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Contributions to the regional geology of the Broken Hill area from geophysical data

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The Lower Proterozoic Willyama metamorphic complex and overlying Adelaidean sediments in the Caloola, Kantappa, and Torrowangee Synclinorial Zones form an area of Precambrian outcrop with notable topographic relief. Surrounding areas are the Mundi Mundi Plains to the west, the Menindee Trough to the southeast, and the Bancannia Trough to the east. Other topographic highs are formed by Precambrian and Palaeozoic rocks in the Bynguano Range to the east of the Bancannia Trough, and by Ordovician sediments in the Scopes Range which lies between the Bancannia Trough and the Menindee Trough.

The Willyama Complex is fringed to the southeast and east by an area within which a considerable proportion of the Earth's crust has anomalously high magnetic susceptibility. However, the remainder of the Willyama Complex is distinguished from surrounding areas by having a considerable proportion of its crustal section composed of material with anomamously low magnetic susceptibility.

The Willyama Complex and overlying Adelaidean sediments form a block which is bounded by major structures, including north-trending structures to the east and to the northwest. The Redan Fault forms the major boundary of Precambrian outcrop to the southeast of Broken Hill, but shallow basement persists about another 30 km to the southeast, to the edge of the Menindee Trough.

Northeast to north-northeast trends within the Willyama Complex continue beneath the southern part of the Torrowangee sediments and terminate against the north-northwest-trending Euriowie Inlier—an interpreted horst structure.

A north-northwest structural trend is inferred in the basement to the Caloola Synclinorial Zone. North-trending features are apparent in the Kantappa Synclinorial Zone and in the basement to the east and west of the Precambrian block.

There are four persistent magnetic marker horizons within the Adelaidean sediments of the Caloola Synclinorial Zone. Magnetic horizons within other areas of Adelaidean sediments are less well developed. Pre-Adelaidean basement beneath the Caloola Synclinorial Zone is inferred to be at a depth of about 3500 m; beneath the Kantappa Synclinorial Zone it is at a depth of a few hundred metres.

The magnetic basement beneath the Mundi Mundi Plain is divided by an east-west structure at 31°39′S, to the south of which the basement is at a depth of about 150 m, and to the north of which the basement depth increases from 500 m to 7000 m in the north. The area of deep basement is inferred to be overlain by a thick sequence of Adelaidean sediments.

An inferred intrusive body about 40 km east of Broken Hill may have been localised by the intersection of a number of major structures in this area. Magnetic basement in this area occurs at depths in the order of 150 m. This and other areas of shallow basement beneath the Mundi Mundi plain and to the southeast of the Redan Fault may have considerable base-metal exploration potential.

The Bancannia Trough is usually fault-bounded on both sides. On the western side a south-southeast extension of the Nundooka Creek Fault forms the boundary of the main trough while further to the southwest a north-south structure forms the boundary of a shallower extension of the Trough. Palaeozoic sediments within the Trough reach a maximum depth of about 8000 m, and are underlain by extensive areas of andesite which are inferred to have originated from three igneous centres beneath the Trough.

The Menindee Trough has a magnetic basement at a maximum depth of about 7000 m.

Airborne spectrometer data delineate the major surface geological and drainage features. The outcrop area of Willyama Complex is well defined by above average radiation levels. The largest anomalies have been recorded within the Euriowie Inlier and over areas of reported uranium occurrences in the west of the Precambrian block.

Introduction

The silver-lead-zinc deposits of Broken Hill occur within the Lower Proterozoic Willyama Complex. The main ore deposit has been mined continuously since the end of last century, and has been responsible for approximately half of Australia's total production of silver, and three-quarters of the total of lead and zinc production. Known reserves at Broken Hill for individual working mines are sufficient to maintain current rates of production for some 12 to 20 years.

The Geological Survey of New South Wales has been involved in a major detailed geological mapping program over the Willyama Complex since 1974. In 1975 the Bureau of Mineral Resources (BMR) completed two airborne magnetic and radiometric surveys: a regional coverage of the Broken Hill 1:250 000 map sheet (Wyatt, in prep. a), and a detailed coverage of the northern part of the Willyama Complex (Wyatt, in

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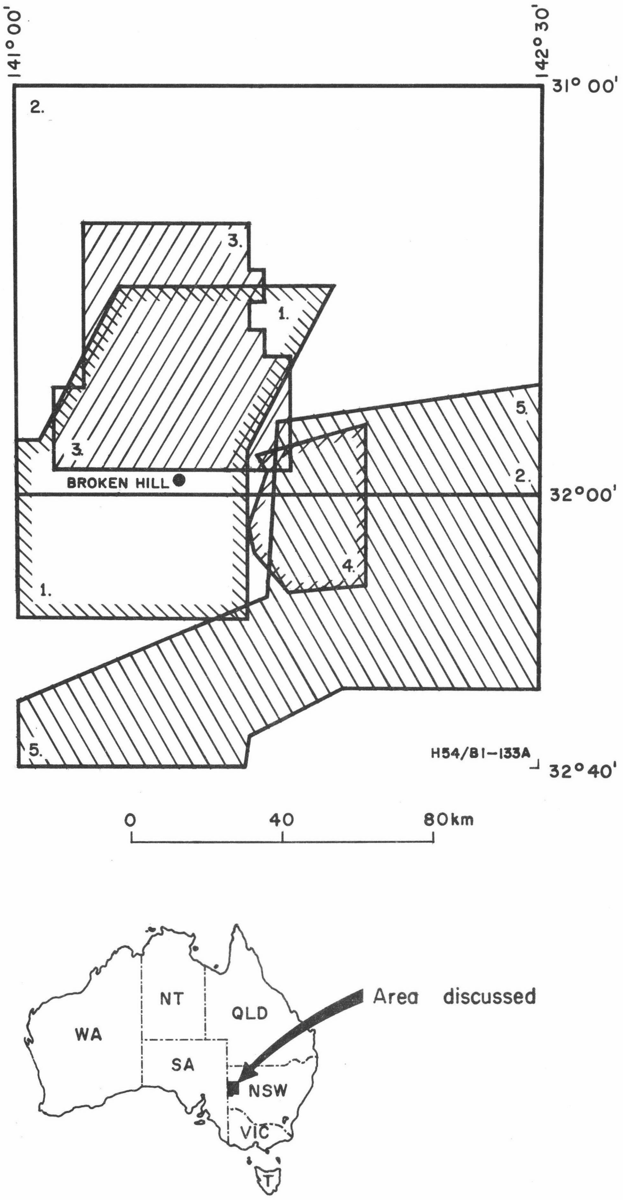

Figure 1. Locations of airborne surveys: 1. Spence, 1963; 2. Wyatt, in prep. a; 3. Wyatt, in prep. b; 4. North Broken Hill Limited, 1971; 5. Crosby, 1963.

prep. b). The mapping program and geophysical surveys were designed to aid mineral exploration in the area by delineating stratigraphy and structure.

This paper presents a description and interpretation of the broader scale geophysical anomalies outlined by the 1975 regional airborne survey and an earlier BMR survey (Spence, 1963). Gravity and other aeromagnetic data have been used where appropriate to provide a more complete regional outline. Regional gravity data are available over the entire area, and aeromagnetic coverage is shown in Figure 1.

An interpretation of the detailed survey data over the Willyama Complex is currently being carried out by the Geological Survey of New South Wales.

Major geological features

Geological nomenclature used throughout the paper is from Rose (1968), and Cooper & others (1975). A description of the geology of the Broken Hill 1:250 000 map sheet is given by Cooper (1975). Figure 2 shows the main geological features of the area. A Precambrian basement block trends approximately north through Broken Hill and is flanked to the east, south, and west by younger basins. Ordovician and older rocks form basement highs in the Bynguano and Scopes Ranges.

The Precambrian block

In this paper the term Precambrian block refers to the Willyama Complex and Adelaidean sediments, contiguous with outcrop around Broken Hill. The block forms a notable topographic high, rising about 200 m above the surrounding plains.

In places it is bounded by prominent escarpments; elsewhere the boundary with the surrounding plains is more gradational. The prominent escarpments may represent places of Cainozoic epeirogenic uplift (Rose, 1975). The best-developed escarpment is the north-northeast-trending Mundi Mundi Fault on the western side of the block. To the north, this fault is cut by the less prominent north-northwest-trending Kantappa Lineament, which forms the northwest boundary of the block. To the northeast, the Precambrian outcrop is bounded by the Nundooka Creek Fault and its probable extension to the southeast.

The eastern boundary of the block is irregular and gradational, but trends roughly north-south. The southern boundary is similarly irregular, and trends approximately south-southwest. To the southwest, outcrop continues into South Australia.

The two major divisions within the block are the earlier Proterozoic metamorphic complex (the Willyama Complex), and an Adelaidean upper Proterozoic sequence of sediments.

The **Willyama Complex** is considered (Scheibner, 1976) to form part of a continuous Precambrian basement which extends from the outcropping Gawler craton in South Australia to just west of Cobar in New South Wales. The Willyama Complex and the Wonominta beds form the easternmost outcrops of this basement complex.

The Willyama Complex consists of regionally metamorphosed rocks ranging from granulite facies southeast of Broken Hill through amphibolite facies to greenschist facies in the north (Binns, 1964; Thomson, 1976). The main rock types are psammitic to pelitic metasediments, granitic gneisses, quartz-feldspar-biotite-garnet gneisses, medium to coarse-grained quartz-feldspar rocks, and amphibolites (Stevens, 1976). Deformation is intense and faulting is widespread. The main structural direction is north-northeast, with subordinate north-northwest trends in the north and east-west trends in the south. Towards the north and west of its outcrop area, the Complex has been intruded by post-metamorphic Mundi Mundi Granite.

