS 03' EASTERLY.

GEOLOGICAL RELIABILITY DIAGRAM



A Detailed Mapping with air photo interpretation
B2 Airphoto interpretation with several ground traverses

Geology by: Australian Mining and Smelting Co. Ltd., C.R.A. Exploration Pty. Ltd., Enterprise Exploration Co. Pty. Ltd., J. B. McManus, North Broken Hill Ltd., E. O. Rayner, G. Rose, B. P. Thomson.
Compiled by: G. Rose 1967
Drawn by: Mercury Press Pty. Ltd., Hobart



Section A-B
Vertical Exaggeration 1:4·2
Folding Diagrammatic

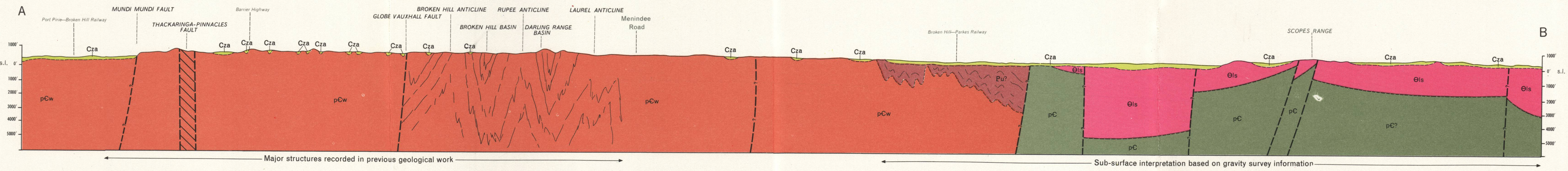


Plate 2B

MENINDEE
NEW SOUTH WALES
SHEET SI 54-3

Copies of this map may be obtained from the Department of Mines, Sydney, N.S.W.

Printed in Australia by V. C. N. Blight, Government Printer, N.S.W.