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Contents

Abstract

High-resolution aeromagnetics, radiometrics and gravity data for the Innamincka and Strzelecki 1:250 000-scale map sheet areas in far northeast South Australia have been integrated with regional seismic profiles and extensive well intersections to reveal a geologically complex subsurface of several stacked basins above a basement of differing adjoining Proterozoic blocks.

Non-filtered reduced-to-pole TMI imagery reveals relict, stacked WNW-flowing drainage channel systems in the 500 m-thick Cainozoic Lake Eyre Basin. That drainage differs from the modern ephemeral system which meanders towards Lake Eyre and Lake Blanche. The basin's most surficial sediments are aeolian.

The 3 km-thick Jurassic-Cretaceous Eromanga Basin containing significant oil and minor gas fields unconformably underlies the entire region. It covers the prolific oil and gas-producing 2.5 km-thick Late Carboniferous to Triassic Cooper Basin. Rejuvenations of underlying basement features inherited into the Cooper Basin have been critical for generating some structures for trapping petroleum.

At greater depths below the Cooper Basin, the underlying prospective Early Cambrian to Middle Ordovician Warburton Basin has two depocentres. A basement-detached trough adjacent to the Birdsville Track Ridge is flanked to the southeast by a widespread shelf area above cratonic basement. Burial metamorphism of early felsic volcanics could imply up to 7-8 km of post-Middle Ordovician subsidence. The volcanics are succeeded by carbonates. The shelf sequence grades laterally into the other depocentre, a rift trough with basalts, located beneath the central Cooper Basin. The magnetic basalts indicate rift structures.

Fractionated Big Lake Suite granodiorites, mostly formed conspicuous gravity and magnetic lows, intruded the rift portion of the Warburton Basin in the Early Carboniferous. Associated small magnetic anomalies are interpreted as highly magnetised skarns, produced by contact metasomatism of Warburton carbonate roof pendants.

Emplacement of the granites was followed by very rapid uplift to expose and erode them prior to new subsidence and commencement of Cooper Basin sedimentation by the Late Carboniferous. Differential compaction of Cooper Basin strata draped over an undulating Late Carboniferous landscape produced non-tectonic structures, critical for trapping petroleum. Cupolas interpreted from the gravity data locate some of the non-tectonic structural highs.

Geophysical modelling reveals that most aeromagnetic and gravity anomalies are source in Proterozoic basement, Cambrian basalts and Palaeozoic granites.

The Patchawarra Trough and the underlying Warburton Basin, rest on adjacent elongate NE-trending rock bodies with high magnetic susceptibility and moderate density. Their tops are about 7 km deep but a depth extent of at least 15 km is indicated. These anomalies are interpreted as lower crustal or upper mantle material which has risen into the upper crust during extension. The southeastern edge of these bodies are fault-bounded with up to 3.5 km of block uplift evident. Episodic uplift in Permian and Triassic times affected the Cooper Basin to form the Gidgealpa, Merrimelia, and Innamincka Ridges, a critical structure for trapping petroleum and separating troughs with different 'basement' geology.

The Gidgealpa, Merrimelia, and Innamincka Ridges separate the Patchawarra Trough from the deeper Nappamerri Trough. It is located above a prominent northeast-trending gravity low of considerable depth extent interpreted to be Big Lake Suite Granodiorite masses. Intense gravity lows are interpreted as cupolas. Weaker compaction of Cooper Basin sediments draped over them formed closed structures suitable for trapping petroleum.

Another gravity low over the Tenappera Trough, is interpreted to be sourced by Early Devonian granites intruded into Proterozoic basement. Small associated magnetic anomalies are also interpreted as skarns, perhaps formed by metasomatism of Neoproterozoic carbonates. If present farther south, at shallower depths, they may be attractive to minerals explorers.

North-striking metamorphosed Proterozoic rocks account for large-amplitude magnetic anomalies beneath southern the Strzelecki Sheet area and are interpreted as the northern extent of the Willyama Supergroup or Curnamona Craton. The eastern edge of this Proterozoic province, evident in aeromagnetic data, is marked by the Koonenberry Fault which possibly turns into an east-west trending fault beneath the Cooper Basin.

Magnetic units of unknown origin are also present beneath the region. In the far south-west of the Strzelecki Sheet area, a province with northeast trends passes beneath the Cooper Basin, while in the far north of the Innamincka Sheet area there is another basement province. Both provinces are provisionally assumed to have sources in Proterozoic rock units, perhaps an undrilled equivalent of the Arunta Block.

Introduction

High-resolution airborne geophysical data were acquired by AGSO in 1997 over the Strzelecki and Innamincka 1:250 000 scale map sheet areas in the far northeast of South Australia (Richardson, 1998), as a contribution to the National Geoscience Mapping Accord (NGMA). This study area covers most of the South Australian portion of the Cooper Basin, a prolific oil and gas producer (Fig. 1).

The work was undertaken in the lead-up to the 1999 introduction of competitive bidding for Cooper Basin acreage in South Australia, exclusive of existing production tenements (*PESA News* December/January 1998/99, p. 49). It also represented an early activity in AGSO's new Central Australian Basins Gas Project ('CABGAS') being designed to encourage more exploration for gas in Australia's deeper and older basins.

This paper presents an interpretation of the high-resolution aeromagnetic and available gravity data covering the study area to assist in the understanding of its geological evolution, basin formation and basin framework. Brief comments are also provided on the surficial cover as interpreted from the radiometric and aeromagnetic data acquired.

The study area is geologically complex and largely covered by surficial sediments. It is underlain by several stacked basins which overlie adjoining provinces of igneous and metamorphic rocks (Figs. 2 & 3). It also straddles the interpreted location of the Tasman Line, an enigmatic structure dividing Australia into a western region of exposed Precambrian cratons and fold belts overlain by Neoproterozoic and Phanerozoic basins, and an eastern region of exposed Phanerozoic fold belts overlain by younger basins (Veevers, 1984; Scheibner & Basden, 1996).

Extensive drilling for petroleum has revealed that surficial sediments up to 400 m-thick, forming part of the extensive Cainozoic Lake Eyre Basin, almost entirely cover the study area. They lie unconformably on a portion of the widespread, petroleum productive, 3 km-thick Jurassic to Cretaceous Eromanga Basin. This basin overlies c.50,000 sq. km of the 2.5 km-thick oil and gas-producing Late Carboniferous to Triassic Cooper Basin.

Many well intersections also reveal that the extensive, prospective Cambrian to Ordovician Eastern Warburton Basin unconformably underlies the Cooper Basin. Beneath the Cooper Basin, basalts are locally present in the Warburton sequence. Proterozoic metamorphic and igneous rocks form separate provinces and Early Carboniferous granitoid intrusions also form part of the basement beneath the Cooper Basin in the study area.

The Eastern Warburton Basin is traditionally considered to be economic basement despite several hydrocarbon discoveries. The top Warburton Basin seismic reflector together with older lithologies and intrusives are mapped as the 'Z' horizon (Fig. 4).

Most aeromagnetic and gravity anomalies in the region have significant components of their sources in basement units. Structures within them are evident in the data. Most major structures have apparently been inherited into the overlying basins, following episodic movements and rejuvenation. Hence the potential field data sets are important for assisting to understand the regional geological evolution, basin formation, basin framework, basin structure and petroleum occurrences.

Stratigraphy

Proterozoic

Proterozoic metasediments have been recorded in 8 wells from the Cooper Basin area (Fig. 1). They include: protomylonitic pegmatitic gneiss in Haddon Downs 1, to the north of the study area, considered to be part of the Arunta Block (Rankin & Gatehouse 1990); highly sheared and folded, quartz-sericite schist considered to be part of the Willyama Supergroup in Fortville 3 (Gatehouse, 1986), to the south of the study area, and; steeply dipping orthoquartzite of possible Proterozoic age in Daralingie 1 (Gravestock et al., 1995), in the south-west of the study area.

Eastern Warburton Basin

The subsurface Cambrian to Ordovician Eastern Warburton Basin underlies large portions of the Cooper Basin mostly at 2-4 km beneath the surface. Its stratigraphy was established by Gatehouse (1983a; 1983b; 1986). Poor control on formation boundary relationships, owing to a lack of cored intersections, means subdivision of the Warburton Basin is primarily lithostratigraphic.

Gatehouse defined the following stratigraphic units: Mooracoochie Volcanics (felsic volcanics); Kalladeina Formation (well dated carbonates; Sun, 1996); Dullingari Group (dominantly shales); and Innamincka Formation (red beds, Fig. 2). The recognition of Warburton Basin lithologies on wireline logs is described by Boucher (1997a).

More recent studies specific to the Eastern Warburton Basin include Carroll (1990) Gravestock and Gatehouse (1995) Gravestock et al. (1995) Roberts et al. (1990) Sun et al. (1994) Sun (1996) and Zang (1992; 1993a; 1993b). Overall tectonic evolution has been analysed by Apak (1994) Apak et al. (1993; 1995) Boucher (1991; 1994a; in prep.) Carroll (1990) Kuang (1985) Roberts et al. (1990) and Mancktelow (1979).

Mooracoochie Volcanics

The type section of the Mooracoochie Volcanics is in Gidgealpa 3 (Gatehouse, 1983a; 1983b) and a detailed study of volcanic facies, sedimentology, geochemistry, distribution and correlation has been made by Sun (1996). The wide variety of rock types present include rhyolite, dacite, latite, minor basalt, ignimbrite, syn-eruptive hyaloclastites, carbonates, epiclastic conglomerates and sandstones.

Gatehouse (1986) proposed the Mooracoochie Volcanics combined to form the Gidgealpa Volcanic arc (Fig. 5) which he believed linked to the Wonominta Block.

Prehnite is present in Mooracoochie Volcanics at Gidgealpa 5. If of burial metamorphic origin, then burial depths of approximately 7 or 8 km can be implied (Boucher, 1994a)

The acid, Mooracoochie Volcanics would not be expected to produce significant aeromagnetic anomalies at the depths they occur. Magnetic susceptibilities of acid volcanics are variable, typical susceptibilities range from 1×10^{-4} to 7×10^{-3} and 6×10^{-2} to 1×10^{-2} SI (Clark 1997). Hence any magnetic anomalies in the Gidgealpa Volcanic Arc (Fig. 5) would come from either above or below the volcanics.

Kalladeina Formation

The Kalladeina Formation is a Middle to Late Cambrian carbonate and shale succession unconformably overlying the Mooracoochie Volcanics with a type section in Kalladeina 1 (Gatehouse 1983a; 1983b). It comprises two major types of lithologies representing two stages of deposition. The early stage comprises mainly carbonate dominated lithologies including bioclastic wackestone, packstone, grainstone, dolomitic limestone, siltstone and shale, and shale/calcareous mudstone interbeds. It indicates a relatively broad shelf to basin depositional system (Sun, 1996). The late stage consists mainly of mixed siliciclastic/carbonate lithologies including shale, siltstone, sandstone and minor sandy limestone, possibly representing a shallow marine shelf environment (Sun, 1996).

Unaltered carbonates of the Kalladeina Formation would not be expected to produce magnetic anomalies at the depths they occur. Unaltered carbonates range in susceptibility from 1 x 10^{-5} to 1 x 10^{-3} SI. (Clark 1997). However, highly magnetised skarns may form due to metasomatism induced by contact metamorphism, with susceptibilities ranging from 0.1 to 5 SI. (Clark 1997).

'Jena Basalt'

The 'Jena Basalt' is an informally named rock first identified as a highly magnetically susceptible lithology in cuttings (Boucher, 1991). It was formerly included with the Mooracoochie Volcanics (Gatehouse, 1986) and denotes initial rifting within the Warburton Basin (Boucher, in prep.). Altered 'Jena Basalt' has been cored in Murteree A-1 and basalt interbedded with deep marine limestones occurs in Gidgealpa 7 core (Sun 1996).

Cuttings of 'Jena Basalt' are present in Murteree A-1, Jena 1 and 6, Kobari 1, Gidgealpa 1 and Mudlalee 1. Reworked 'Jena Basalt' occurs in Dullingari 1, Kalanna 1 and Gidgealpa 1 (Gravestock et al., 1995). Recently, Ordovician basalt below the 'Z' horizon has been discovered in thin sections of cuttings from Pondrinie 5, 7 and 9 and Merrimelia 2, north of the Nappamerri Trough (Sun & Gravestock, in prep).

The 'Jena Basalt' has the geochemical affinity of a 'within-plate' continental rift lava inviting comparison with the larger East African Rift (Boucher, 1991). Volcanism within rift basins typically occurs at the onset of rifting. Trilobites in Gidgealpa 1 constrain the minimum age of the 'Jena Basalt' to the Middle-Late Cambrian boundary (Sun 1996).

Boucher (1991; 1994a) suggested that the 'Jena Basalt' was the northerly extension of a Cambrian rift extending through the Wonominta Block beneath covering basins (Fig. 5). Early Cambrian lavas in the block have been dated at 525 Ma (Zhou & Whitford 1994; Crawford et al., 1997). These lavas and the Truro Volcanics in South Australia are Early Cambrian (Gravestock & Gatehouse, 1995) both slightly older than the 'Jena Basalt'. However, the more northerly 'Jena Basalt' may represent another episode of volcanism along linked rift structures.

Basalts typically have a susceptibility range of 6 x 10^{-2} to 6 x 10^{-1} SI (Clark 1997). However, thin and extensive basalt flows at depth do not produce significant magnetic signatures. Only when thick basaltic piles accumulate do they produce anomalies.

Dullingari Group

In the type section of the Dullingari Group, in Dullingari 1 (Gatehouse 1983a; 1983b) two different turbiditic units exist: a lower dark grey to black pyritic shale, and an upper greenish siltstone and shale, separated by a thin bed of pebbly sandstone or conglomerate. The Dullingari Group is, in part, a basinal, lateral facies equivalent to the Kalladeina Formation (Sun, 1996). Assuming a lithostratigraphically defined unit, all shale intersections in the Warburton Basin tend to be included as Dullingari Group. Hence, the unit is mapped widely across the basin.

Like carbonates, shales typically range in susceptibility from 1 x 10^{-5} to 1 x 10^{-3} SI. (Clark 1997) and would not source large magnetic anomalies at the depths they are found.

Pando Formation

The Pando Formation (Gravestock et al., 1995) is a glauconitic sandstone and siltstone/shale unit previously recognised as part of the Dullingari Group (Gatehouse 1986; Taylor et al., 1991). The sandstone is marginal to shallow marine, bioturbated, fine to coarse-grained, with abundant glauconite and heavy minerals (especially zircons) and is interbedded with minor buff to grey siltstone and shale, which is pyritic in places. Stratigraphically, the Pando Formation was originally mapped beneath the

Mooracoochie Volcanics (Gravestock et al., 1995). However, it is now considered to be equivalent to the Innamincka Formation (Zang, 1993a; 1993b).