The **Adelaidean** rocks unconformably overlie the Willyama Complex, and occur in three graben-like structures known as the Caloola, Torrowangee, and Kantappa Synclinorial Zones (Scheibner, 1976). These zones trend north-northwest across the northern part of the Willyama Complex.

The Adelaidean rocks are mainly sediments which have undergone only minor metamorphism. They are deformed into broad open folds, generally with moderate dips. The main structural trends are north-northwesterly, swinging to a more northerly direction in the northwest.

Good outcrop occurs in the Caloola and Torrowangee Synclinorial Zones, but not in the Kantappa Zone.

The synclinorial zones are separated by inliers of Willyama basement. The Euriowie Inlier lies between the Caloola and Torrowangee Zones, and the Campbells Creek High (Cooper & others, in prep.) lies between the Toroowangee and Kantappa Zones.

A further outcrop of rocks of probable Adelaidean age occurs to the southwest of Broken Hill, around 32°24′S, 141°09′E.

Other basement highs

The **Bynguano Range** is a north-northwest trending belt of Precambrian and Palaeozoic rocks in the northeastern part of the area. The Wonominta beds form the Precambrian core of this range, consisting of highly deformed low-grade metamorphic rocks such as quartz-muscovite and muscovite schists, amphibole schist, phyllite, slate, and chert (Cooper, 1975).

The Wonominta beds are overlain to the west by a relatively undeformed sequence of Early Cambrian to Early Ordovician rocks, which includes the Mount Wright Volcanics at the base. This sequence is in turn overlain by Devonian sandstones. Numerous major faults occur in the Bynguano Range, mostly following the north-northwest trend of the range itself.

The **Scopes Range** is a south-southwesterly trending basement rise lying to the south of the Bynguano Range. There are minor outcrops of Wonominta metasediments within the Scopes Range, but most of the rocks consist of late Cambrian to Early Ordovician Scopes Range beds.

Gravity data (Fig. 6) indicate an extension of shallow basement southwest of Scopes Range, between the Willyama Complex and a prominent gravity gradient which marks the northwestern edge of the Menindee Trough.

Younger basins

Apart from the basement highs, most of the area is covered by a blanket of Quaternary and minor amounts of Tertiary sediments. Deposition is currently taking place in many of the lower lying areas, and appears to have been maintained throughout the Cainozoic by epeirogenic movements along some of the major faults bounding the basement highs (Rose, 1975).

The **Mundi Mundi Plain** lies to the west of the Mundi Mundi Fault; it is on the southeastern margin of the Frome Embayment of the Great Australian Basin. The absence of a strong negative Bouguer gravity anomaly over the Mundi Mundi Plain suggests that the thickness of undeformed sediments is much less than in the Bancannia and Menindee Troughs.

The **Bancannia Trough** is a north-northwest-trending Phanerozoic depositional basin lying between the Precambrian block and the Bynguano Range. Its southeastern end abuts the Scopes Range. It is outlined by a negative Bouguer gravity anomaly with a minimum value of −25 milligals. The Trough has a seismic basement at a maximum depth of about 7000 m (Planet Management and Research Pty Ltd, 1968). Bancannia South No. 1 (Fig. 5) penetrated 3258 m of mainly Devonian sediments within the Trough, and bottomed in aphanitic andesite below 3350 m (Baarda, 1968).

The **Menindee Trough** lies to the southeast of the Scopes Range and the Precambrian block. It is outlined by a northeast-trending negative gravity anomaly with a minimum value of −45 milligals. The Menindee Lakes, which are a present-day drainage centre, lie along the axis of the gravity anomaly. Tertiary, Cretaceous, and Permian sediments—to a depth of about 900 m—underlain by Devonian sediments, have been inferred from seismic data (Bembrick, 1975).

Aeromagnetic interpretation

The aeromagnetic interpretation is intended to elaborate on the nature of the structural units described in the previous section. Qualitative and semi-quantitative methods of interpretation (Vacquier & others, 1951; Gay, 1963) have been used on the magnetic profiles (H54/B1-64), which are available from the Australian Government Printer Copy Service. It should be emphasised that depth estimates from aeromagnetic data indicate a maximum probable depth to the anomaly source, and that in some cases the true depth may be shallower.

There are some minor discrepancies when relating the regional magnetic data to the mapping of Rose (1968), and Cooper & others (1975). These can be traced back to the use of different base maps.

The Precambrian block

Willyama Complex. There are many elongated and other anomalies within the Complex. They follow the main structural trends and are associated with outcropping rocks. A more detailed discussion of these anomalies will be presented at a later date. This paper deals only with broad-scale features.

The two main magnetic features associated with the Willyama Complex are: a regional magnetic high along the southeastern edge of the Complex, continuing along the eastern edge of the Precambrian block; and a regional magnetic low associated with the remainder of the Complex (Fig. 5).

The portion of the regional magnetic high to the southeast of Broken Hill—the Redan magnetic complex zone—is associated with near-surface magnetic sources. This zone strikes approximately northeast, and has been outlined by the data of Spence (1963), North Broken Hill Ltd (1971), and Crosby (1963) (Fig. 2). Aeromagnetic coverage is incomplete over the southwestern part of the zone. The northern half of the Redan magnetic complex zone coincides fairly closely with a negative Bouguer gravity anomaly of about −13 milligals amplitude (Pecanek, 1976). The Redan gneiss, quartz-feldspar rock with magnetite as the main mafic component, is common in the area (Stevens, 1976). This rock type has a lower density than most of the Willyama Complex, and probably accounts in part for the coincident gravity and magnetic anomalies.

However, magnetic model studies indicate that magnetic susceptibility probably increases with depth, and that the anomaly can be largely accounted for by a block of magnetic material below about 4500 metres, with its northern boundary dipping moderately to the north.

The Redan magnetic complex zone is bounded to the south by a distinct magnetic low which is inferred to indicate a fault (the Redan Fault) bordering the Willyama outcrop.

To the northeast of the Redan magnetic complex zone, the orientation of the regional magnetic high swings to a northerly trend. Two magnetic anomalies occur to the east of the Precambrian outcrop. That at 31°57′S, 142°00′E is associated with minor magnetic

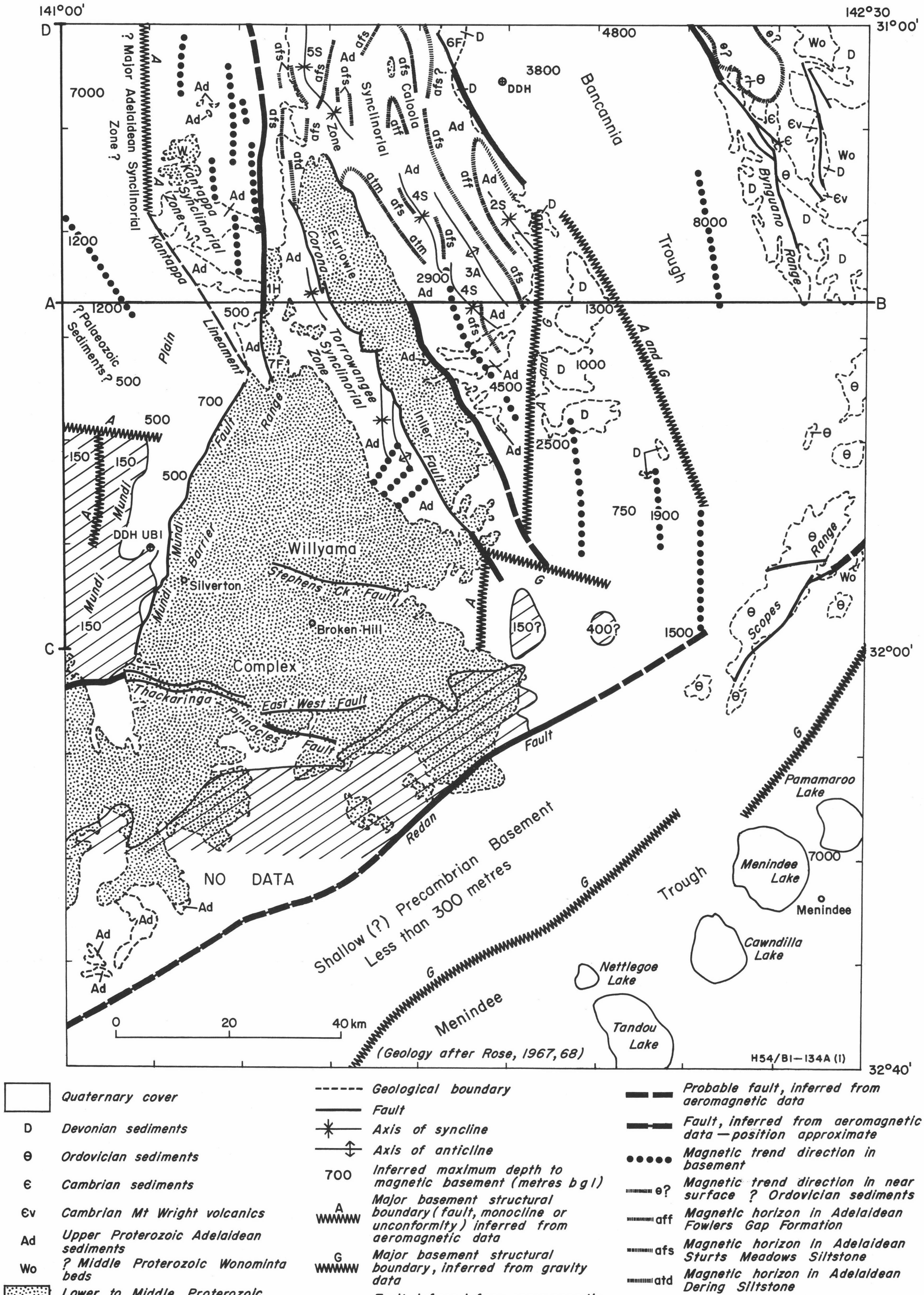

Figure 2. Regional geology and aeromagnetic interpretation.

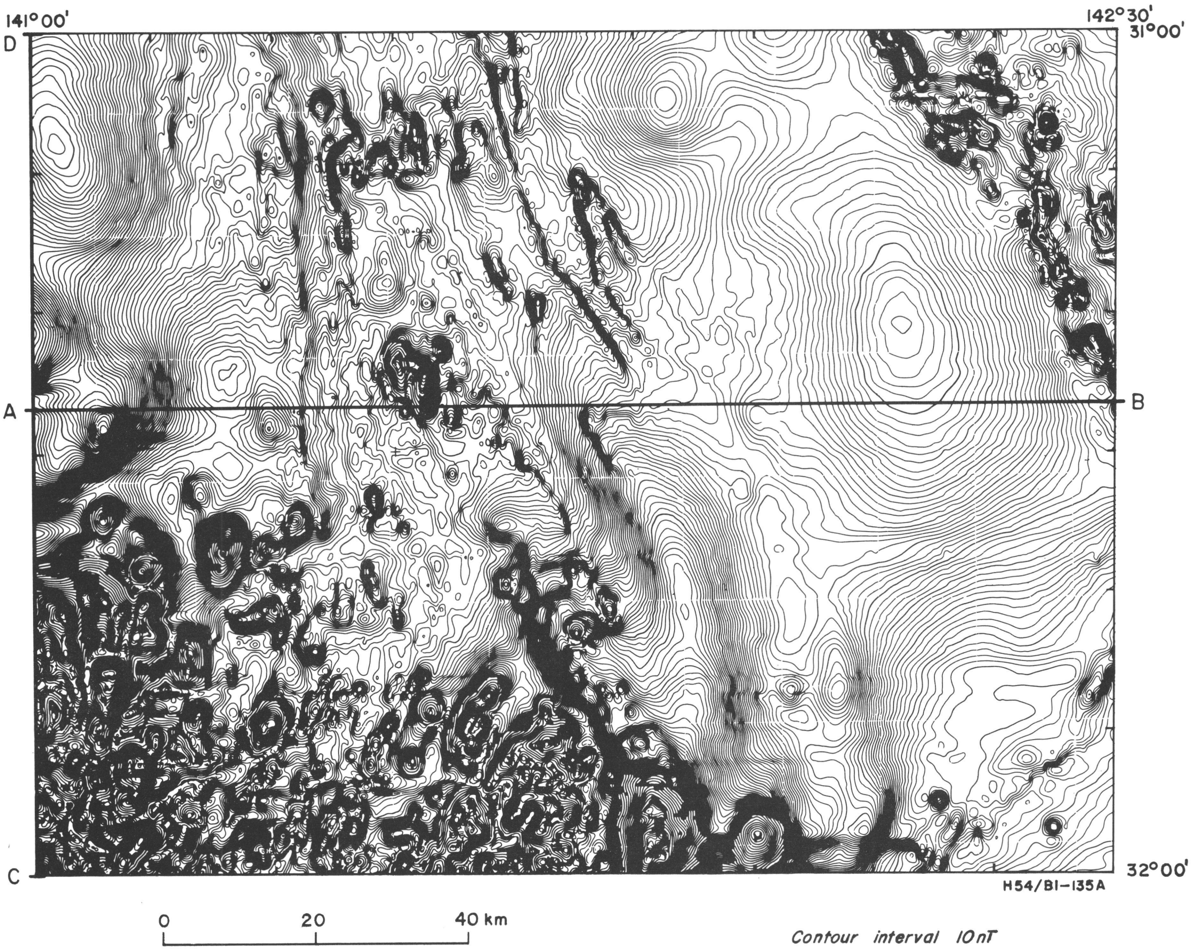

Figure 3. Magnetic contours from Wyatt, in prep. a.

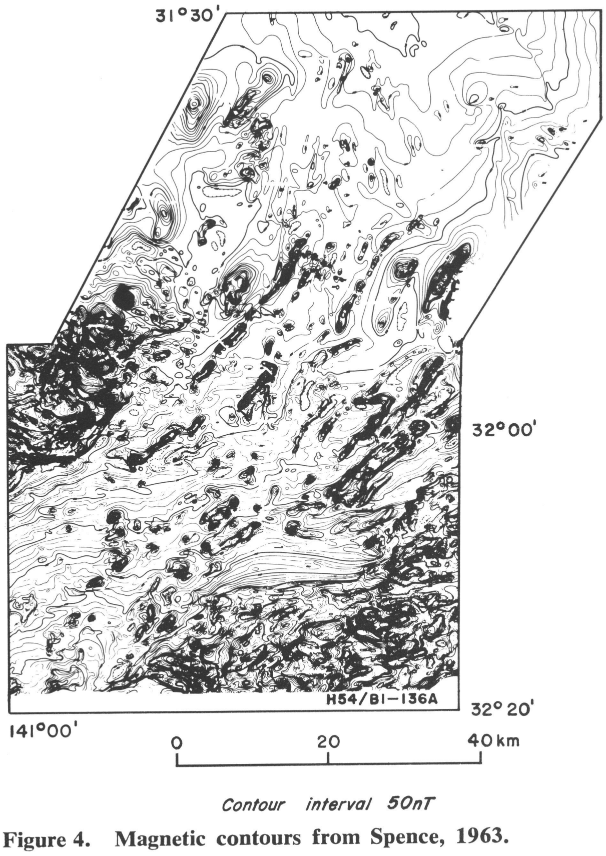

Figure 4. Magnetic contours from Spence, 1963.

sources at a depth of about 400 m—probably Willyama Complex beneath Quaternary sediments—but the major source of the anomaly is inferred to be at a depth of about 1000 metres. Similarly the second anomaly, at 31°57′S, 141°52′E, is associated with minor (?Willyama) magnetic sources at about 150 metres depth, but is inferred to have its major source at a depth of about 1000 m. This anomaly lies along a southerly extension of a north-south structural boundary (see below, and Fig. 2), and is elongated in a north-south direction. The anomaly also lies close to extensions of other major structures, namely the faults bounding the Euriowie Inlier, the Stephens Creek Fault, and northeasterly trends to the north of the Redan Fault (Fig. 2). It is possible that this anomaly may represent an intrusion localised by one or more of these structures.

To the north of these two anomalies, there is a discontinuity in the gravity pattern in the vicinity of 31°52′S (see Stackler & Brunt, 1967). The discontinuity is also evident, to a lesser extent, in the magnetic pattern. To the north of the discontinuity two elongated basement magnetic anomalies persist over a considerable distance, both diminishing in intensity to the north: the western anomaly indicates a magnetic body at depth within the southern portion of the Euriowie Inlier, while the easternmost has its source in magnetic basement at an inferred depth of about 2500 m beneath the western edge of the Bancannia Trough. The north-south magnetic trends in this area are paralleled by the gravity contours, which indicate