Sandstones also typically have susceptibilities in the range of 1×10^{-5} to 1×10^{-3} SI. (Clark, 1997). However, depending on the amount of detrital heavy minerals, susceptibilities may be slightly higher. Several kilometres beneath the surface, they would not produce easily recognisable or mappable signatures.

Innamincka Formation

This unit is the formalised name for a thick redbed unit, which was extensively cored in Innamincka 1 where it was previously known as the 'Innamincka Red Beds' (Sprigg, 1967). The Innamincka Formation is diachronous with the upper part of the Kalladeina Formation (Sun, 1996; Gravestock et al., 1995; Gravestock & Gatehouse 1995). The Innamincka Formation has been interpreted as shallow marine (Ludbrook, 1961; Gravestock & Gatehouse 1995) more specifically a southward prograding delta system (Zang, 1993b).

Like the Pando Formation, the Innamincka Formation would not produce significant and recognisable aeromagnetic signatures.

Big Lake Suite granodiorite intrusions

Granodiorite has been intersected in wells in the Big Lake area. Zircon dating of the Big Lake Suite has revealed late Carboniferous ages of 298 +/- 4 Ma and 323 +/- 5 Ma (Gatehouse et al., 1995).

The Big Lake Suite intrudes the Warburton Basin. Prehnite in Mooracoochie Volcanics at Gidgealpa 5 suggests burial of the intruded rocks could have reached depths of 7 or 8 km (Boucher 1994a). If granodiorite emplacement occurred then, it may have been emplaced at these depths too. If so, a 7 to 8 km thickness of sediments would need to have been eroded to expose the granites before deposition of the Patchawarra Formation in Early Permian time at Moomba or a little earlier at Big Lake. This suggests a significant tectonic event occurred in the Late Carboniferous, producing up to 8 km of uplift in only a few million years. This movement also imparted a northeast-trending structural grain on the 'basement', which would be inherited throughout Cooper Basin deposition. The rapid uplifting event contrasts strongly with the relatively mild sag, with deposition of up to 4 km of sediments, and relatively little apparent subsequent uplift since Late Carboniferous time.

Contact metamorphism of Warburton Basin sediments has been recognised in Moomba 2 (Gravestock et al., 1995). Inspection of thin sections of Warburton Basin core and cuttings revealed further evidence of contact metamorphism in Koree 1 and possibly in Arrakis North 1. Most of the thin sections are from cuttings and from within the 'altered zone' (Boucher, 1996; 1997a) at the top of the Warburton Basin. The metamorphism is difficult to recognise in cuttings due to the relatively small size of each cutting fragment when compared to contact metamorphic spots. In places, e.g. Moomba South 1, no evidence of contact metamorphism could be seen in cuttings of shales and siltstone at six metres above the intruding granodiorite.

Granitoids have magnetic susceptibilities ranging from 6×10^{-3} to 8×10^{-1} SI (Clark 1997).

Cooper Basin

The Cooper Basin sequence reaches 2.5 km-thick and unconformably overlies the Warburton Basin, Big Lake Suite and Proterozoic basement elements. The unconformity is mapped as the 'Z' seismic horizon (Fig. 4) and colloquially referred to as 'top basement'. The top of the Cooper Basin lies between 1.5 and 2.5 km beneath the surface.

Early studies on the Cooper Basin (Kapel, 1966; Grund, 1966; Martin, 1967) led to subdivision of its strata into the Late Carboniferous to Permian Merrimelia Formation and Gidgealpa Group and the Triassic Nappamerri Group, although Williams & Wild (1984) indicated that the Merrimelia Formation was part of the Gidgealpa Group. Gatehouse (1972) and Kapel (1972) further subdivided the Gidgealpa Group. This nomenclature is widely used and relationships of units are shown in Fig. 3.

The Merrimelia Formation and Tirrawarra Sandstone comprise a glacio-lacustrine and glacio-fluvial system overlain by fluvial and peat swamp Patchawarra Formation facies. The Murteree and Roseneath Shales are lacustrine siltstones, respectively overlain by fluvio-deltaic Epsilon and Daralingie Formations. The Toolachee Formation unconformably overlies the Daralingie Formation before it grades into the Nappamerri Group. All three units are dominantly fluvial.

Subdivisions of the thick Nappamerri Group sequence in Queensland (Powis 1989) are not widely used in South Australia as the Nappamerri Group is considerably thinner (cf. Channon & Wood, 1989; Papalia, 1969; Youngs & Boothby, 1985).

The shift of depo-axes during the Late Triassic was in response to reactivation of older structures (Kuang, 1985). At that time coal measures accumulated at Leigh Creek Wopfner (1985) considered these movements to be a forerunner to events that were to initiate the Eromanga Basin in the earliest Jurassic.

Further details of Cooper Basin stratigraphy in South Australia are provided by Apak (1994), Apak et al. (1993; 1995), Boucher (1997b), Gravestock et al. (1995; 1998), Fairburn (1992), Grund (1966), Hill & Gravestock (1995), Seggie et al. (1994), Stuart (1976), Stuart et al. (1988), Thornton (1973; 1979), Williams & Wild (1984) and Williams et al. (1985).

Clastic sediments of the Cooper Basin should range in susceptibility from 1×10^{-5} to 1×10^{-3} SI. (Clark 1997), none of which would be expected to produce significant aeromagnetic anomalies at depth. However detailed studies by Kivior and Boyd (1997) recognised numerous small magnetic sources at various depths within the Cooper and Eromanga Basins.

Eromanga Basin

Unconformably overlying the Warburton and Cooper basins, is the Jurassic to Cretaceous Eromanga Basin. It is up to 3 km-thick in the region and represents relatively uniform infill of a vast, slowly subsiding basin. The Eromanga Basin consists of fluvial and lacustrine Jurassic sediments overlain by marine to paralic and terrestrial Cretaceous sequences (Bradshaw & Yeung, 1992; Bradshaw, 1993). Details of its stratigraphy in the region are provided by Alexander & Sansome (1996) Callen et al. (1995) and Krieg et al. (1995) as summarised in Fig. 3.

Like the Cooper Basin, little significant magnetic response would be expected from the Eromanga Basin.

Lake Eyre Basin

The Lake Eyre Basin consists of non-marine sediments up to 400 m-thick (Fig. 3) deposited between several structural events. They unconformably overlie deeply weathered Eromanga Basin strata. Details of Lake Eyre Basin stratigraphy are given in Callen et al. (1995), Gravestock et al. (1995) Krieg et al. (1990), Moussavi-Harami & Alexander (1998), Wopfner (1974), and Wopfner et al. (1974).

Like the Cooper and Eromanga Basins, little significant magnetic response would be expected from the Lake Eyre Basin, however, the recent small 'B5' aeromagnetic survey revealed near surface anomalies that were not evident in older data (Frears & Tucker, 1994).

Geophysical Data

Between August and November 1997, a semi-detailed regional airborne geophysical survey was flown over the Innamincka and Strzelecki 1:250 000-scale map sheet areas in northeast South Australia along east-west flight lines 400 m apart and at a flight height of 80 m above ground. Total magnetic intensity, 256-channel gamma-ray spectrometric and digital elevation data were recorded (Richardson, 1998).

Various data enhancements of the geophysical data were used for the study.

Total magnetic intensity – reduced to the pole

A gradient-enhanced image with northerly illumination of the total magnetic intensity, reduced to the pole grid, is shown in Fig. 6. The reduction to the pole process was carried out to remove magnetic polarity effects due to the non-vertical inclination of the magnetic field in this region.

This image contains a series of narrow, high-frequency anastomosing and curvilinear anomalies, with overall WNW-ESE trends across the entire survey region. These high frequency anomalies, of similar width and amplitude, were also observed in the smaller 1810 km^2 'B5' airborne survey west of Moomba (Fig. 6). That survey, jointly funded by the Department of Mines and Energy of South Australia and Santos, was flown to determine the suitability of aeromagnetic and radiometric data in petroleum exploration (Frears & Tucker, 1994).

Cultural features are evident in the image as fine linear anomalies caused by gas pipe lines and as small circular anomalies caused by well heads, processing plants and buildings.

Low pass filtered image of total magnetic intensity

Figure 7 is a low pass filtered image of the total magnetic intensity, reduced to the pole grid. A low pass filter, with a cut-off wavelength of 5000 m, was designed to remove the high frequency magnetic effects of near-surface features, while leaving the broader magnetic anomalies due to basement features intact.

Inspection of the residual grid, i.e. the difference between the low pass grid and the original total magnetic intensity grid, showed only the high frequency anomalies. No broader wavelength anomalies were present in the residual grid, signifying that no field information attributable to the deeper sources was removed.

Vertical gradient of low pass filtered, total magnetic intensity

Figure 8 is the vertical gradient of the low pass filtered grid of Fig. 7. The vertical gradient process sharpens anomaly edges and separates overlapping anomalies. The enhancement of the anomaly shapes produces a more realistic representation of source body shape, as well as enhancing any structural information present in the data. The vertical gradient process also enhances the magnetic effect of high frequency anomalies, caused by shallow sources, relative to low frequency, deeper sourced anomalies.

Applying a vertical gradient to the original unfiltered (non-low pass filtered) total magnetic intensity grid, results in an image totally dominated by the high frequency anomalies. So removal of the high frequency anomalies, by the low pass filtering process, has allowed for the enhancement of detail within the broader anomalies, which would otherwise have been totally obscured.

Gravity data

An image of the Bouguer gravity field, using values from the Australian National Gravity Database (Murray, 1997) is shown in Fig. 9. The numerous small circular 'bumps' in the northern section of the image are due to an incorrectly levelled gravity survey.

The gravity field is dominated by two northeast-trending gravity troughs, separated by a northeast-trending gravity high.

The first gravity trough extends from the Nappamerri structural trough in the east of the survey area, beneath the Moomba Dome and then west beneath the Pando Ridge. The second northeast-trending gravity trough is situated south of the Mulga 1 well.

In the northwest of the survey area there is a region of generally low gravity values, surrounded by gravity highs. These include a broad positive anomaly in the region of the Tirrawarra field and a linear gravity ridge along the northeastern edge of the central gravity low.

Gamma-ray spectrometric data

Figure 10 is a ternary image of the relative equivalent concentrations of K (red) Th (green) and U (blue) in the surficial geology.

Geological mapping by Townsend & Thornton (1975) and (Gravestock et al. 1995) shows that the region is underlain mainly by Quaternary aeolian sand, alluvium incised by braided to southerly-meandering ephemeral channels, and claypans. The Innamincka Dome, in eastern Innamincka Sheet area, exposes thin Eyre Formation and other undifferentiated Tertiary strata from the immediately underlying kaolinitic shales, siltstones and fine sandstones of the uppermost Eromanga Basin sequence (Fig. 10). The bedrock units are deeply weathered. In places, there is a cover of duricrust, with gibbers (Townsend & Thornton, 1975).

Dominant, closely-spaced northerly trends in the radiometric data reflect the orientations of aeolian sand dunes which are widespread throughout most of the area. In the field, these sands are white, yellowish and deep red (Townsend & Thornton, 1975). Sharp colour changes in the radiometric data reflect their *in situ* derivation from wind sorting of the underlying unconsolidated regolith.

Leached bedrock crops out at the Innamincka Dome. In the data, it is prominently displayed in blue. Enrichment in U probably denotes relative abundances of clays, especially in the kaolinitic Winton Formation strata and in the clay-rich lower portions of weathered profiles. Some relative enrichment of U is also apparent in the duricrust, where it is probably adsorbed in goethite.

Colluvial deposits from the Innamincka Dome shows up in lighter blue, indicating derivation of that detritus from outcrop. Other small blue patches in the data are evident in the far northwest and southeast corners of Innamincka Sheet area, where bedrock is also exposed.

The yellowish regions in the radiometric data are underlain by alluvium and modern claypans. These units are not notably radioactive and have mixed, relatively low abundances of the radioelements.

The reddish regions in the radiometric data are underlain mainly by dune sands. The reddening in the image, caused by increased K concentration, is probably caused by greater winnowing and loss of clay and silt fractions following wind sorting.

Magnetic susceptibility data

Boucher (1991) and Tucker (1993) used magnetic susceptibility measurements to assist in distinguishing formation boundaries from within the Warburton, Cooper and Eromanga Basins. The average Cooper Basin values were found to be 2.5×10^{-3} SI, which is in the upper range for sediments. The higher of these values came from the Nappamerri Group redbeds. Unaltered 'Jena Basalt', which was first recognised as being unusually highly susceptible (Boucher 1991), averages 0.75 SI which lies in the upper range for basalt (Clark 1997). Direen (1998) found the susceptibility of the nearby Neoproterozoic Mount Arrowsmith Volcanics to be 0.1 SI and attributed the magnetic anomalies in the area as sourced by these basalts.

Boucher (1994b) compiled magnetic susceptibility data from cores, cuttings and sidewall cores in an attempt to define the sources of any aeromagnetic anomalies that may have been sourced from within or above the Warburton Basin (Frears & Tucker 1994). Low values were found from cores and cuttings of clastic sediments, acid volcanics and granitoids. The only elevated values were found from cuttings contaminated by steel shavings from the drill bit. That study, and that of Tucker (1993), could not determine the sources of the large and deep magnetic anomalies. The 'Jena Basalt' is the only sampled unit with a high magnetic susceptibility.

Depth to magnetic source modelling

Depth to magnetic source modelling was conducted on the low-pass filtered data, using Naudy's (1971) automatic depth determination routine. The Naudy method analyses profile data and estimates the depths to the top of dipping dykes and edges. Depth estimation was computed using the AutoMag application (Shi & Boyd, 1994) a module of the ModelVision software package. A description of its use is given by Gunn (1997).

The AutoMag solutions were generated using a dipping dyke model, and were applied to profiles extracted from the low-pass filtered grid. In situations where circular anomalies occur, direct forward modelling was used to compute the source depths. Although the depth estimates were computed using the low pass filtered, total magnetic intensity data, for clarity of presentation they are plotted on the vertical gradient image (Fig. 8). All interpreted depths occur at or below the 'Z' horizon.

Geophysical Interpretation

The interpretation of the basement units to the Cooper Basin is shown in Fig. 11. It is based on the various potential field geophysical images, depth horizon images and well log data, which have been incorporated into a GIS package prepared by Primary Industries and Resources South Australia (PIRSA). Geophysical modelling (Fig. 12) and depth to magnetic source modelling (Fig. 8) also formed a basis for the interpretation.