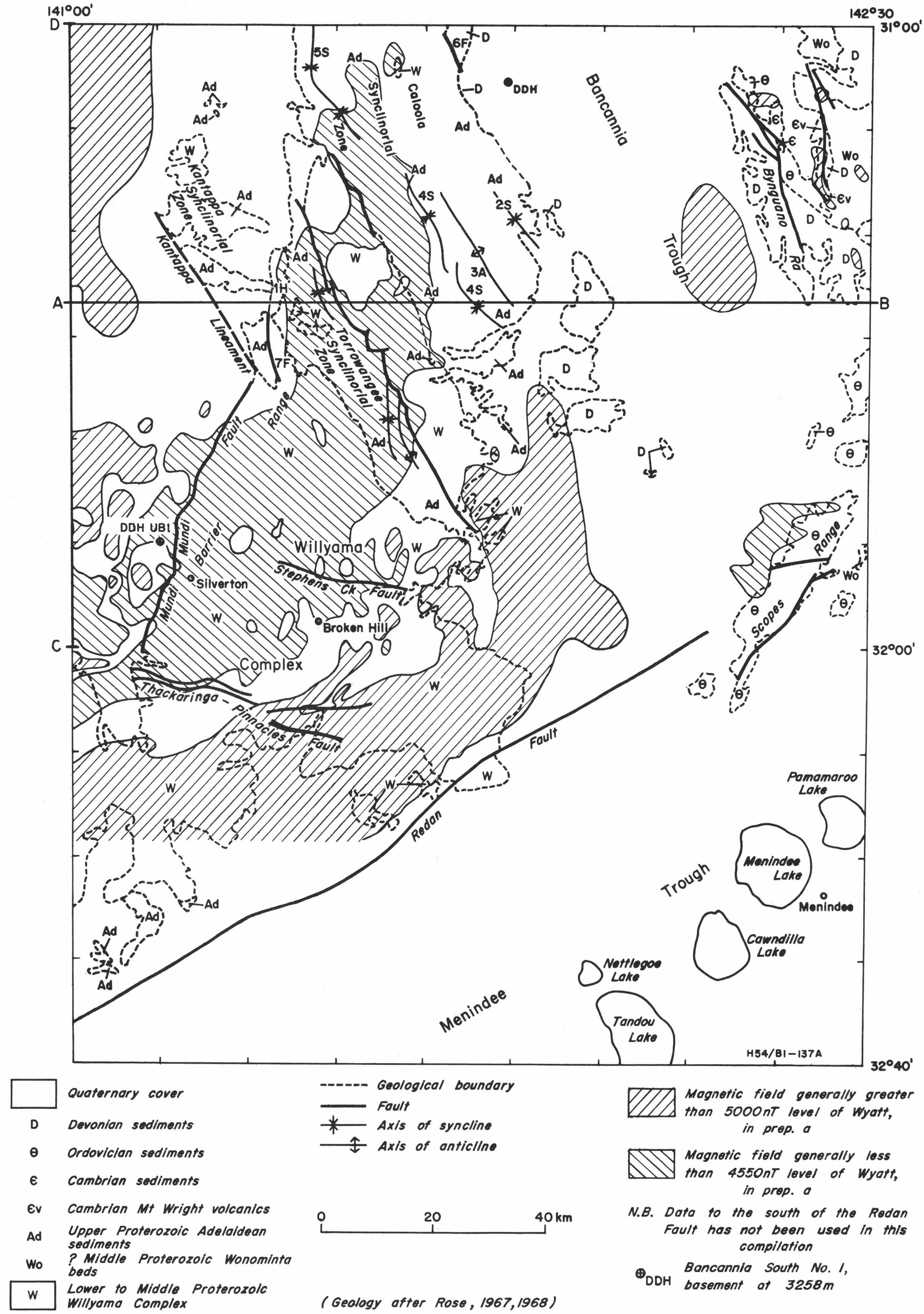

Figure 5. Relationship of regional magnetic field to geology.

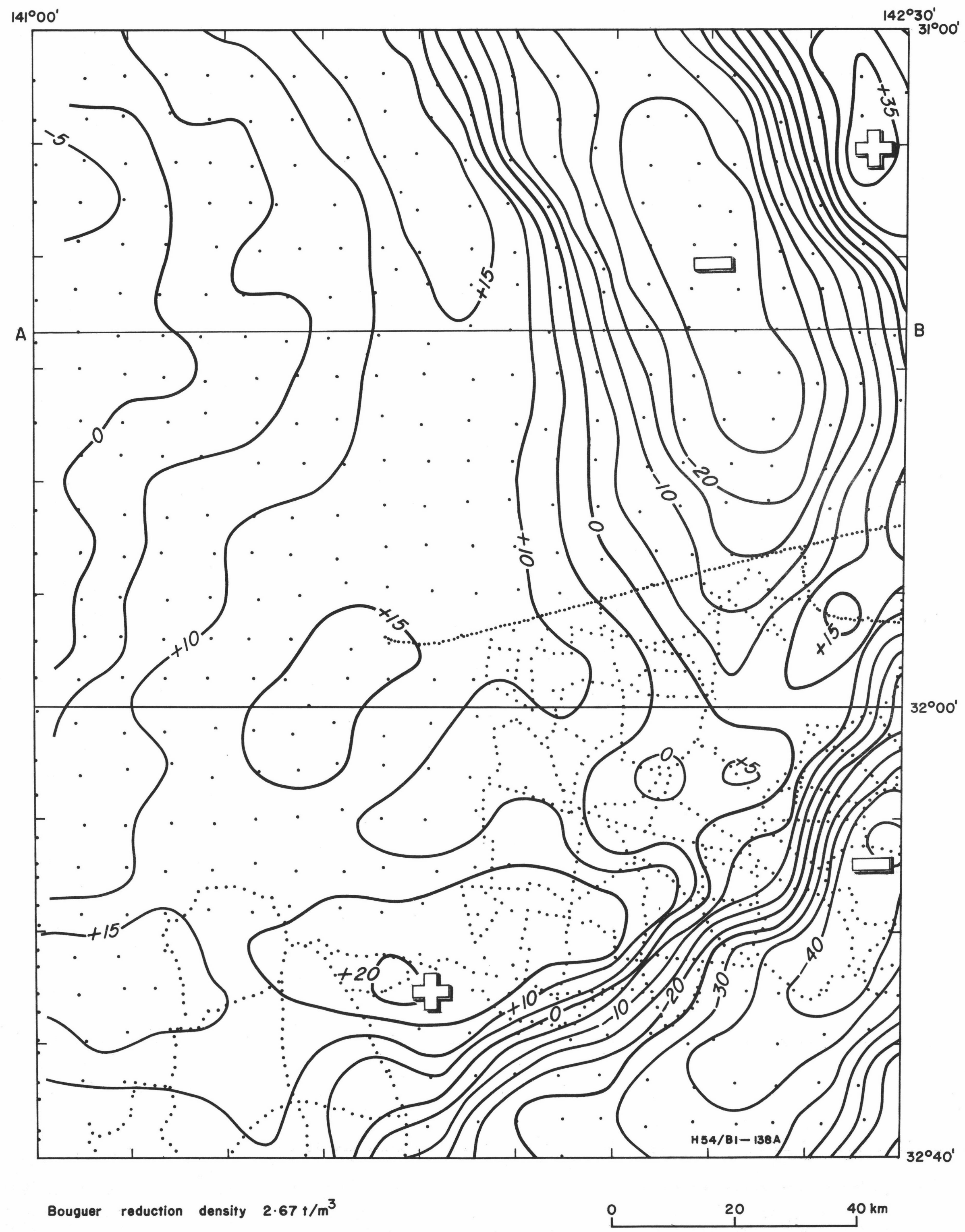

Figure 6. Bouguer gravity contours.

a north-south fault or monocline or dipping unconformity lying between and extending north of the two magnetic anomalies, and forming the eastern boundary of the Precambrian block (Fig. 2).

In summary the regional magnetic high at the edge of the Willyama Complex is mainly associated with deep magnetic sources, which underlie the Complex and extend in an arc from the Redan magnetic complex zone to the southeastern portion of the Euriowie Inlier.

In contrast to this regional high, that part of the Willyama Complex to the north and west of Broken Hill coincides with a regional magnetic low (Figs. 5 & 7). This broad low is a feature of petrophysical significance, and not merely the concomitant to surrounding highs. The variation in magnetic field strength over such broad areas indicates major changes in magnetic properties through a considerable proportion of the Earth's crust, and implies a significant difference in the nature of the crust beneath much of the Willyama Complex.

In Figure 7 a distinction is made between the Willyama Complex and a more magnetic basement to the east and west.

Major stratigraphic and structural directions within the Complex can be inferred from trend directions of elongated anomalies. Figure 4 shows that the dominant direction from the East-West Fault (Fig. 2) south to the Redan magnetic complex zone is east-west. Over most of the remainder of the Complex, trends are northeast to north-northeast. This trend persists in the Willyama basement beneath the southern portion of the Torrowangee Synclinorial Zone, but terminates abruptly against the Euriowie Inlier. Over most of the outcrop area of the Euriowie Inlier, the magnetic contour directions (and by inference the structural directions) are variable and irregular, and in many places are in marked contrast to adjacent trends on either side of the Inlier. The Euriowie trends are truncated abruptly at the boundaries of the Inlier, indicating steeply dipping and probably faulted boundaries.

On the western side of the Complex, the prominent linear Mundi Mundi scarp is generally assumed to be a fault, although there is very little direct evidence of faulting. The aeromagnetic data tend to confirm that the feature is a fault, because no magnetic anomaly crosses the line of escarpment, and the line coincides with a clear break in magnetic pattern over much of its length. Where there is no clear break, it is because there is no distinctive pattern on either side of the line. Towards the southwestern end of the fault, anomalies to the west are of much higher amplitude than those to the east.

Despite the fact that the Redan Fault marks the southern limit of major Willyama outcrop, it is considered to be subsidiary to the major fault system on the margin of the Menindee Trough 25 km or more to the southeast (Thomson, 1976). A small area of Willyama outcrop has been mapped to the south of the Redan Fault, at 32°11′S, 141°47′E (Rose, 1967) and gravity data indicate relatively shallow basement between the Redan Fault and the Menindee Trough. The broadly spaced aeromagnetic data (Crosby, 1963) indicate that quite strong magnetic anomalies exist over the area, and that depths to magnetic basement are generally between zero and 300 metres.

Adelaidean. The Adelaidean rocks show generally simpler magnetic patterns, with a few magnetic horizons standing out from a generally non-magnetic sequence. Although the total thickness of Adelaidean sediments is quite considerable, especially in the Caloola Synclinorial Zone, there is no negative gravity anomaly over the sediments; this implies that they are of similar density to the basement rocks.

Within the Caloola Synclinorial Zone there are two fairly continuous magnetic marker horizons, and a few less continuous horizons (Fig. 2). The uppermost magnetic marker is a narrow horizon near the top of the Fowlers Gap Formation within the Caloola Syncline (2S on Fig. 2). This horizon is not apparent in the outcrop of Fowlers Gap Formation in the Floods Creek Syncline (5S on Fig. 2, 31°03′S, 141°27′E; Cooper & others, 1975), indicating possible erosion of the upper Fowlers Gap Formation. The magnetic anomaly associated with the horizon in the Caloola Syncline, although continuous, diminishes considerably towards the eastern limit of outcrop.

Both limbs of the anomaly appear to persist for about 10 km to the east of the inferred structural boundary at the edge of the Precambrian block; there is, however, interference from other patterns in this area, making the continuity uncertain.

The other major magnetic horizon occurs within the Sturts Meadows Siltstone. The horizon forms the centre of three troughs in the Eight Mile Creek Syncline (4S on Fig. 2) and also occurs, on the eastern limb of the Sturts Meadows Anticline (3A on Fig. 2). It extends north around the nose of the anticline into the Floods Creek Syncline (5S on Fig. 2). However, it is less continuous, and may not be confined to a single stratigraphic level in this area.

The magnetic pattern indicates that Sturts Meadows Siltstone may fold around both sides of the anticlinal inlier of Corona Dolomite (Cooper & others, 1975, 3°04′S, 141°40′E) in an area of no outcrop.

On the western edge of the Floods Creek syncline there is a north-south-striking anomaly which appears to transgress lithological boundaries at a low angle, passing from Sturts Meadows Siltstone in the north, to Dering Siltstone in the south.

Other discontinuous magnetic horizons occur within the Floods Creek Formation and the Mitchie Well Formation.

A basement magnetic trend a little to the west of the axis of the Eight Mile Creek Syncline has an estimated source depth between 2900 and 4500 m, suggesting that this is the maximum depth of Adelaidean sediments in this area (Fig. 2).

Over much of the Kantappa and Torrowangee Synclinorial Zones the anomalies are of small amplitude (generally less than 30nT) and are discontinuous. Over most of the Torrowangee Synclinorial Zone, the magnetic trends generally parallel the north-northwesterly structural trends—except towards the south where a northeasterly trend reflects the trends of underlying Willyama basement.

In the northwestern segment of the area, west of 141°28′E, the magnetic contour direction (and by inference the structural direction beneath Quaternary cover) is dominated by northerly trends. The trends occur in the Kantappa Synclinorial Zone, and also occur in the margins of the Caloola and Torrowangee Synclinorial Zones and in the northern part of the Willyama Complex (the Campbells Creek High at 1H on Fig. 2).

The Kantappa Synclinorial Zone is bounded to the southeast by the Wilangee Fault (7F on Fig. 2; Thomson, 1977). This fault approximately coincides with a north-striking magnetic gradient which extends more than 25 kilometres north along 141°22′E. This gradient is inferred to indicate a northerly extension of the Wilangee fault, forming the eastern boundary of the Kantappa Synclinorial Zone beneath Quaternary cover, and marking the boundary between the major occurrence of Willyama Complex and a more magnetic basement to the west (Fig. 7).

To the south, a sharp magnetic peak is superimposed on the magnetic gradient. This peak coincides with Wilangee Basalt, which occurs in sporadic outcrops immediately to the west of the Wilangee Fault (Rose, 1968). Interpretation of magnetic profiles across the peak (Fig. 7) indicates that the basalt occurs as a

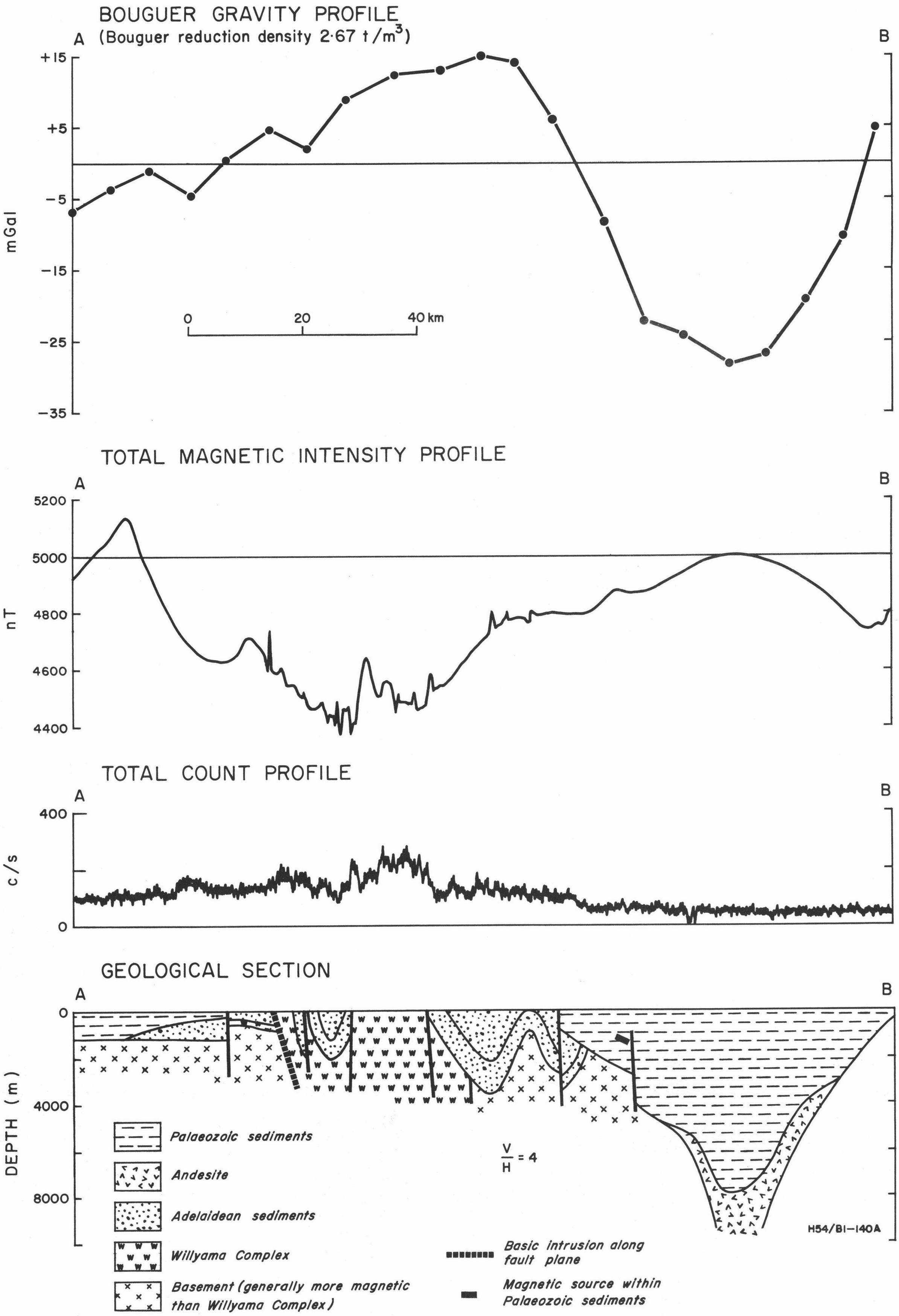

Figure 7. Geological section and geophysical profiles along 31°27′S.

narrow sheet dipping at about 45° to the east. (This dip estimate is based on the assumption of magnetisation in the direction of the Earth's field.) The basalt is regarded by Cooper (1975), and Cooper & others (in prep.) as being a flow sheet disconformably underlying the Adelaidean sediments. However, if the basalt dips to the east, it may be discordant with the Adelaidean sediments which are inferred to dip shallowly to the west (Cooper & others, in prep., fig. 28). Hence the basalt in this area may occur in a dyke intruded along fissures associated with the Wilangee Fault.

A few small magnetic peaks are also evident at other points along the inferred extension of the Wilangee Fault (e.g. flight line 2160). These may indicate further basalt intrusions associated with the fault plane.

The pre-Adelaidean basement on the western side of the fault is probably at a depth of a few hundred metres—accurate estimates are not possible because of interference from small irregular anomalies superimposed on the main gradient.

The anomaly at 31°28′S, 141°19′E has an inferred maximum source depth of about 500 metres, and occurs over the same area as a number of smaller irregular anomalies with much shallower source depths. The shallower magnetic sources are probably within Adelaidean rocks, while the deeper source is probably a pre-Adelaidean basement feature. The numerous small anomalies in the area between the inferred Wilangee Fault (7F on Fig. 2) and the Kantappa Lineament may have sources in either Adelaidean strata or shallow pre-Adelaidean basement.

The Kantappa Lineament is marked on some magnetic profiles by a small anomaly of less than 10nT amplitude. The lineament also coincides with the westernmost extent of small magnetic anomalies with near surface sources, and is thus inferred to be a fault along which the Precambrian (Adelaidean and older) rocks have been downthrown to the west. To the north of the Kantappa Lineament, the small anomalies extend only as far west as a line bearing north along 141°9′E (Fig. 2). It is inferred that a structural boundary limiting the extent of shallow Precambrian rocks occurs along this line.

Other basement highs

Bynguano Range. Small perturbations of the magnetic field (less than 40nT) occur over the outcrop area of the Precambrian Wonominta beds, but no regular pattern is readily discernible. Two discrete anomalies unrelated to any particular geological features occur at 31°07′S, 142°24′E and 31°14′S, 142°29′E; the first over Precambrian outcrop, and the second over an area of Quaternary cover adjacent to Precambrian outcrop.

The Cambrian Mount Wright Volcanics are clearly related to a line of magnetic anomalies of about 600 nT amplitude striking south to south-southeast in the vicinity of longitude 142°25′E. The shape of the anomalv at 31°12′S, 141°24′E, indicates that the Volcanics dip at about 30° to the east. (This dip estimate is based on the assumption of magnetisation in the direction of the Earth's field.)

This line of anomalies extends to the south-southeast, through an area mapped as Precambrian with Quaternary cover, and through an area of Devonian outcrop (Rose, 1968). The estimated depth to the source in the latter area is about 800 m. It is thus inferred that the Mount Wright Volcanics extend through the area mapped as Precambrian with Quaternary cover, and beneath the Devonian strata.

An anomaly at 31°12′S, 142°20′E occurs over an anticline in lower Cambrian strata. Although Mount Wright Volcanics do not crop out here, it is possible that the anomaly could be caused by near surface Mount Wright Volcanics in the core of the anticline.