We have concluded that the sources of the magnetic anomalies evident in Fig 7 all occur at or below the base of the Cooper Basin sequence. This finding is based on depth to source estimates and the lack of significant magnetic sources within the overlying sedimentary section.

Geophysical bodies have been identified and interpretations of them are as follows:

Patchawarra Trough magnetic anomaly

A large magnetic anomaly, evident in the low pass filtered image of Fig. 7, overlies the Patchawarra Trough. This anomaly consists of several individual peaks surrounding a prominent magnetic low.

The vertical gradient image (Fig. 8) enhances the internal detail of this anomaly by revealing a set of northeast-trending structures which indicate that the anomaly is caused by several adjacent magnetic sources with northeasterly elongations. The depth to magnetic source modelling (Fig. 8) indicates depths of over 7000 m to the top of most of these sources.

A shallower northeast-trending elongate anomaly, with a source depth less than 6000 m, is situated along the southeastern edge of the broader anomaly. It corresponds to known structural basement highs along the Gidgealpa and Merrimelia Ridges (located in Fig. 4).

The gravity field in this region (Fig. 9) shows a northeast-trending gravity ridge, corresponding to the Gidgealpa and Merrimelia Ridges, and a circular gravity high, corresponding to the central magnetic low situated in the region of the Tirrawarra field. No distinct gravity low, as would be expected by the low-density sediment infill of the Patchawarra Trough, is evident. This fact implies the existence of a dense mass beneath the Patchawarra Trough, whose positive gravity effect is counterbalancing the gravity effect of the sediments.

Forward modelling of both the magnetic and gravity fields along two northwest-trending profiles is shown in Fig. 12. Results suggest the presence of a deep body of homogenous physical properties, with a large depth extent, best accounts for the observed magnetic and gravity fields. The interpretation of cross-section 1 (Fig. 12) suggests relatively high magnetic susceptibility values of up to 0.037 SI. This is in the upper susceptibility range of rock types (Clark, 1997) and could correspond to mafic and ultramafic material. A density value of 2.92 $g.cm^{-3}$ is also consistent with mafic and ultramafic intrusives. Where the profile crosses the magnetic low and the gravity high, in the vicinity of the Tirrawarra field (cross section 2 in Fig. 12) the causative body has a lower magnetic susceptibility (0.012 SI) a higher density (2.99 g.cm^{-3}) and a circular intrusive character.

The maximum depth extent of the body labelled as 'deep intrusive' in Fig. 12 has been modelled to be 15 km. This is the approximate depth for which the anomalously high temperature gradient (~38 °C/km) in the Cooper Basin region (O'Sullivan & Kohn, 1997) would exceed the Curie Point, the point beyond which magnetic bodies cease to be magnetic. It is possible that the intrusive body may have a considerably larger depth extent, which cannot be resolved by computer modelling of the magnetic field.

The source rock type for the central, denser and less magnetic portion of the intrusive body is uncertain. Possibilities include a separate, later, differentiated intrusive body, perhaps of anorthositic composition.

The highly magnetic, dense, apparently intrusive, sub-Patchawarra Trough body may have resulted from magma formed by decompression processes associated with crustal extension related to basin formation in the area. (cf. processes described by White (1992) and Gunn et al. (1996)). Another possibility is that the body originated as magma developed by hot-spot activity, while subsequent thermal subsidence in the area initiated basin development.

The sub - Patchawarra Trough magnetic body is below seismic basement and probably deeper than the base of the Eastern Warburton Basin (Fig. 13).

The modelled, shallower southeastern edge of the sub-Patchawarra Trough magnetic body appears to be fault-bounded with up to 3.5 km of uplift indicated (Figs. 8 & 13). The parallelism and close coincidence in positions of the shallower portion of the intrusive body and the Gidgealpa-Merrimelia-Innamincka Ridge suggests that the two features may be related. The geophysical model which best fits the data suggests the sources of the anomalies are offset by a reverse fault.

Gravity low over Nappamerri Trough and Big Lake Suite granodiorite

Inspection of the Z-horizon image (Fig. 4) reveals that the Nappamerri Trough has a large area of greater depth than the Patchawarra Trough. However, the Eromanga and Cooper Basin sediment fill revealed by seismic data is insufficient on its own to account for the large northeast-trending gravity low beneath the Nappamerri Trough (Fig. 9). Also, low-density sediments in the Daralingie platform region in the western Cooper Basin are of insufficient thickness to account for the extension of the gravity low beneath the platform.

The density contrast between the intrusion of interpreted possible mafic/ultramafic (2.92 g.cm^{-3}) composition beneath the Patchawarra Trough compared to a 'background' density of 2.8 g.cm^{-3} used in the computer modelling (Fig. 12) is also not large enough to account for the disparity in the gravity field. To account for the entire gravity low, a large low-density body with a considerable depth extent is required. This low density body is interpreted to be an extension, at depth, of the Big Lake Suite granodiorite whose existence is known from drilling (Fig. 9).

Intense gravity lows within the broad gravity trough correspond to subcropping Big Lake Suite granodiorite beneath the Cooper Basin and are interpreted to be cupolas emanating from the larger batholithic mass. Granodiorite has been intersected in wells from the Moomba and Wooloo areas, and are interpreted as cupolas which also are interpreted to occur in several other locations (Fig. 11). The Wooloo cupola, however, corresponds to a magnetic anomaly of 3.5 km (Fig. 8). Frears & Tucker (1994) modelled the top of this anomaly to be no deeper than the 'Z' horizon and therefore within the granodiorite. There is no distinct geochemical difference to suggest why the Wooloo Cupola should have a magnetic response when the remaining Big Lake Suite does not (Boucher in prep.).

Results of computer modelling support the large batholithic mass interpretation, as revealed in cross-section 1 in Fig. 12, which passes over the intense gravity low where Big Lake Suite granodiorite subcrops in the Moomba area. It reveals the low density body of granodiorite composition (2.76 g.cm^{-3})

directly below the Cooper Basin sediments. However, cross-section 2 in Fig. 12 passes through the broad gravity trough between the intense gravity lows. It shows the same low density body, modelled at depth, well below the base of the Cooper Basin sediments.

Magnetic high over gravity low, Moomba area

A roof pendant of contact metamorphosed Warburton Basin sediments (Figs. 11 & 19) is known to be present in the Moomba Field (Gravestock et al., 1995). Contact metamorphism detected in Koree 1 indicates it lies above an occurrence of Big Lake Suite granodiorite suggested by the gravity low. Given the difficulty of recognising contact metamorphism in cuttings elsewhere, it cannot yet be ascertained if the magnetic anomaly is due to contact metamorphism. The volume of contact metamorphosed sediments is not considered large enough to produce an observable magnetic signature at the depth at which it occurs, unless its source is a skarn. As carbonates are present in the Warburton sequence, this is possible.

Gravity low over Tenappera Trough

The source of the northeast-trending gravity low situated beneath the Tenappera Trough (Fig. 9) is interpreted to be due to another region of granitoids (Gravestock & Jensen-Schmidt 1998). Shallower cupolas projecting upwards from the main granitoid body (Fig. 11) could produce the more intense circular gravity lows, within its broader gravity trough, however, none of the sparse drill holes have intersected granitoids.

Results of modelling (cross-section 3, Fig. 12) along profile 3 (Fig. 9) show the top of this interpreted granitoid mass to be at a depth of approximately 6000 m with a density of 2.64 $g.cm^{-3}$. The lower density compared to the modelled value for the Big Lake Suite granodiorite (2.76 $g.cm^{-3}$) suggests a more leucocratic rock with a higher silica composition than the Big Lake Suite. A sample from Roseneath 1 well, located on the same gravity trend in Queensland (Fig. 15), has an Early Devonian age of 405+/-2 Ma (Murray, 1986) also indicating that this belt is unrelated to the Big Lake Suite. The granite at Roseneath 1 well has a similar age to the Tibooburra Granodiorite (410 Ma; Thalhammer et al., 1998) and to many other Early Devonian masses surrounding the Late Silurian to Early Carboniferous Darling Basin farther to the southeast (Yeates, in prep).

Magnetic highs over Proterozoic

The southern region of the low pass filtered magnetic image (Fig. 7) consists of a series of large-amplitude, northerly-striking anomalies. Their sources are beneath the southern Cooper Basin. Some wells in this region have penetrated regionally metamorphosed Proterozoic rocks. Their presence indicates that Proterozoic rocks extend northwards into the survey area from the Willyama Supergroup and Curnamona Craton (Gatehouse, 1986).

The Proterozoic rocks are interpreted to have been intruded by granitoids beneath the Tenappera Trough, and possibly also by more southerly masses of the Big Lake Suite.

In NSW, the Koonenberry Fault separates mainly Proterozoic rocks from Palaeozoic elements to the east (Mills, 1992; Crawford et al., 1997). This fault either extends into the far-east of the survey area along the same trend (Fig. 14) or turns east-west as indicated on depth structure maps (cf. Fig. 4). This area is interpreted to contain the easternmost extent of subsurface upper crustal Proterozoic rocks in the region.

To the west of the Proterozoic, in the southwestern portion of the survey area, is a region of moderate to low amplitude magnetic anomalies bound by a northeast-trending fault (Fig. 11). The character and strike of these magnetic anomalies differ from the Proterozoic units to the east and are considered to represent a separate block. The age of these units is not known and they have been labeled as 'Unknown Magnetic Units' in Fig. 11.

The northern one-third of the Innamincka Sheet contains anomalies over a sparsely drilled area in northeast South Australia which extends into southwest Queensland and the far southeast of the Northern Territory. They collectively form a broad magnetic unit (Fig. 11) whose sources are possibly a

Proterozoic meta-sedimentary complex. Rankin & Gatehouse (1990) attributed the Proterozoic in Haddon Downs 1 as part of the Arunta Block.

Possible magnetic skarns

Magnetic anomalies situated on and to the south of Mulga 1 well (Fig. 7) are situated in the region of the northeast-trending gravity low beneath the Tenappera Trough. The source bodies to these magnetic units have a limited depth extent and are modelled in cross-section 3 (Fig. 12) as highly magnetic bodies immediately above a granite cupola.

The interpreted magnetic susceptibility of 0.1 SI (Fig. 12) places the source rock type in the upper range of ultramafic rocks (Clark, 1997) or the extreme upper range of mafic and metamorphosed mafic rocks and well above susceptibility values for sediments and metasediments. However, its modelled susceptibility value also places it in the range of a skarn, possibly produced by Fe-metasomatism of any existing Proterozoic carbonate-bearing units by the interpreted Devonian granite intrusion there.

The existence of secondary alteration assemblages due to magnetite and hematite deposition is consistent with an interpretation by Gow et al. (1993) of volcano-plutonic complexes within the Gawler Craton protruding into platform sediments of the Stuart Shelf farther southwest in South Australia. Though no carbonates have been found in sparse drill holes to support the presence of possible skarns in the survey area, they do occur in the Neoproterozoic Balcanoona Formation (Preiss 1993) south of the Cooper Basin.

In the absence of definitive data, the skarn model is therefore attractive. It may also be significant for future mineral exploration. Potential targets, if present, would also be more likely at shallower depths in southwesterly directions from the survey area. The same would also apply if fractionated Big Lake Suite granodiorite intruded Warburton Basin carbonates at shallow depths instead of 2 km beneath the surface.

'Jena Basalt' magnetic high

Several wells have encountered 'Jena Basalt', the only lithology within the Warburton Basin sequence with significant measured magnetisation within the Cooper Basin region. The basalt has been found in six wells in the region of Jena 1 and Kobari 1 wells (Fig. 7) and in four wells situated on or near the Toolachee Ridge (located in Fig. 4). All these wells are situated on or near the edges of positive magnetic anomalies. Ordovician basalt has recently been found in cuttings from the Pondrinie area (Fig. 4; Sun & Gravestock, in prep.). It is thus possible that Ordovician basalts may also enhance magnetic anomalies in the area. Similarly, basalt found just below 'Z' in Gidgealpa (Sun 1996) would contribute to the aeromagnetic anomalies there

Preliminary modelling of the Jena and Kobari magnetic anomalies revealed that they could be replicated by a source model consisting of a magnetic layer, with susceptibility values consistent with basalt, and with the modelled depths to the top of the layer being the same as the depths to the intersected basalt (1535 m in Jena 1; 1676 m in Kobari 1). The thickness of 'Jena Basalt' in both wells is not known, as neither has penetrated a complete section. The depth estimates (Fig. 8) of the two anomalies give similar values as encountered for the intersected depths of the basalt in the two wells, adding support to the interpretation that the two magnetic anomalies are produced by thick sequences of 'Jena Basalt' (c. several hundred metres thick).

Of the four wells encountering 'Jena Basalt' in the Toolachee Ridge region, two encountered 'Jena Basalt' with a thickness of less than 40 m and the other two wells did not penetrate beneath the basalt. All four wells encountered the basalt between 2100 m and 2200 m depth. This is considerably shallower than the estimated modelled depths to source which exceeded 3700 m in this region.

The discrepancy between both depth estimates, when combined with preliminary modelling, suggests a large depth extent of the source body for the Toolachee Ridge anomaly. The 'Jena Basalt' in the

Toolachee Ridge area is therefore interpreted to be of insufficient thickness to produce a magnetic anomaly at the depths at which it is found.

Lake Eyre Basin curvilinear magnetic anomalies

A series of narrow, high-frequency anastomosing and curvilinear anomalies were recognised in the interpretation of the 'B5' aeromagnetic survey (Frears & Tucker 1994). However, the cause of these was not determined as they could not be seen on seismic sections nor could they be identified from magnetic susceptibility measurements in well data. The gradients of the anomalies indicate that they have sources within a few hundred metres of the ground surface. Kivior and Boyd (1997) have conducted depth estimates on some of these anomalies which places them in this depth range. It was assumed these features were from Tertiary or Quaternary drainage systems. Callen (1992, 1995) indicated that the Lake Eyre Basin consisted in part of braided stream, channel and floodplain deposits beneath the surface dune system and showed a consistent southeast transport direction. Statham Lee (1994) attempted to determine if these features were from magnetic material in palaeo-channels by correlating these data to 1:100 000 NOAA-AVHRR images to the small aeromagnetic survey. Whilst similar trending features were observed, the correlation was found to be inconclusive.