Other magnetic sources in the area occur beneath shallow Quaternary cover in the vicinity of 31°5′S, 142°15′E. The anomalies are not entirely continuous, but may trace out a fold structure in ?Ordovician sediments, dislocated in places by faults (Fig. 2). The magnetic horizon trending southeast from 31°00′S, 142°10′E has a fairly consistent northeasterly dip.

Scopes Range. A number of magnetic anomalies occur in the Scopes Range which cannot, with the information available, be correlated with particular lithologies, but which follow general structural trends in the area.

The aeromagnetic data indicate a possible northeasterly extension of the fault at 32°53′S, 142°24′E as shown in Figure 2. Two potassium anomalies along this fault line are presumably caused by Precambrian outcrop.

Younger basins

Mundi Mundi Plain. The magnetic pattern divides the Mundi Mundi Plain into two distinct regions, to the north and south of a major structural boundary in the basement, at 31°39′S. This change in magnetic pattern is illustrated by the magnetic profile running north-south along longitude 141°E (Fig. 8).

The southern region consists of a magnetic complex zone (Fig. 2), the source rocks of which lie beneath Quaternary cover at an inferred depth of about 150 m. The complex zone lies entirely to the west of the Mundi Mundi Fault so that the source rocks are nowhere evident as outcrop. The magnetic pattern shows some similarities to the Redan magnetic complex zone, although the anomalies are generally of lower amplitude. There are no strongly developed trend directions, although a number of north-south features are apparent. Drillhole DDH.UB1, within the zone at 31°51′S, 141°10′E, intersected pyroxenite at a depth of 180 m (Crase, 1969). However, pyroxenite may not extend throughout the zone, as the complex magnetic pattern implies a heterogeneous composition.

To the north of the structural boundary at 31°39′S the magnetic pattern changes abruptly. Broader anomalies indicate depths to magnetic basement of about 500 m to the north of the structural boundary, increasing northwestwards to about 7000 m.

The gravity contour plan (Fig. 6) gives no indication of the east-west structural boundary, nor does it indicate particularly deep low-density cover rocks in the area where the depth to magnetic basement is inferred to be possibly as much as 7000 m. There is a decrease in Bouguer gravity values to the west of the Mundi Mundi Fault—the minimum value is −5 milligals, compared to minimum values of −25 milligals and −45 milligals in the Bancannia and Menindee Troughs. It is therefore inferred that at most there may be 1500 m of lower density Palaeozoic, or more recent, sediments in this area, and that where magnetic basement is particularly deep, it may be overlain by higher density Adelaidean strata. (The minor magnetic effects of Adelaidean rocks below 1500 m would not be apparent.)

Bancannia Trough. The major north-northwesterly basin of the Bancannia Trough is outlined by the −15

Figure 8. Aeromagnetic profile along 141°E.

milligal Bouguer gravity contour (Fig. 6). A shallower zone exists to the southwest of the main basin, between the −15 milligal contour and the eastern limit of the Precambrian block. These two areas are further distinguished by different characteristic magnetic patterns, separated by a fairly clearly defined boundary. The boundary is inferred to be a major structural boundary within the basement, which appears to be a continuation of the Nundooka Creek Fault (7F on Fig. 2). The eastern side of the Trough also appears to be fault-bounded. This is inferred from the abrupt change in magnetic pattern at the margin of the Trough.

Within the main basin of the Bancannia Trough, there are three broad magnetic anomaly closures centred at 31°05′S, 141°52′E, 31°00′S, 142°02′E, and 31°21′S, 142°12′E with inferred maximum source depths of 8000 m, 4800 m and 3800 m respectively (Fig. 2). The anomaly with estimated source depth of 3800 m is centred about 6 km east of Bancannia South No. 1, which reached an andesitic basement at a depth of 3258 m. It is inferred that the source of all three anomalies within the Bancannia Trough is andesitic or related basic rocks. A computer model study of the largest of the three anomalies indicates that it could not be caused by a flat-lying sheet of magnetic material beneath part of the Trough, nor by a vertical-sided block of magnetic material beneath the centre of the anomaly. However, a combination of these two models, with a vertical-sided block beneath a near-horizontal sheet at the base of the Trough, is a satisfactory magnetic model. The three anomaly centres may indicate vertical conduits which fed andesitic flows or sills beneath the Palaeozoic sediments (Fig. 7).

The largest of three anomalies is elongated along an axis with an azimuth of 170°, but the other two anomalies are nearly circular and show no basement trend direction.

Within the shallower zone to the southwest of the main basin, the magnetic pattern indicates a definite structural trend direction approximately parallel to the adjacent north-south structural boundary of the Precambrian block. The largest anomaly within this zone is an elongated anomaly immediately to the east of the Precambrian block, with an estimated source depth of about 2500 m. Bouguer gravity values indicate that the basement of the Palaeozoic sediments is considerably shallower than 2500 m in the area of this anomaly, and it is therefore inferred that the Palaeozoic sediments are underlain by higher density Adelaidean sediments, which are in turn underlain by magnetic basement at a depth of about 2500 m. This is similar to the situation illustrated in Fig. 7.

Other anomalies within the shallower zone are of smaller amplitude; because of their relatively shallow source depths, they are inferred to have sources within the Palaeozoic sediments. These sources may be magnetic horizons within the sediments—the anomalies may indicate the locations of structural highs outlined by the magnetic horizons. In particular, the anomaly centred at 31°47′S, 142°06′E may indicate an anticline with a north-south trending axial plane.

There is an irregularly shaped zone around 31°21′S, 141°56′E covering about 200 sq km in which the magnetic field varies irregularly with an amplitude up to 25 nT. The pattern, which can be best seen on profiles, indicates near surface magnetic sources. The geological map indicates Quaternary cover in this area, and it is inferred that the source of the magnetic variation is most probably lateritic layers within the Quaternary cover.

Menindee Trough. This area is only partly covered by aeromagnetic data (Crosby, 1963). As with the Bancannia Trough, there is a broad magnetic anomaly closure centred over the Menindee Trough. The estimated depth to the source of the anomaly is about 7000 m, and it is inferred that this is the depth to which sediments extend within the Trough. Despite similar depths to magnetic basement in the two Troughs, Bouguer gravity values over the Menindee Trough are considerably lower than over the Bancannia Trough (−45 milligals compared with −25 milligals). This may be partly due to greater thicknesses of Permian and more recent sediments in the Menindee Trough.

Radiometric interpretation

Figure 9 shows total count data from the Broken Hill map sheet with a contour interval of 10 counts per second (c/s). Shading has been added to emphasise count rates greater than 130 c/s and 200 c/s. Symbols indicate areas where anomalies are caused by preferential concentrations of either potassium, uranium, or thorium.

Because of the small crystal volume employed on the survey (3700 cc NaI) and the associated statistical noise, data recorded over different geological units and localities were analysed by averaging count rates in each channel (Table 1). Where all rock units from one group or subgroup had similar spectral signatures (e.g., all units of the Euriowie Sub-Group) their data were

Kp *Anomaly due mainly to Potassium source (Precambrian outcrop)*

Kg *Anomaly due mainly to Potassium source (Mundi Mundi granite)*

K *Anomaly due mainly to Potassium source (Quaternary)*

U *Anomaly due mainly to Uranium source*

Th *Anomaly due mainly to Thorium source*

L *Lake*

•3 *Site of reported Uranium mineralisation*

Δ8 *Mountain*

Contour interval 10 c/s

130 - 200 c/s

> 200 c/s

1	Corona	5	Hen and Chickens
2	Eldee Creek	6	Great Western
3	Brinkworth Well	7	Broken Hill
4	Mundi Mundi	8	Mount Robe

0 20 40 km

Figure 9. Total count contours.

combined. Dissimilar units, such as the various masses of Mundi Mundi Granite, have been treated separately. The relative proportion of potassium, uranium, and thorium for each unit, group, or locality is indicated on the trivariate distribution diagram (Fig. 11). This diagram highlights any distinctive concentrations or depletions in a particular radioelement.

The abundances of the radioelements generally vary sympathetically with one another and with the silica content of igneous rocks. Under oxidising conditions, uranium is mobilised more easily than thorium. Low U/Th ratios in igneous rocks may therefore indicate oxidising conditions before crystallisation, or extensive leaching during the post-crystalline history of the rock, or both (Adams & Gasparini, 1970).