Some of these curvilinear anomalies are also present over the eroded Innamincka Dome, suggesting they are stacked relict palaeo-drainage systems preserved in the aeromagnetic data set. Throughout the Innamincka and Strzelecki Sheet areas, these anomalies have an overall WNW-ESE trend.

If these curvilinear features do represent palaeo-drainages, then they differ from the present-day ephemeral drainage which flows either westwards to Lake Eyre in the north of the survey area or southwards towards Lake Blanche, as is evident in the gamma-ray spectrometric data (Fig. 10).

Implications of the Geophysical Interpretation for Tectonic Evolution of the Basins

The Eastern Warburton Basin has at least two elements (Fig. 16). East of the northeast-trending Birdsville Track Ridge (Fig. 4) is a basement-detached trough. To the southeast, it becomes platformal until it merges into a rift trough beneath the central Cooper Basin (Fig. 16; Boucher, in prep).

The basement-detached trough lies mainly outside the survey area. It is unlikely that the carbonates and acid volcanics within this portion of the Warburton Basin are magnetic. Within the rift, however, aeromagnetic data have defined the rift-related 'Jena Basalt'. Gravity data reveal the Carboniferous Big Lake Suite intrusives.

The two depocentres are distinguishable by their age, position and differences in directions of sediment input (Figs. 16 and 17). The basement-detached trough and shelf sequence are known to be Early Cambrian to Early Ordovician, but may have had a Neoproterozoic beginning (Gatehouse, 1996). The rift trough is farther southeast and is known to contain Middle Cambrian to Middle Ordovician strata.

Warburton basement-detached trough

Roberts et al. (1990) described a Warburton Basin depocentre adjacent to and east of the Birdsville Track Ridge. Relatively undeformed sediments within this depocentre thicken rapidly towards the Birdsville Track Ridge and were interpreted as the deformed fill of a half graben followed by later structural inversion (Roberts et al., 1990). However, similar features occur in foreland basins.

A composite seismic line through the western part of this depocentre (Fig. 13) shows thickening of Kalladeina Formation strata towards the ridge, where they unconformably overlie the Mooracoochie Volcanics. The thickest section drilled is at Kalladeina 1, which penetrated 1658 m of Kalladeina Formation carbonates and 42 m of acid volcanics before reaching total depth (Gatehouse, 1986; Sun 1996). The base of the Mooracoochie Volcanics cannot be seen on seismic data and no well has yet penetrated the volcanics anywhere in the basin, so the thickness of Mooracoochie Volcanics is unknown. It is possible that the lower units of the Mooracoochie Volcanics are older than their oldest recorded Early Cambrian age.

The youngest part of the Kalladeina Formation, in Kalladeina 1, is Early Ordovician but the formation was eroded prior to deposition of Eromanga Basin sediments in the Mesozoic (Fig. 13) and the 'Z' horizon (top Birdsville Track Ridge and top Warburton Basin) shows little relief.

The western margin of the basement-detached trough is the Birdsville Track Ridge. The extent of the trough's northern and southern margins should approximate that of the ridge, if it is genetically linked. However, seismic data are currently too sparse to ascertain if this is so. The eastern limit of the depocentre is also uncertain.

A third Warburton Basin depocentre is present northwest of the Birdsville Track Ridge but is little known in that sparsely drilled area.

The eastern limit of the Proterozoic continental crust can be inferred from the known location of the Mooracoochie Volcanics (Fig. 16) which would have erupted on to the Proterozoic craton (Boucher in prep.). Interpretation of wireline logs from 88 wells reveals intersections of Mooracoochie Volcanics (Boucher 1997a; b). Their known extent trends sub-parallel to the Birdsville Track Ridge (Fig. 16) for as far as 125 km from the ridge. It is uncertain if the Mooracoochie Volcanics occur farther to the southeast, beneath younger sediments and volcanics. The most easterly known limit of the Mooracoochie Volcanics therefore provides a minimum easterly limit for the basement detached trough and a most westerly limit for the rift trough (Fig. 16).

The known sedimentary fill in the basement-detached trough and shelf is Kalladeina Formation carbonates (Fig. 17). It is probable, however, that these facies grade into clastic sequences close to the Birdsville Track Ridge, from where sediments were shed. It cannot be determined how much sediment has been subsequently eroded. Uplift would have accompanied inversion or subsequent structural reactivations, prior to deposition of the Eromanga Basin sediments (Fig. 13).

Roberts et al. (1990) inferred that the Delamerian Orogeny affected the Birdsville Track Ridge, accounting for a compressional phase. However, lack of folding in Warburton Basin sediments there indicates that the basement-detached trough itself has not been significantly affected by any of the central Australian, Palaeozoic orogenies (eg. Kapel, 1972; Gatehouse, 1986; Roberts et al., 1990).

There has been some minor easterly tilt of the trough, as shown in Fig. 13 where strata dip to the east. However, as the original depositional slope would have been towards the Birdsville Track Ridge, some tectonism is apparent.

Prehnite in felsic Mooracoochie Volcanics in the vicinity of the Gidgealpa field suggests their burial to 7-8 km (Boucher, 1994) much deeper than their present depths of a little over 3 km. This latter depth is compatible with that modelled from the aeromagnetic data (Figs. 12 and 13). If burial occurred at depth, as implied by burial metamorphic prehnite, then subsequent uplift has not significantly deformed the basement-detached trough.

Warburton rift trough

The rift trough-portion of the Warburton Basin developed mostly east of the basement detached trough (Figs. 16 and 17). The existence of a rift trough is inferred from the geochemical affinity of the basaltic lavas ('within-plate' continental rift basalts) the type of sediment infill and the direction of sediment input. Also, deep marine sediments are present within the rift itself and shelf-edge sediments are present on the rift margins, supporting the interpretation of a rift.

The 'Jena Basalt' has a stratigraphic position that is close to the Middle-Late Cambrian boundary in the Gidgealpa area (Sun, 1996) i.e. 498 Ma (Fig. 2; Young & Laurie, 1996). Eruption of the 'Jena Basalt' would have approximated the onset of rifting according to the narrow, linear continental rift model of Cas and Wright (1987).

The association of the 'Jena Basalt' with deep-water carbonate and mudstone/shale facies (Sun 1996) indicates the rift was sufficiently developed to allow marine deposition. Marine deposition was widespread at this time (Cook, 1988). More recent recognition of late Middle Cambrian to early Late Cambrian slope-to-basin carbonate facies indicates sediment input into the rift from the north (Sun, 1994; 1996). Therefore, the rift became another depocentre of the Warburton Basin.

Other possible rift elements

As discussed above, rift elements have characteristics which can be recognised in the subsurface. They include diagnostic contour patterns in depth-structure contour maps, drilled locations of 'Jena Basalt' and aeromagnetic anomalies interpreted as similar basalt. Such data have been evaluated to interpret the rift elements shown in Fig. 16.

The northwest-trending Koonenberry Fault (Fig. 14) marks the eastern edge of the magnetic Neoproterozoic to Early Palaeozoic Koonenberry zone (World Geoscience Corporation, 1995), a portion of the Wonominta Block. Recent mapping and geochemical studies of two lavas suites (Crawford et al., 1997), have revealed distinctions between the 586 +/- 7 Ma alkaline mafic and felsic Mount Arrowsmith Volcanics (of continental rift affinity overlain and intruded by calc-alkaline rocks) and another unit, the Early Cambrian Mount Wright Volcanics of transitional alkaline and continental rift affinity.

Together with the Warburton Basin basalts, they indicate Late Neoproterozoic and Early Cambrian episodic rifting along the Tasman Line, the boundary between known Precambrian on the west and wholly Palaeozoic terrain to the east (Veevers & Powell, 1984). Two modes of strain, involving initial dextral shear followed by plate divergence, have been proposed by Veevers and Powell (1984) and could account for the episodic nature of volcanism along the rift.

The Koonenberry Fault can be traced north-westwards in aeromagnetic data (World Geoscience Corporation, 1995) as far as the eastern Strzelecki Sheet area (Figs. 11 & 14) where it appears to terminate against or into an east-west trending structural feature that is also evident in the depth-structure map (Fig. 4). This east-west structure trends towards the Murteree Ridge, which is composed of various Warburton Basin sediments and volcanics.

In contrast, the few wells south of the Murteree Ridge, have intersected either 'Jena Basalt' or Proterozoic metasediments only. It is therefore possible that the Eastern Warburton Basin may have been accreted on to the Proterozoic craton in the vicinity of the Murteree Ridge, where there are some Cambrian basaltic eruptive centres (e.g. at Kobari 1). Similarly, the Tinga Tingana Ridge and Weena Trough (Fig. 4) may be other remnant rift-related features, as inferred in Fig. 16.

The Toolachee Ridge is a line of north-south trending domes which is unique to the Cooper Basin region (Fig. 4). Some 'Jena Basalt' occurs in this area (Fig. 16). The ridge and the adjoining Tarwonga Embayment may also represent a down-faulted Proterozoic block against a rift margin. The Nappacoongee Ridge may be similar as it is associated with an aeromagnetic high. However, no 'Jena Basalt' has been found in cores or cuttings, but reworked basalt occurs close by in the Dullingari Field (Gravestock et al., 1995).

Boucher (1991) proposed that the Wooloo Trough (Fig. 4) was a remnant of a Cambrian rift, linking basalts on the Murteree Ridge to the Mooracoochie Volcanics and subsequently found basalts at Gidgealpa (Sun 1996). Given that the Wooloo Trough is flanked by granitoids, this rift element seems less likely. Instead this trough may represent a depression developed over a shear zone within the pluton, parallel to the Lake Blanche Lineament of Wopfner (1985). Any shearing may have exploited an earlier rift structure and/or utilised it during emplacement of the granite.

Orthoquartzite of possible Proterozoic age in Daralingie 1 provides a minimum easterly position for a rift margin. Warburton Basin sediments surround this well, suggesting a rift margin is close by. Any sediments to the west of the margin would therefore have to be younger, post-rift fill.

The location of the rift margin in Fig. 16 becomes uncertain north of the Wooloo Trough. It must, however, lie to the east of the Gidgealpa field where Mooracoochie Volcanics were erupted on to the Proterozoic craton. The Merrimelia and Yanpurra Ridges (Fig. 4) possibly accreted against the rift margins as proposed for the Murteree Ridge. The geophysical modelling (cross-section 2, Fig. 12) indicates uplift of the ridge.

A shallow depression exists north of the Yanpurra Ridge that could represent a failed part of the rift. It has Mooracoochie Volcanics and therefore Proterozoic crust to the east. This trend aligns with the northeast-trending Yanpurra Ridge (Fig. 4) implying this ridge forms part of the rift margin and a link to the Merrimelia and Gidgealpa Ridges.

It has been proposed that the 'Jena Basalt' was part of a Cambrian rift system, based on the known location of Cambrian basalts and some early aeromagnetic data (Boucher, 1991; Fig. 5). Components of the rift system would include the 'within-plate' and 'mid-ocean ridge basalts' beneath the Cainozoic Murray Basin in eastern South Australia (Rankin et al., 1991) and other basalts in the Wonominta Block of western NSW. The latter include Early Cambrian 'within-plate basalts' at Mt. Wright and late Neoproterozoic 'within plate' basalts at Mt. Arrowsmith, Packsaddle and Nundora (Crawford et al., 1997; Kruse, 1982; Mills, 1994; Zhou & Whitford, 1994). Direen (1998) indicated that the magnetic anomlies within the Koonenberry fold and thrust belt in western New South Wales are from rift basalts. Their associated aeromagnetic anomalies outline portions of a zig-zag trend towards the Warburton Basin (Fig. 5).

Most of the syn-rift sedimentary fill comprises the Dullingari Group with some interfingering Kalladeina Formation (Sun, 1996). Some units of coarse clastics are present within the Dullingari Group, including feldspathic sandstones and thin breccias and pebbly sandstones (Sun, 1996). Gatehouse and Cooper (1986) considered the Dullingari Group to be a turbidite facies.

Sun (1996) determined that sediment transport was from the northwest towards the southeast during late Middle Cambrian to early Late Cambrian times in the north-western part of the Cooper Basin area. By Early Ordovician time, sediment transport direction was interpreted from the northeast towards the southwest further towards the east of the study area (Zang, 1993b; Gravestock & Gatehouse, 1985) and from west to east in the Daralingie area (Gravestock et al., 1995) beneath the southwest Cooper Basin. The differences reflect the basinward drainage at the onset of rifting and during rift evolution. These events also superceded the Early Cambrian sediment transport direction which was north-westwards towards the basement-detached trough (Fig. 16).

Sagging followed the rift phase and the trough became an aulacogen. The principal fill in the sag phase is the south-westwards prograding sequence of deltaic sediments, the Innamincka Formation (Fig. 2). These Early to Middle Ordovician strata are the youngest preserved sediments in the rift trough (Gatehouse, 1986; Sun, 1996; Zang, 1993a; 1993b). However, it is possible that some younger sediments may have eroded during Carboniferous uplift. None of these formations has been proven on the rift platform south of the Murteree Ridge.

The Innamincka Formation probably interfingers with Dullingari Group shales towards the centre of the aulacogen (Zang, 1993b). It is uncertain how long this sag phase lasted or how far to the west it might have extended.

Warburton Basin sediments beneath the central portion of the Cooper Basin in South Australia have been subjected to compressional tectonism, producing tightly folded to overturned beds and thrust faulting (Carroll, 1990; Gravestock et al., 1995; Apak, 1995; Sun, 1996; 1997). Mostly, this is confined to the troughs and ridges in the rift trough. However, some of the sag-phase sediments are gently deformed in the Daralingie area, but not northwest of the Gidgealpa and Merrimelia Ridges over the cratonic platforms.

Implications of the Geophysical Interpretation for Hydrocarbon Accumulations

Fields of the Cooper and Eromanga Basins

Oil and gas field in the South Australian portion of the Cooper Basin are shown in Fig. 1. Their distribution has been influenced by lineaments and structural corridors recognised by Campbell & O'Driscoll (1989) and Boucher (1997c; 1998).

Major 'structures' and 'structural' closures within the Cooper and Eromanga Basins are inherited from Warburton Basin or older features. Prominent structures (e.g. the Gidgealpa, Merrimelia, Innamincka Ridges; Fig. 4) have at various times been attributed to either extensional, compressional or strike slip tectonism (e.g. Battersby, 1976; Kuang 1985; Stanmore, 1989; Sun, 1997; Apak et al., 1997). This and other large structures were active as early as Warburton Basin time, prior to the onset of Cooper Basin deposition and have been episodically reactivated since (Gravestock & Jensen-Schmidt, 1998; Moussavi-Harami & Alexander, 1998).