The most striking feature in Figure 9 is the higher radioactivity associated with outcrop of the Precambrian Willyama Complex. This reflects the presence of rocks of acid igneous origin and the predominance of pelites over psammites in the metasediments. The outcrop boundaries of the Willyama Complex are well defined by the 130 c/s contour (Fig. 9). The highest radioactivity (greater than 250 c/s) was recorded within the western part of the Precambrian block in a five-km-wide strip which extends from Mount Robe for about 20 km to the southwest. Total count contours for this area are shown in Figure 10 together with known uranium occurrences and areas of high $\frac{eU}{eTh}$ ratio. Total count response exceeds 250 c/s and $\frac{eU}{eTh}$ ratio approaches 4 in parts of this strip. Known uranium occurrences in this zone are at Eldee Creek, Mundi Mundi and Brinkworth Well, where autunite and other secondary radioactive minerals have been reported from sheared schist zones and small greisen

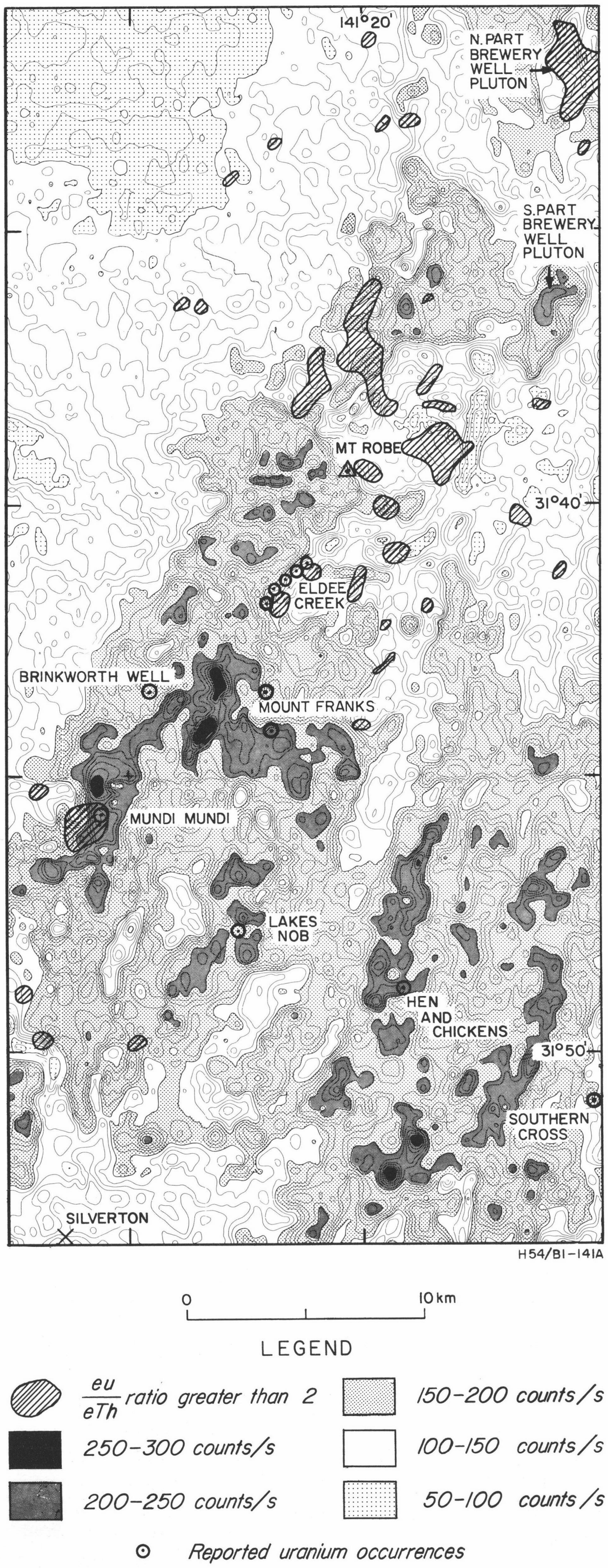

Figure 10. Total count contours in Barrier Range area.

veins (Rayner, 1960). Although Rayner suggests a genetic tie between the mineralisation and the Mundi Mundi Granite, no evidence has been found to support this. The highest radiation was recorded between Eldee Creek and Mundi Mundi. The Hen and Chicken mine produced a slight increase in uranium and the $\frac{eU}{eTh}$ ratio, but no anomaly was recorded over the Great Western mine or the Broken Hill line of lode. Uranium mineralisation has been reported from each of these mines (Willis & Stevens, 1974).

Steep gradients delineate the NNW-trending boundaries between the Fowlers Gap Beds and older rocks, along both sides of the Euriowie Inlier, and between the Torrowangee Group and Willyama Complex. Higher uranium and $\frac{eU}{eTh}$ ratio values occur over much of the exposed part of the Euriowie Inlier, particularly around 31°17'S, 141°30'E. This area is the probable source of rutherfordine encrustations on the Corona dolomite of the Torrowangee Group; migration may have occurred along the fault system which separates the two rock groups (Willis & Stevens, 1974).

All outcrops of Mundi Mundi Granite have a consistently high potassium content, but show considerable variation in uranium and thorium. The Mount Woowoolahra granite (**14**)* at 31°15'S, 141°14'E has radioelement concentrations which are similar to the average for the Willyama rocks, but the Poolamacca Inlier (**15**) near 31°29'S, 141°29'E is depleted in thorium. The two parts of the Brewery Creek pluton have completely different signatures: the northern part (**16**) at 31°32'S, 141°24'E is depleted in thorium and is characterised by a high $\frac{eU}{eTh}$ ratio on Figure 10; the southern part (**17**) at 31°36'S, 141°24'E is enriched in uranium and is clearly delineated by a total count anomaly on Figure 10.

Several areas have abnormlly low thorium readings compared with potassium and uranium values. The pegmatite (**13**) mapped on the geological map of the Broken Hill District (AIMM, 1968) is characterised by high $\frac{eU}{eTh}$ and high $\frac{K}{eTh}$ ratios. The Mundi Mundi Granite at Brewery Well 31°33'S, 141°24'E has identical radioelement ratios and is probably genetically related to the pegmatites. The most northerly and northeasterly 5 km of the Euriowie Inlier has a relatively high $\frac{K}{eTh}$ ratio.

Several small inliers of Precambrian rocks have relatively high potassium content and are very depleted in uranium. These include Willyama rocks, which outcrop in the core of an anticline of Adelaidean rocks at 31°05'S, 141°37'E and immediately north of the Mount Woowoolahra Granite (**11**). In the Scopes Range, potassium anomalies occur over Precambrian outcrop at 31°51'S, 142°29'E and over interpreted Precambrian outcrop (**10**) at 31°51'S, 142°23'E. Potassium anomalies also occur in the Bynaguano Range over outcrop of the Precambrian Wonominta beds (**9**).

Two areas—around 32°01'S, 141°14'E, and 31°57'S, 141°11'E have high thorium responses. These areas are directly over and 8 km north-northwest of the Thackaringa davidite deposits, which contain traces of the thorium-bearing minerals thorite, monazite, and brannerite (Rayner, 1960; Willis & Stevens, 1974).

The level of radioactivity decreases further away from the areas of outcrop of Willyama Complex, local increases in radioactivity reflecting drainage patterns of the Precambrian block. Similarly in the east of the area the radioactivity decreases away from Precambrian outcrop in the Scopes and Bynguano Ranges. Between 31°08'S, 142°25'E, and 31°16'S, 142°27'E, where windows exist in the Quaternary cover, the Precambrian Wonominta beds produce total count anomalies.

*** Numbers 1 to 24 in the text refer to the reference numbers of Table 1 and Figure 11.**

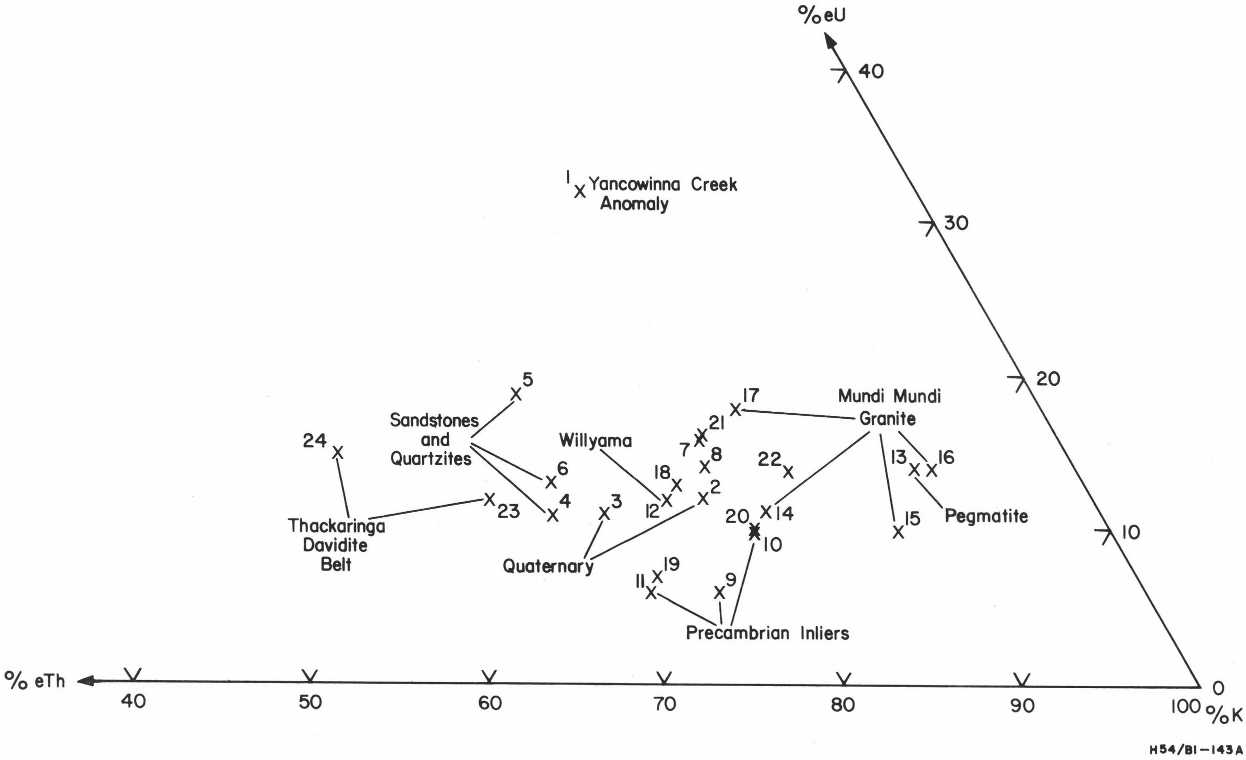

Figure 11. Potassium-Uranium-Thorium distribution diagram. Reference numbers given in Table 1 and text.