However, they differ from many apparent 'structures' (e.g. Moomba) which are palaeo-topographic highs over which Cooper Basin strata have been draped. It is not always easy to distinguish these from genuine tectonic structures.

Facies analysis reveals that following emplacement of the Big Lake Suite, the Moomba area was rapidly uplifted and ultimately eroded to expose much of the granodiorite prior to Cooper Basin deposition which commenced in Late Carboniferous and Early Permian times (Fig. 19). Then, the Big Lake Field area was down dip of the Moomba Field and the Merrimelia Formation and Tirrawarra Sandstone onlapped the Moomba palaeo-high (Fig. 19).

When the granodiorite surface was glaciated and eroded, uranium-enriched detritus was shed off the Moomba palaeo-high and deposited on its flanks as 'Tirrawarra conglomerate'. Its elevated gamma-ray signature has similar log responses to the source granodiorite (39 ppm U in Mooomba 27 cuttings; Boucher in prep). A modern analogue would be the granite at Pyramid Hill in northern Victoria. It protrudes above the surrounding plains, shedding U-enriched sediments into the Murray Basin in a similar fashion and diverting drainage (Fig. 18).

The 'Tirrawarra conglomerate' is succeeded by the Patchawarra Formation, which progressively onlaps granodiorite at Moomba, ultimately covering it (Fig. 19). During Patchawarra Formation deposition, the Big Lake Field area was apparently uplifted relative to the Moomba Field area, due to less compaction over the competent granodiorite. Deposition of the upper Patchawarra Formation then became more restricted in extent at Big Lake Field (Fig. 19). Differential compaction was also occurring when the succeeding Murteree Shale was deposited and structural closure within the Moomba Field is due to this effect (Boucher, 1996).

It is important to distinguish between deposition over palaeohighs and areas affected by structural movements. Both have implications for reservoir and seal geometry. Sediments thin and change facies towards and above palaeo-highs, so lateral changes in reservoir and seal characteristics can occur. In the Cowan field, for instance, the reservoirs do not overlie the top of the structure in the Patchawarra Formation (Fig. 20). Areas affected by structural movements, however, may displace reservoirs and seals, but their thicknesses and continuities will generally remain the same. In the Moomba and Cowan areas, most of the closure occurs over glaciated topography.

Large, rigid batholiths do not deform or compact as easily as softer sediments, so cupolas subcropping beneath the Cooper Basin could theoretically be expected to provide closure in strata above them, hence the importance of the gravity data set for considering this potential play. Similarly, closures over palaeotopographic highs could also be expected above stable platforms underlain by cratonic basement (e.g. the Daralingie area or regions south of the Murteree Ridge). These include residual basaltic palaeotopographic highs delineated by aeromagnetic data, for example at Kobari (Boucher 1994a; Fig. 11)

On the other hand, the tectonic structures of the Cooper and Eromanga Basins are located above places where the 'basement' is deformed. Such places include the Gidgealpa, Merrimelia, Innamincka, Murteree and Nappacoongee Ridges. However, syn-depositional structural growth is present there as well and erosion and down-lap could also be expected. Burial history studies by Moussavi-Harami (1996) indicate that several hundreds metres of sediments have been eroded from such areas, distinguishing them from palaeohighs.

Petroleum occurrences in 'basement'

Very few wells have deliberately penetrated the Warburton Basin. Several that do include Gidgealpa 1 and 2, Dullingari 1, Coongie 1 and Sturt 7. Some of these were early wells drilled before the Permian became a principal drilling target. Despite that, Warburton Basin discoveries have been made in fractured Mooracoochie Volcanics (Sturt 6) and Dullingari Group (Lycosa 1) and there is secondary porosity in the Pando Formation (Moolalla 1) and carbonates (Farina 1) (Taylor et al. 1991; Gravestock et al. 1995; Sun 1996; Boucher 1997a).

The reservoir and sealing potential of 'basement' is dependent on lithology. Fracture porosity is known in Mooracoochie Volcanics from areas that were structurally active. The potential for fracture porosity in other Warburton Basin rock types is currently being studied (Sun, in prep). It is considered unlikely that large granitic masses will develop fracture porosity as they tend to preferentially develop relatively wide-spaced joints. Hence areas where the Big Lake Suite subcrops beneath the Cooper Basin (Fig. 9) are considered unprospective for 'basement' hydrocarbons.

The distribution of Warburton Basin sandstone reservoirs (Pando and Innamincka Formations) are related to the rift margins in the north and western part of the Cooper Basin region and to arenaceous facies within the Dullingari Group at the Toolachee Field. The location of rift-related structures through facies analysis and this geophysical interpretation (Fig. 16) may assist in defining other targets.

Warburton Basin reservoirs are regionally sealed by a zone of 'alteration' at the 'Z' horizon (Boucher, 1996; 1997a). However, very few wells have penetrated this seal to test any potential reservoirs beneath, despite several hydrocarbon discoveries (Taylor et al., 1991; Boucher, 1997a). Indigenous sources for all the known petroleum occurrences in the Cooper Basin region has not yet been recognised. However, multiple sources are known (Boreham & Summons, in press). To date, the discovered Warburton reservoirs are Permian-sourced.

Conclusions

The Innamincka and Strzelecki 1:250 000-scale map sheet areas in the far northeast of South Australia are underlain by several stacked Phanerozoic basins, including the prolific oil and gas-producing Cooper Basin. The basins are underlain by differing provinces of Proterozoic basement, including the Willyama Supergroup, Curnamona Craton and Arunta Block. The sources of the other Proterozoic provinces are unknown.

Modelling techniques applied to the high-resolution aeromagnetics and gravity data reveal basement structure and its composition in places. A prominent northeast-trending structural grain was inherited during deposition of the Cooper Basin.

Lower crustal or upper mantle material has been emplaced into the upper crust beneath the Patchawarra Trough, a depocentre of the Cooper Basin. Reverse faulting along the southeastern edge of this Proterozoic mass resulted in block uplift, forming the GMI Ridge during Cooper Basin deposition. It is an important structure for trapping petroleum.

A prominent gravity low, due to Early Carboniferous Big Lake Suite granodiorite masses, underlies the Nappamerri Trough. The granites have intruded Warburton Basin strata. In places, there are small associated magnetic anomalies, interpreted as skarns formed by metasomatism of carbonates. Intense gravity lows denote cupolas, which form non-tectonic palaeo-topographic highs. Following differential compaction, structures important for trapping petroleum developed in draped Cooper Basin sediments.

A gravity low beneath the Tenappera Trough is due to Early Devonian granite which intrudes Proterozoic basement. This may include carbonates, as aeromagnetic anomalies interpreted as skarns.

Aeromagnetic anomalies indicate areas of Cambrian basalts located in several wells from magnetic susceptibility data and in thin sections of cuttings. These basalts assist to define the location of a Middle Cambrian rift system. Drape and compactional doming over basalt-associated palaeo-topographic highs may also be important in the formation of hydrocarbon traps.

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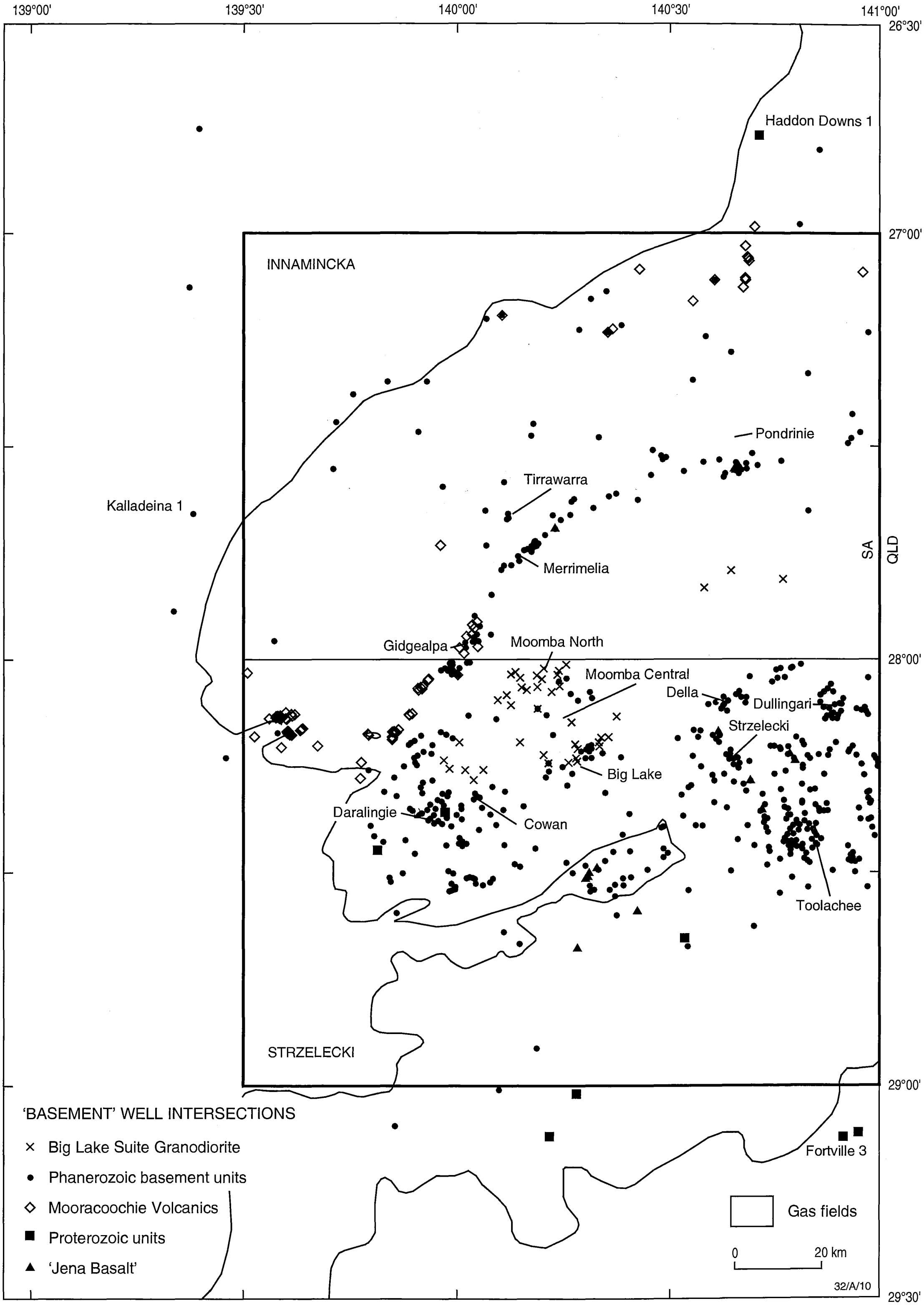


Figure 1. The Cooper Basin, gas fields and key 'basement' well intersections subcropping beneath the Cooper and Eromanga Basins. The airborne survey, covering the Strzelecki and Innamincka 1:250 000-scale map sheets, is also shown.

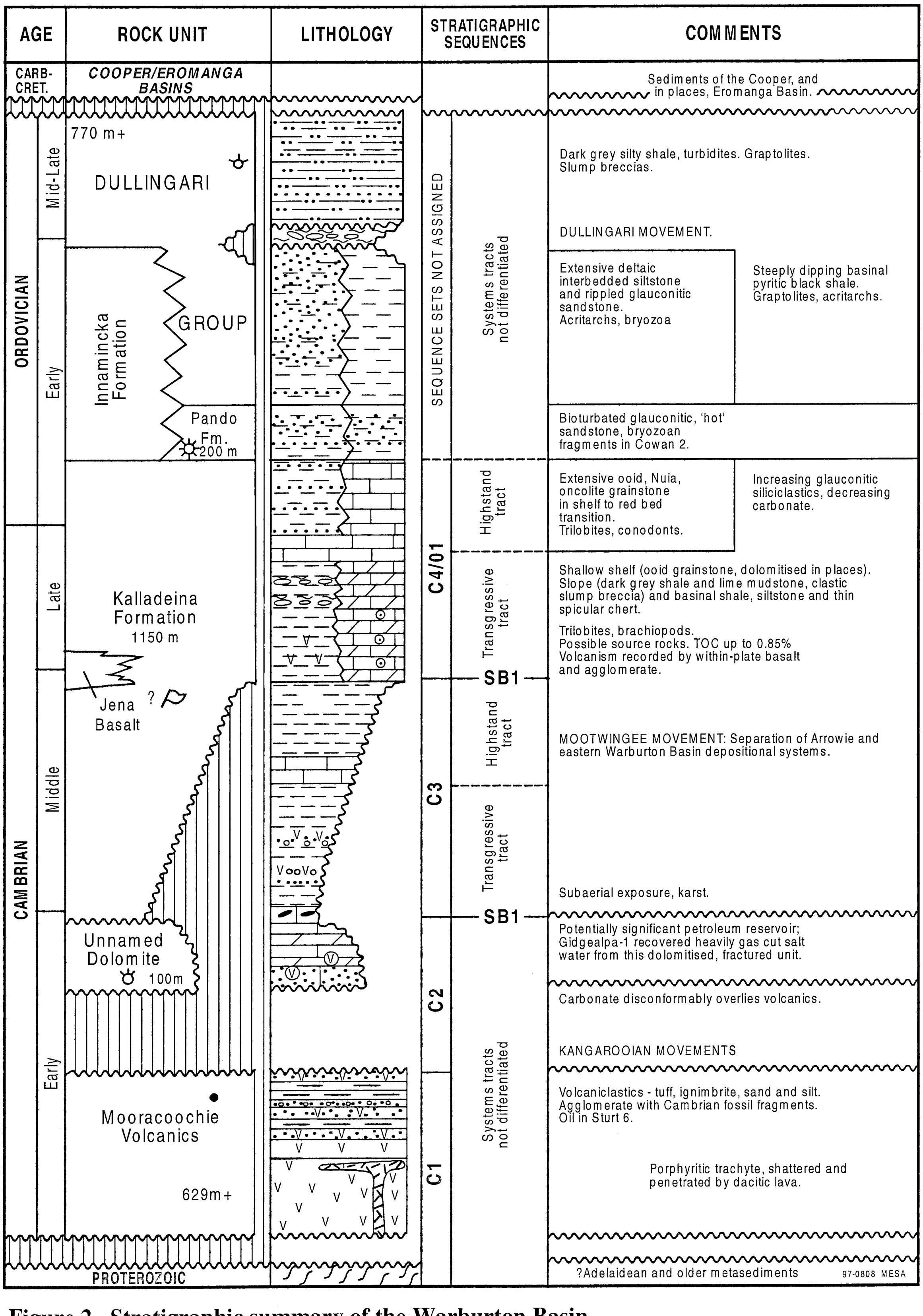


Figure 2. Stratigraphic summary of the Warburton Basin.

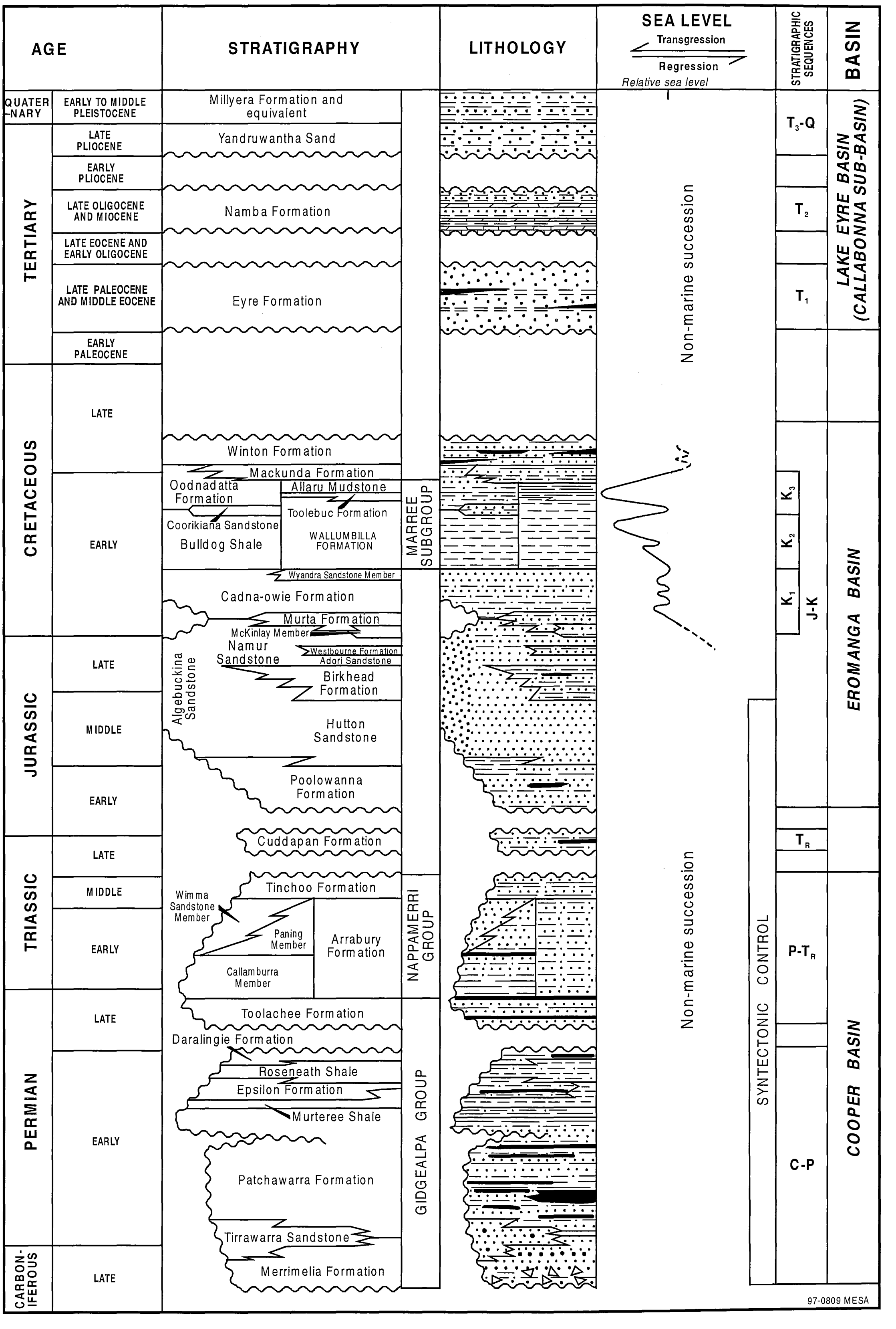
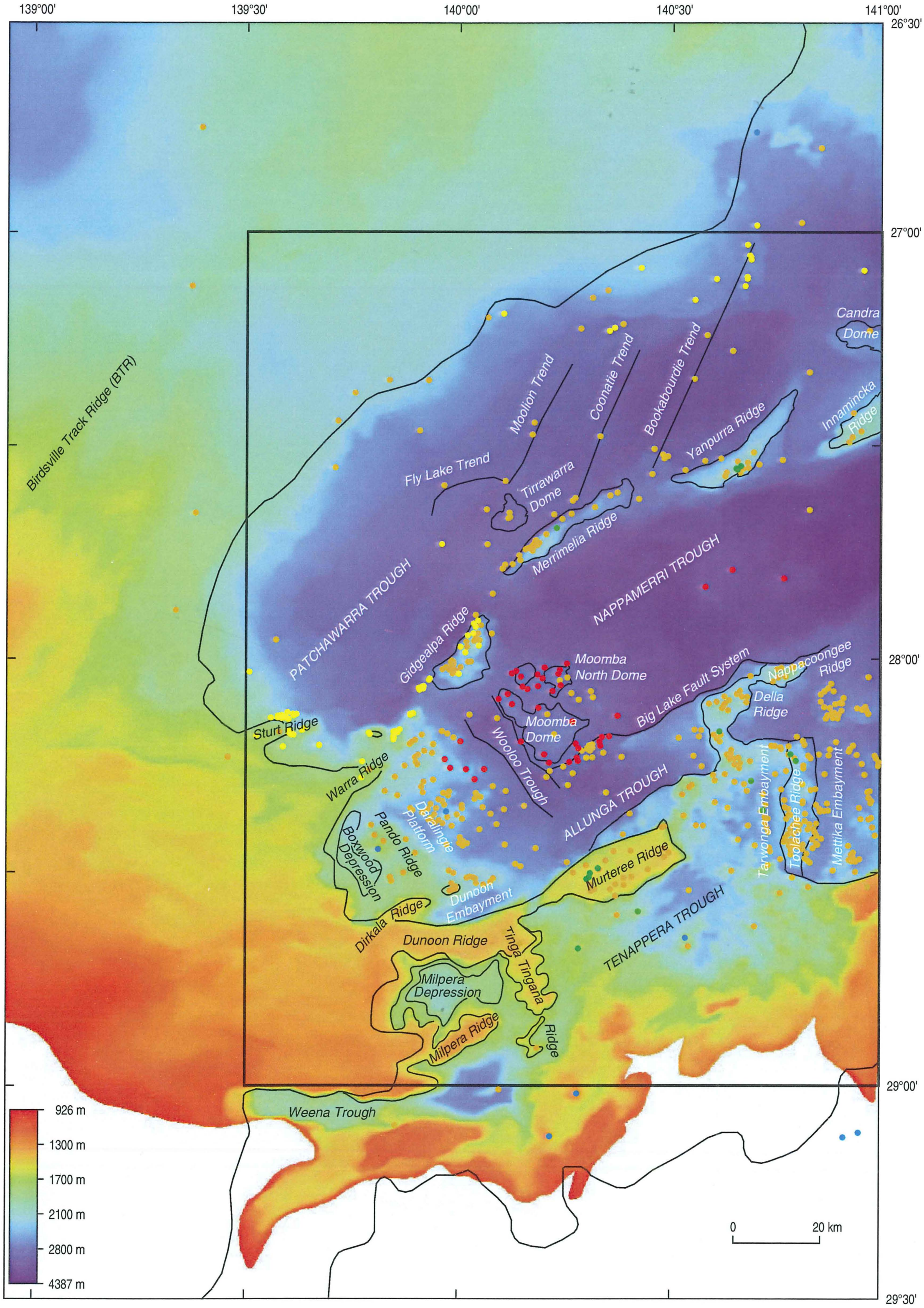


Figure 3. Stratigraphic summary of the Cooper, Eromanga and Lake Eyre Basins.



'BASEMENT' WELL INTERSECTIONS

- Phanerozoic basement units
- Big Lake Suite Granodiorite
- Mooracoochie Volcanics
- 'Jena Basalt'
- Proterozoic units

32/A/19

Figure 4. Top 'basement' ('Z' horizon) depth structure image and structural elements, including key 'basement' well intersections.

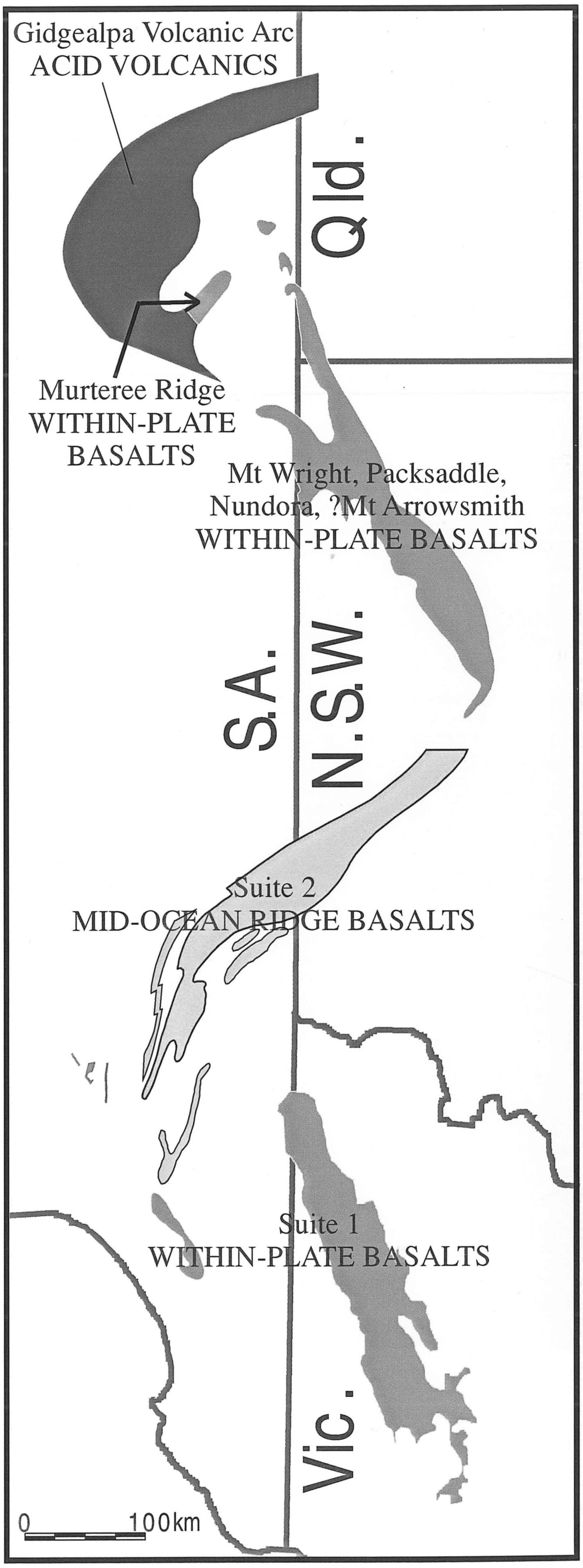


Figure 5. Cambrian rift elements indicated from outcrop, drilling and aeromagnetic data (after Boucher 1991, 1994a).

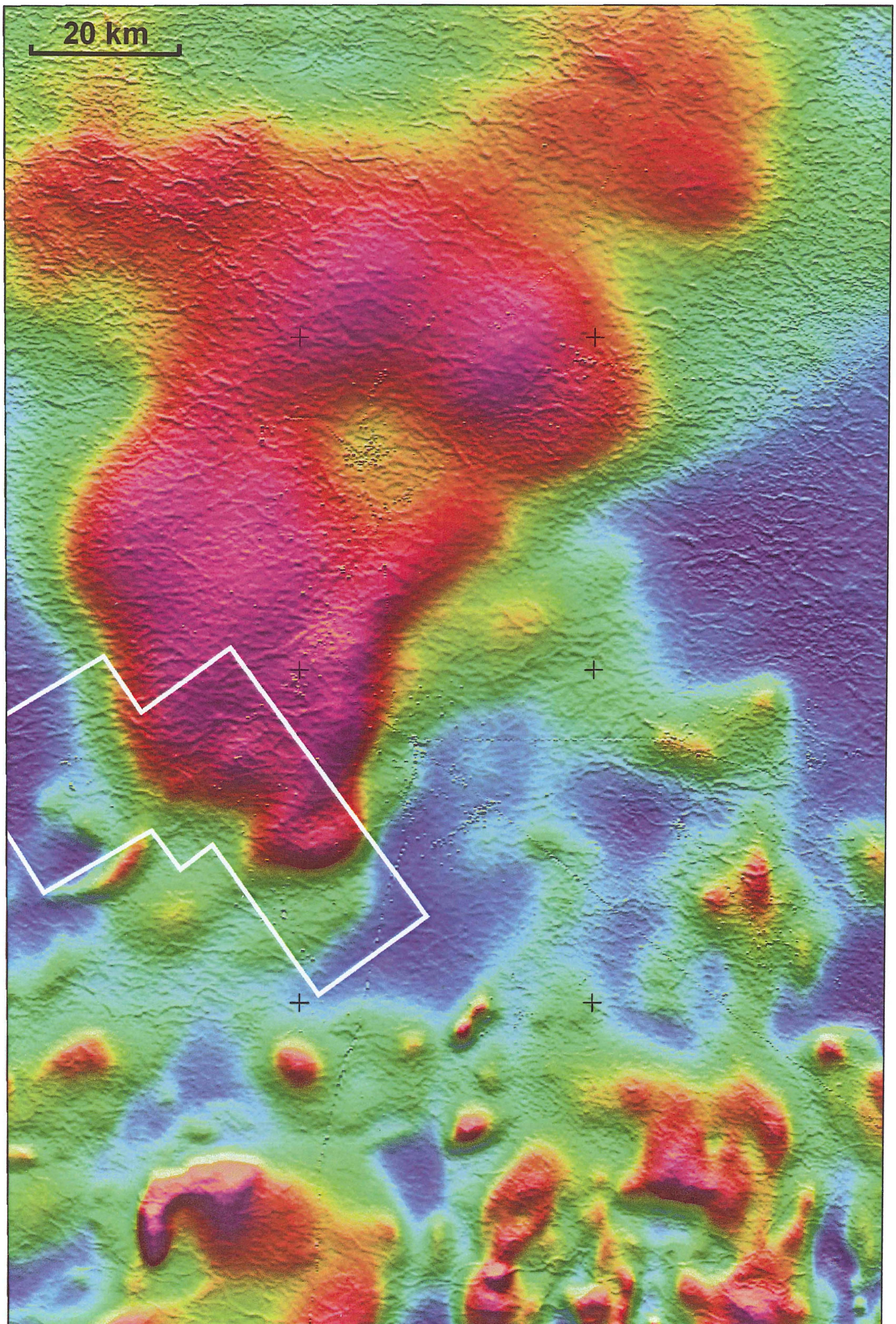


Figure 6. Total magnetic intensity reduced to the pole image with a northerly illumination. The outline of the B5 survey is shown.