Ref. no.	*No. of 1 second samples*	*Average Countrates (c/s)* Total	K	eU	eTh	*Percentage* K	eU	eTh	*Description* Unit	Rock type	Location
1	21	117.6	15.6	10.4	6.2	49	32	19			Yancowinna Creek
2	233	118.8	23.0	4.0	7.5	66	12	22	Qrs	Flood plains, clayey silt and sand	
3	201	80.0	13.2	2.5	6.1	61	11	28	Qrt	Residual sand and gravel	
4	167	130.0	20.5	3.8	11.1	58	11	31	Ols	Scopes Range Beds	
5	131	50.6	6.9	2.5	3.9	52	19	29	Dn	Nundooka Sandstone	
6	27	51.2	7.8	1.8	4.2	57	13	30	Ꝑtc	Camels Hump Quartzite	
7	177	102.9	19.2	4.7	5.9	64	16	20	Ꝑte	Torrowangee Group (Euriowie subgroup)	
8	237	123.6	24.1	5.1	7.9	65	14	21	Ꝑty	Torrowangee Group (Yancowinna subgroup)	
9	30	111.8	23.4	1.9	8.1	70	6	24	pЄ	Wonominta Beds	Bynguano Range
10	45	77.6	16.8	2.5	4.9	70	10	20	pЄ	Wonominta Beds	Scopes Range
11	37	109.9	19.7	1.9	8.2	66	6	28	pЄ	Willyama Complex	Mt Woowoolahra
12	1212	166.3	30.5	5.6	11.6	64	12	24	pЄw	Willyama Complex	
13	77	124.1	31.7	5.5	3.7	77	14	9	pЄwg	Pegmatite	
14	22	126.3	27.8	4.4	7.5	70	11	19	pЄmg	Mundi Mundi Granite	Mt Woowoolahra
15	55	137.0	37.4	4.9	5.5	78	10	12	pЄmg	Mundi Mundi Granite	Poolamacca Inlier
16	72	142.6	37.7	6.6	4.1	78	14	8	pЄmg	Mundi Mundi Granite	Brewery Well (north)
17	31	176.1	33.5	9.2	9.0	65	18	17	pЄmg	Mundi Mundi Granite	Brewery Well (south)
18	310	191.4	35.6	7.2	12.6	64	13	23	pЄwA, pЄwB, pЄwC, pЄwD, pЄwE		
19	38	139.8	27.0	3.0	11.0	66	7	27	pЄwF		
20	60	153.8	32.0	4.8	9.0	70	10	20	pЄwG		
21	219	208.4	38.6	9.3	12.0	64	16	20			Brinkworth Well—Mt Franks
22	31	175.9	37.7	7.4	8.9	70	14	16			Mundi Mundi
23	67	207.0	28.8	6.4	18.5	54	12	34			North of davidite belt
24	41	136.8	14.7	4.8	13.6	44	15	41			Davidite belt

Table 1. Radiometric characteristics of rocktypes.

Within the Adelaidean, low radioactivity characterises the outcrop of Camels Hump Quartzite (**6**) at the syncline about 31°17′S, 141°48′E. Very low count rates (below 50 c/s in the total count channel) are associated with the outcrop of massive dolomite north of Corona. All other units of the Torrowangee Group (**7**, **8**) have similar radioelement ratios to those over the Willyama Complex (**12**), although the absolute count rates and hence radioelement concentrations are considerably lower (Table 1).

The Ordovician Scopes Range Beds (**4**), Devonian Nundooka Sandstone (**5**), and Adelaidean Camels Hump Quartzite (**6**) all show unusually low potassium content and low $\frac{eU}{eTh}$ ratios, indicating thorough weathering and leaching under oxidising conditions (Adams, Osmond & Rogers, 1959).

Drainage channels generally appear as radiometric lows in Precambrian outcrop areas and as highs in areas of Quaternary cover. Near-zero radioactivity is recorded over the lakes (L on Fig. 8).

One flight line recorded a uranium anomaly in alluvium on Yancowinna Creek (**1**) at 31°56′S, 142°01′E. Adjacent flight lines show only potassium enrichment along the northwest-trending floodplain.

Numerous K anomalies occur on the plains to the east and west of the Precambrian block. They are indicated by the symbol K on Figure 8, and correlate with the unit Qrs (**2**) described as fine, black and red, clayey sand over floodplains and outwash areas. This unit has a higher $\frac{eU}{eTh}$ ratio than the Quaternary sand and gravel unit, Qrt (**3**).

Summary

The regional geophysical data indicate a number of major features which are not evident in the outcrop geology.

Much of the area where the Willyama Complex crops out or forms shallow basement is associated with a broad regional magnetic low, implying a thick crustal section of anomalously low magnetisation. This area is fringed by a regional magnetic high to the southeast and east, where magnetic rocks underlie the Willyama at depths of a kilometre or more. The regional magnetic high outlines an arcuate swing in structural directions, from northeasterly (and more locally easterly) trends to the southeast of Broken Hill, to northerly trends in the east and northwesterly trends beneath the southern part of the Euriowie Inlier.

Other structural trends within the Willyama Complex are also outlined by the magnetic data. The predominant northeasterly to north-northeasterly trends within the Willyama Complex can be seen to continue in the basement beneath the southern portion of Torrowangee Synclinorial Zone. These trends terminate abruptly against the north-northwesterly trending boundary of the Euriowie Inlier. The structural trends within the Euriowie Inlier are somewhat erratic. The Euriowie Inlier appears as a sharply distinguished entity on the magnetic contour pattern, and is inferred to be a horst block with steeply dipping sides.

To the southeast of Broken Hill, the inferred northeast-trending Redan Fault lies just beyond the major Willyama outcrop.

North-south structural trends, which can only be seen to a minor extent in outcrop, are shown by the geophysical data to be of considerable significance, occurring on both the eastern and western sides of the Precambrian block. The block is bounded to the east by a major north-south structure, and parallel basement trends persist to the east of the block. The Kantappa Synclinorial Zone is bounded on its eastern and northwestern sides by north-south structures, and within the Zone parallel trends are evident in the Adelaidean sediments and the pre-Adelaidean basement. North-south structural features have also developed within the shallow basement magnetic complex beneath the southern area of the Mundi Mundi Plain.

An east-west structure separates the shallow basement beneath the southern area of the Mundi Mundi Plain from deeper basement to the north.

The Nundooka Creek Fault is inferred to extend to the south-southeast within the basement of the Bancannia Trough, dividing the Bancannia Trough proper from the adjacent shallower zone to the southwest. A parallel fault system forms the eastern boundary of the Trough.

Within the Caloola Synclinorial Zone, four separate and fairly continuous magnetic horizons can be traced, but magnetic horizons within other areas of Adelaidean sedimentation are less well developed.

Adelaidean sediments are inferred to extend to a depth of about 3500 metres within the Caloola Synclinorial Zone, but extend to a depth of only about 500 metres within the Kantappa Synclinorial Zone. However, another area of major Adelaidean deposition may exist to the west of the Kantappa Synclinorial Zone, with a possible depth of 7000 metres.

The basement of the Bancannia Trough is divided into two distinct zones, to the east and west of the inferred extension of the Nundooka Creek Fault. Within the main basin to the east of the Fault, basement structural trends are not strongly in evidence, and the basement is inferred to consist mainly of andesitic material. To the west of the Fault, definite north-south trends are apparent, and the Palaeozoic sediments may be underlain, at least in part of the area, by Adelaidean sediments. The division of the Bancannia Trough into these two distinct zones may have implications for future hydrocarbon exploration, especially if the distinctive basement structural styles have produced different structural styles within the overlying sediments. The maximum depth extent of Palaeozoic sediments within the main basin is inferred to be about 8000 metres.

The maximum depth extent of sediments within the Menindee Trough is inferred to be about 7000 metres.

There may be an area of Palaeozoic and/or Mesozoic sedimentation beneath the northern part of the Mundi Mundi Plain, with a maximum depth extent of about 1500 metres.

The aeromagnetic data outline extensive areas of shallow basement (from near outcrop to a few hundred metres in depth) adjacent to the Precambrian block. These areas occur between the Redan Fault and the Menindee Trough; to the west of the Mundi Mundi Fault, in the southern area of the Mundi Mundi Plain; in an area about 40 km east of Broken Hill; in the Kantappa synclinorial zone where shallow Quaternary cover is probably underlain by a few hundred metres, at most, of Adelaidean sediments.

These areas of shallow basement, particularly the first three, may have exploration potential. Appropriately designed geophysical surveys may be able to locate drilling targets in these areas. Explorationists who find the intersection of major lineaments particularly inviting may be attracted to the area about 40 km east of Broken Hill, where faults bounding the Euriowie Inlier intersect with the meridional structural boundary to the Precambrian block, the possible easterly extension of the Stephens Creek Fault, and major northeasterly trends of the Willyama Complex.

The highest levels of radioactivity are associated with rocks of the Willyama Complex. Pegmatites and the southern part of the Brewery Creek pluton are characterised by low radioactivity, particularly low thorium, compared with other parts of the Willyama Complex.

Areas of high potassium content include the Mundi Mundi Granite, isolated Precambrian outcrops and some recent drainage features.

Uranium enrichment occurs over an area of the Willyama Complex including the Eldee Creek, Mundi Mundi, and Brinkworth Well deposits, over an area to the east of the Corona rutherfordite mineralisation, and over an isolated spot on Yancowinna Creek.

Thorium is concentrated over and to the north of the Thackaringa davidite belt.

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