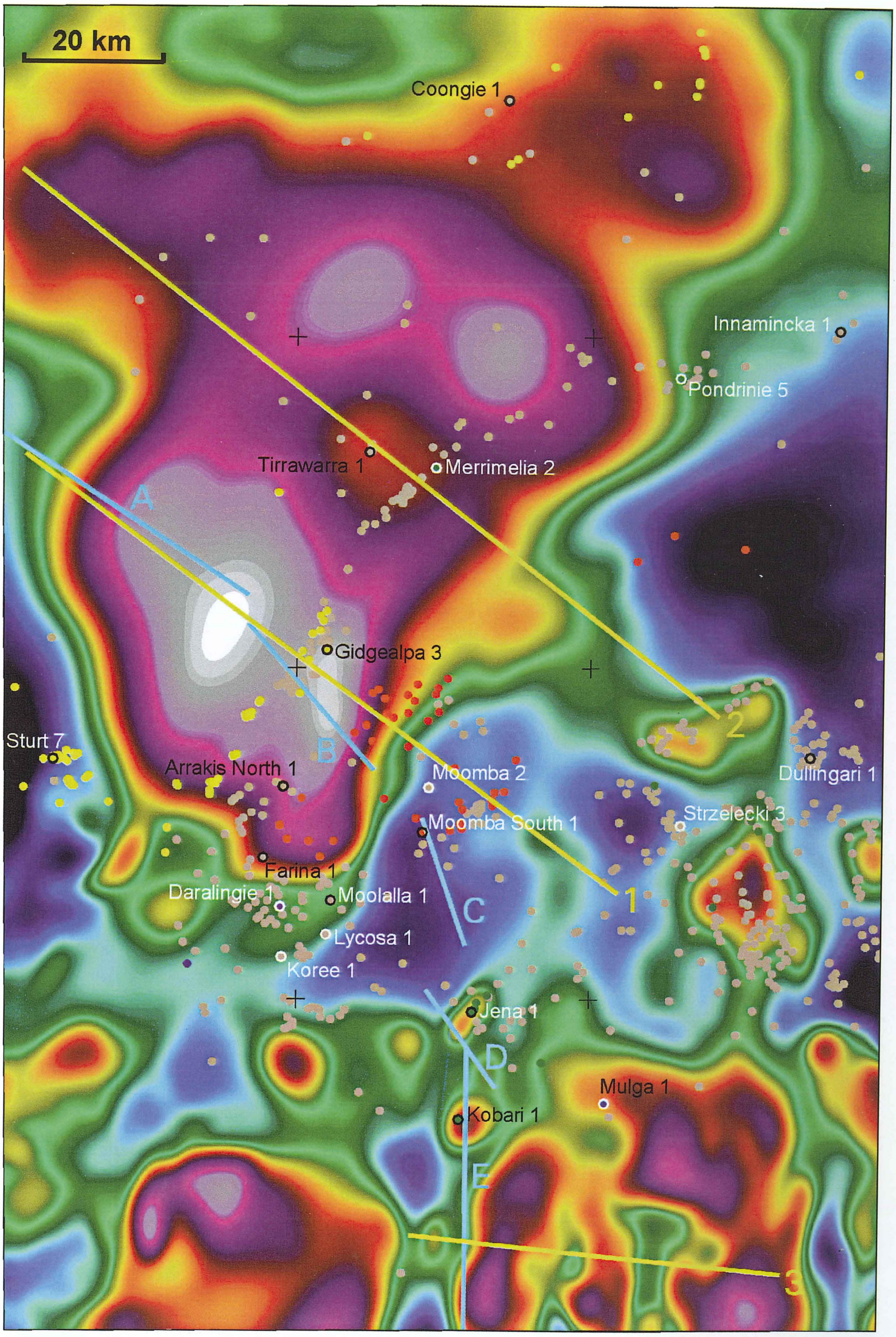


Figure 7. Low pass filtered image of the total magnetic intensity reduced to the pole grid. 'Basement' well intersections (Big Lake Suite Granodiorite – Red, Mooracoochie Volcanics – Yellow, 'Jena basalt' – green, sediments – tan, Proterozoic – blue) and the positions of modelled profiles (Yellow) of Figs. 12a, 12b & 12c are shown. The positions of seismic lines (Fig. 13) are also shown.

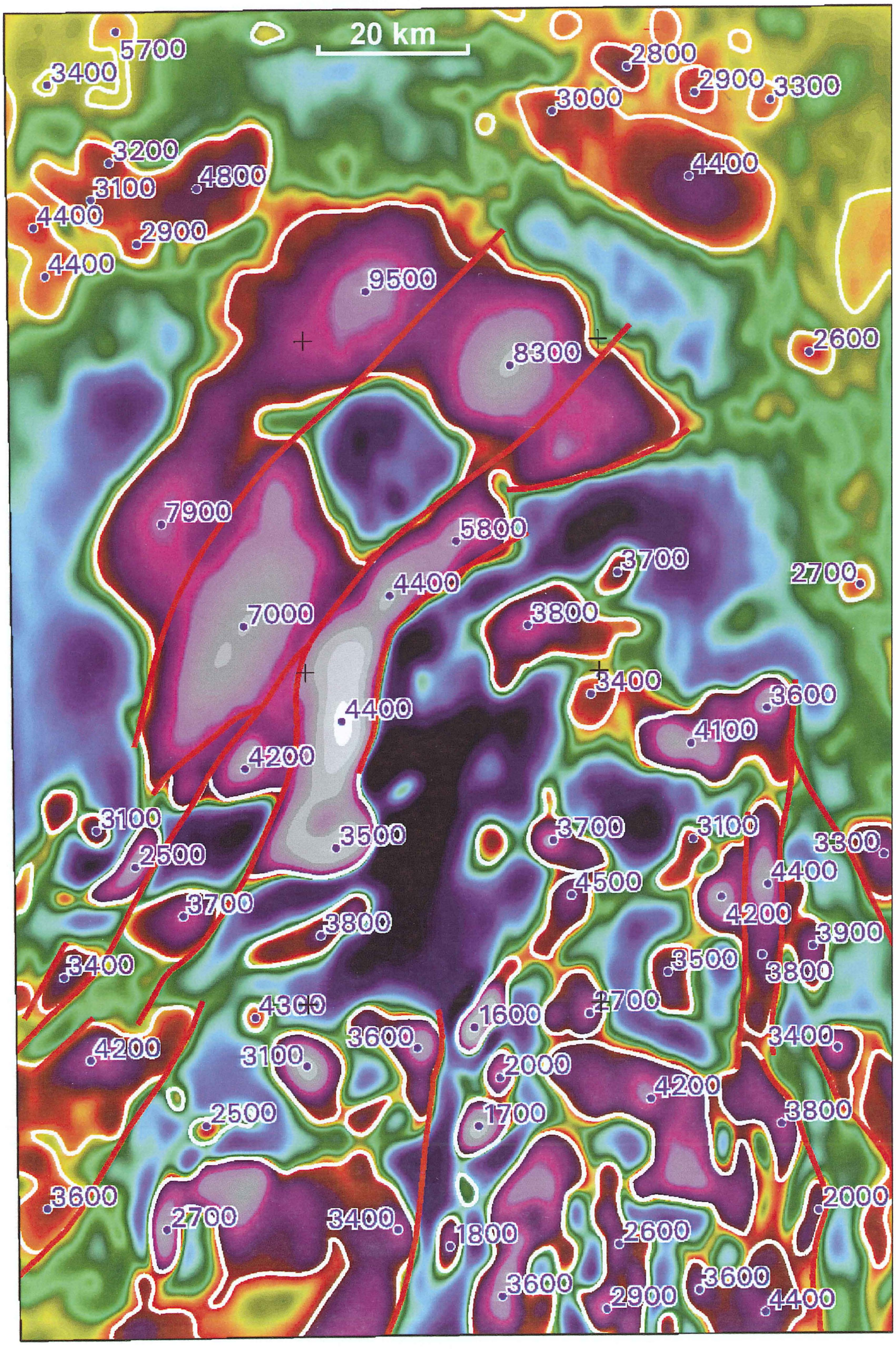


Figure 8. First vertical derivative image, showing the interpreted magnetic bodies and the estimated depths to magnetic sources.

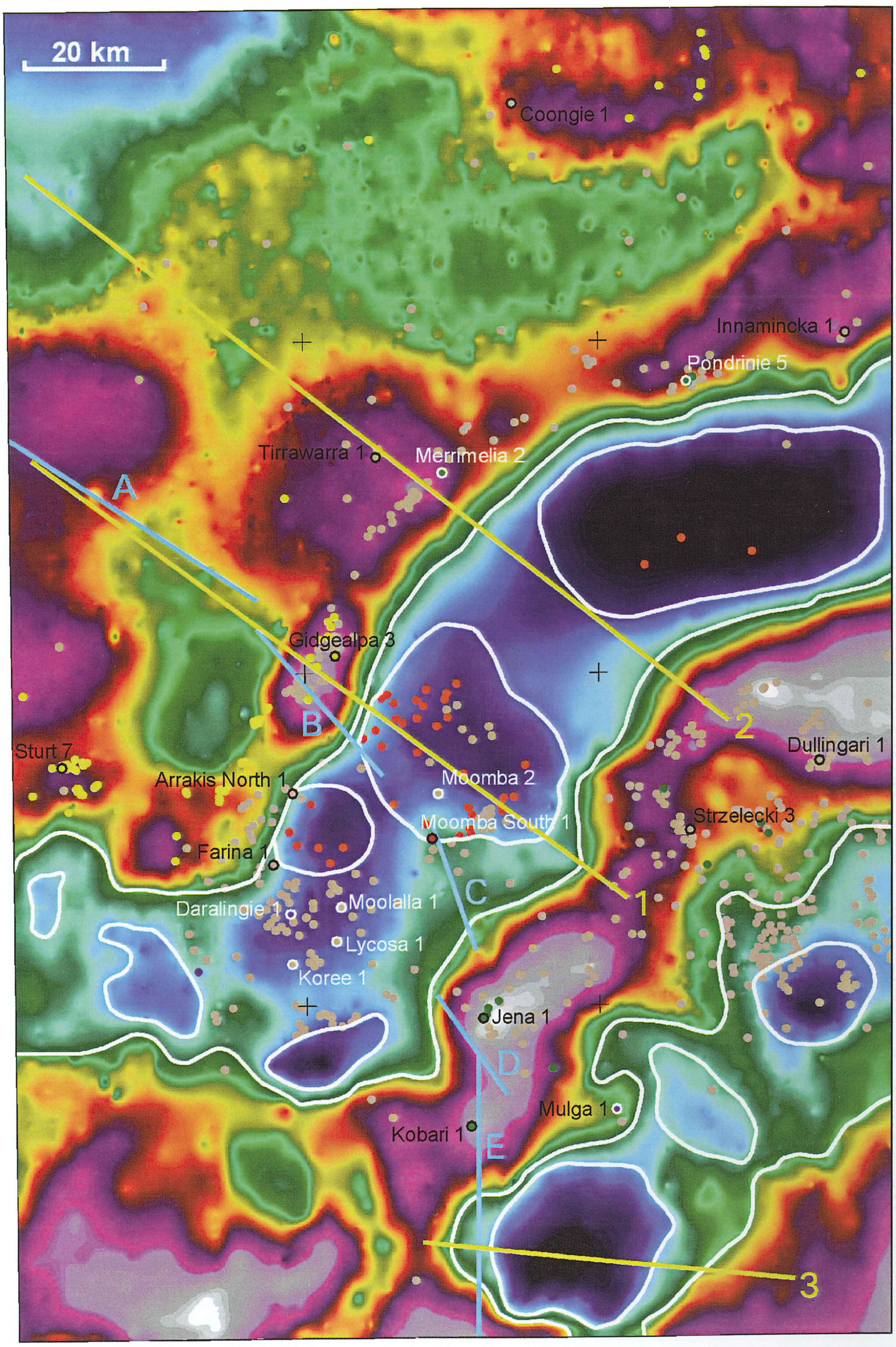


Figure 9. Gravity image showing the positions of interpreted granitic bodies. 'Basement' well intersections (Big Lake Suite Granodiorite – Red, Mooracoochie Volcanics – Yellow, 'Jena basalt' – green, sediments – tan, Proterozoic – blue) and the positions of modelled profiles (Yellow) of Figs. 12a, 12b & 12c are shown. The positions of seismic lines (Fig. 13) are also shown.

Figure 10. Radiometric image of the equivalent potassium (red), thorium (green) and uranium (blue) ground concentrations.

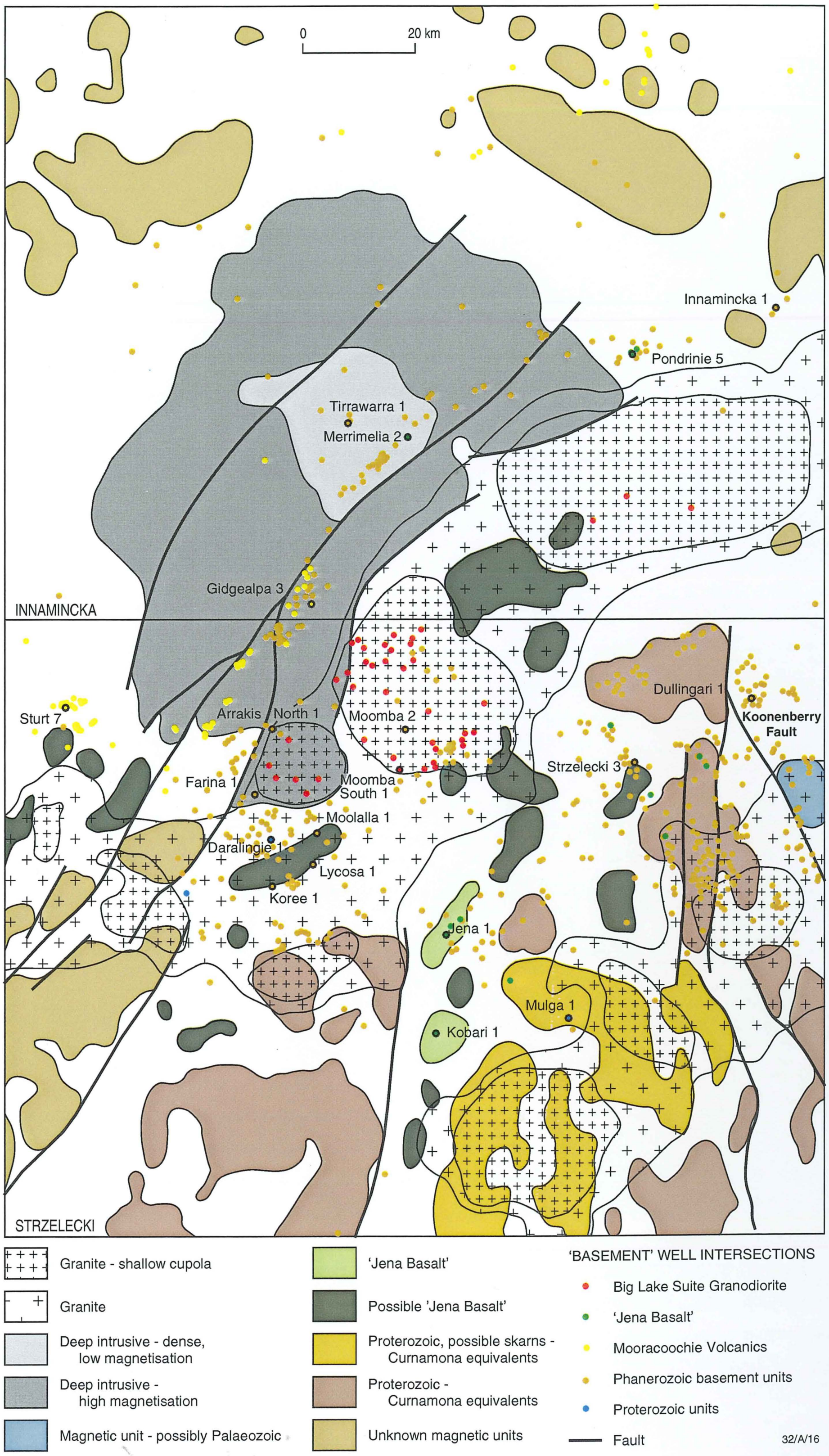


Figure 11. Geophysical interpretation of the Basement rock units and structure of the Cooper Basin.

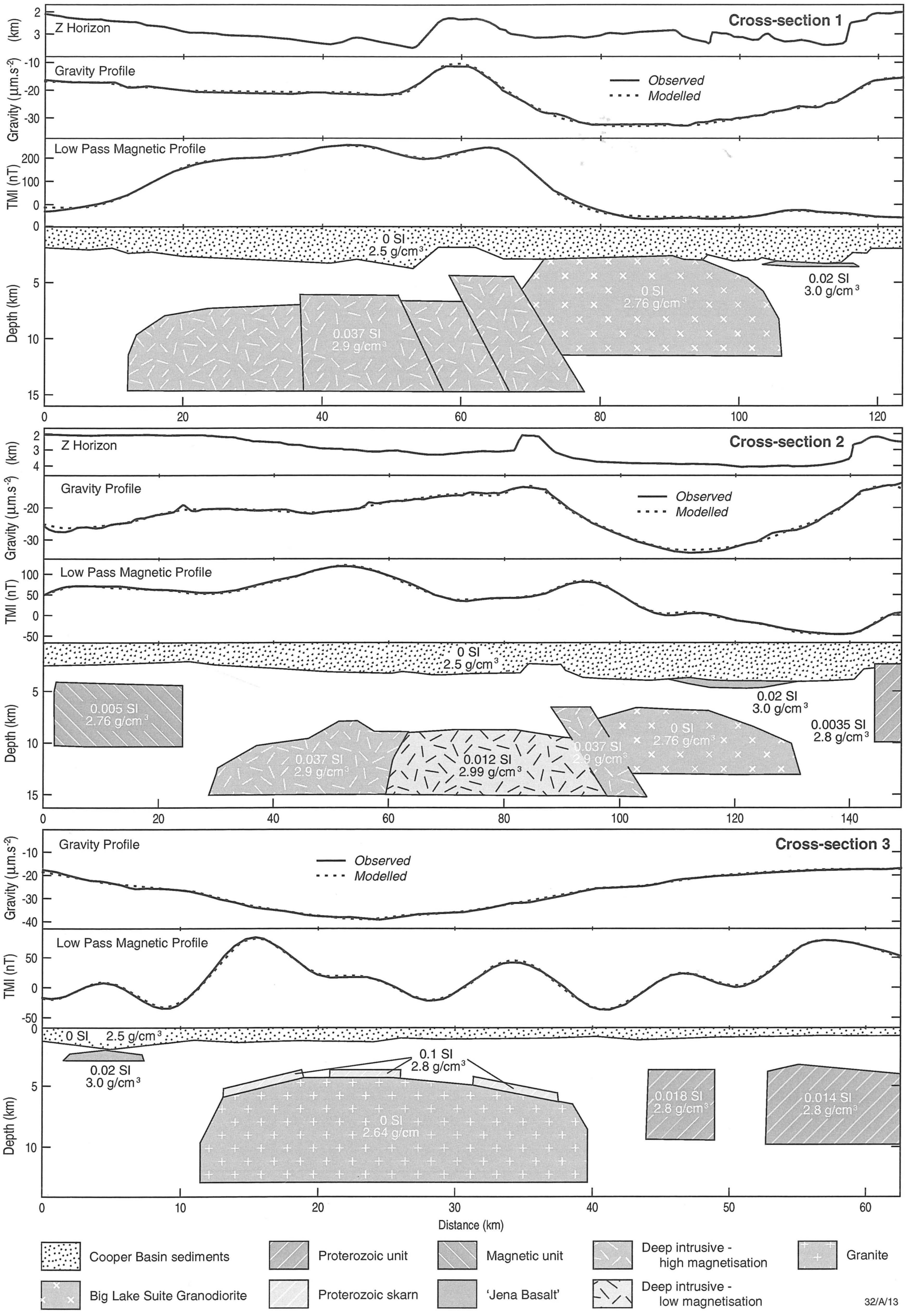


Figure 12. Computer modelling (locations of profiles are shown on figures 7 and 9). A background density of 2.8 $g.cm^{-3}$ and a background susceptibility of 0.0 SI was used.

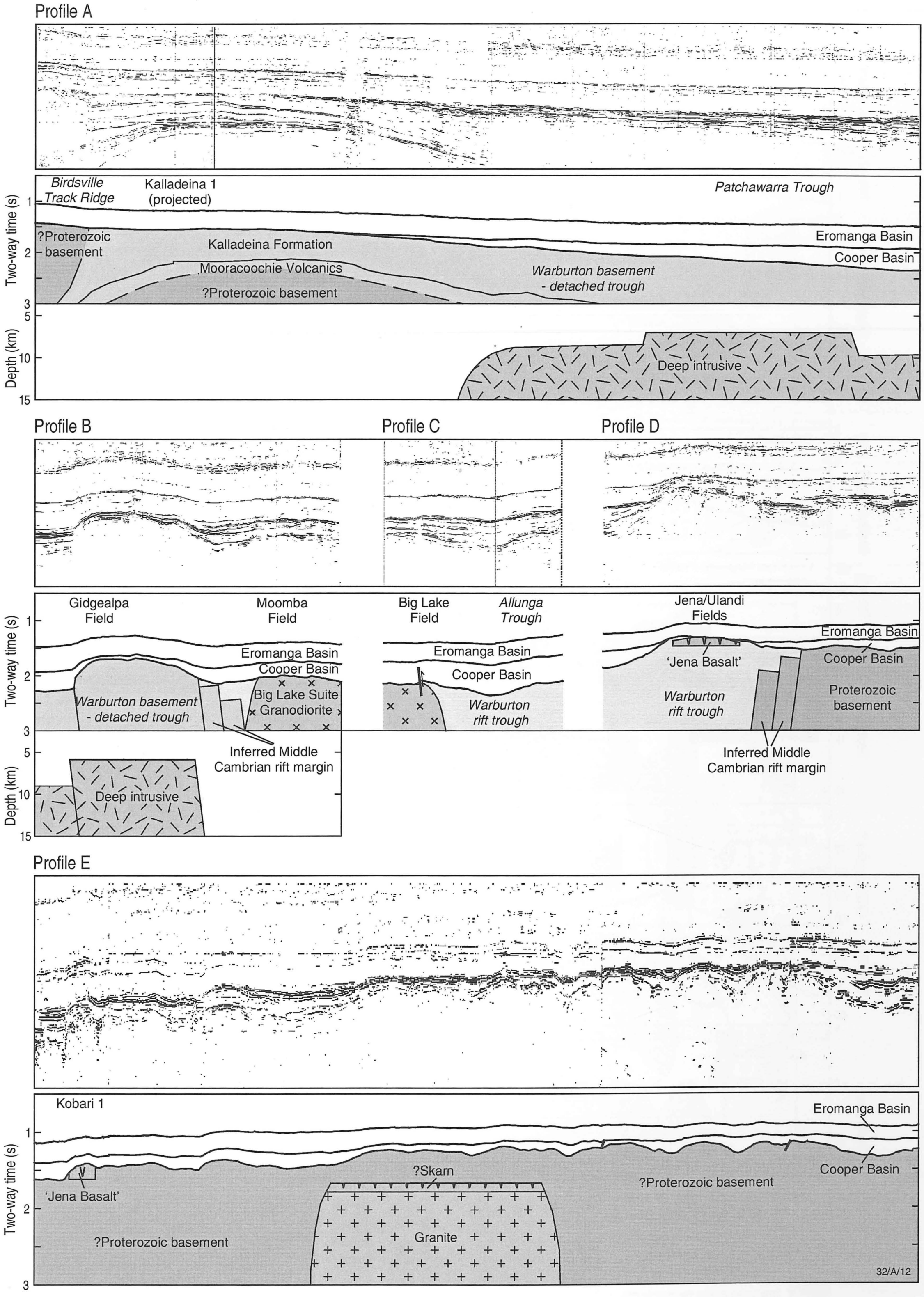


Figure 13. NW-SE Composite seismic line through the Cooper Basin. The location of the seismic is shown in figures 7, 9 & 16. The data has been processed for optimisation above the 'Z'-horizon.

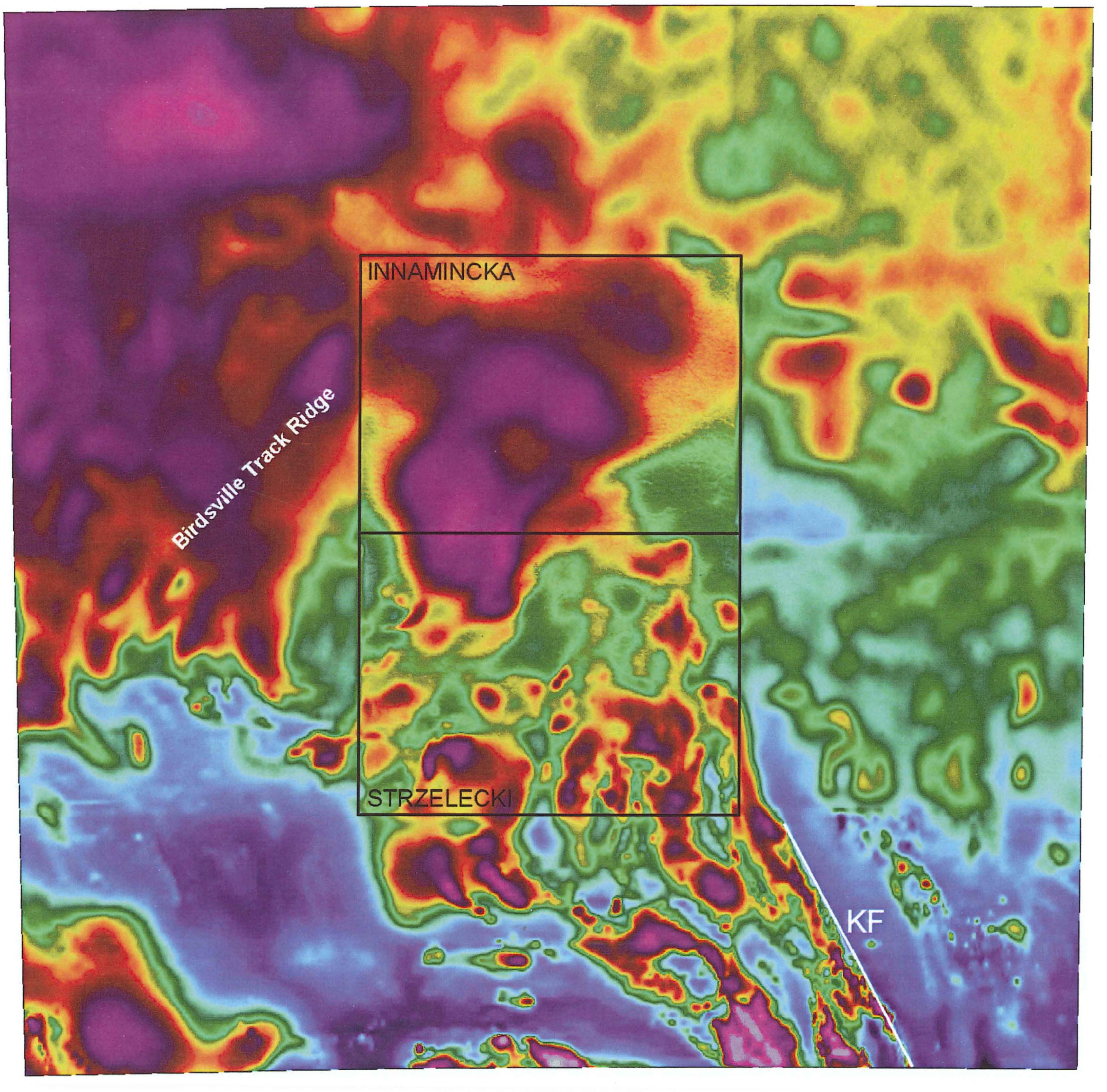


Figure 14. Regional total magnetic intensity, reduced to pole image of the Cooper Basin area, with the airborne survey covering the Innamincka and Strzelecki 1:250 000-scale map sheets shown. The most notable regional structural feature trending towards the Cooper Basin is the NNW trending Koonenberry Fault in western New South Wales. The position of the Birdsville Track Ridge is shown.

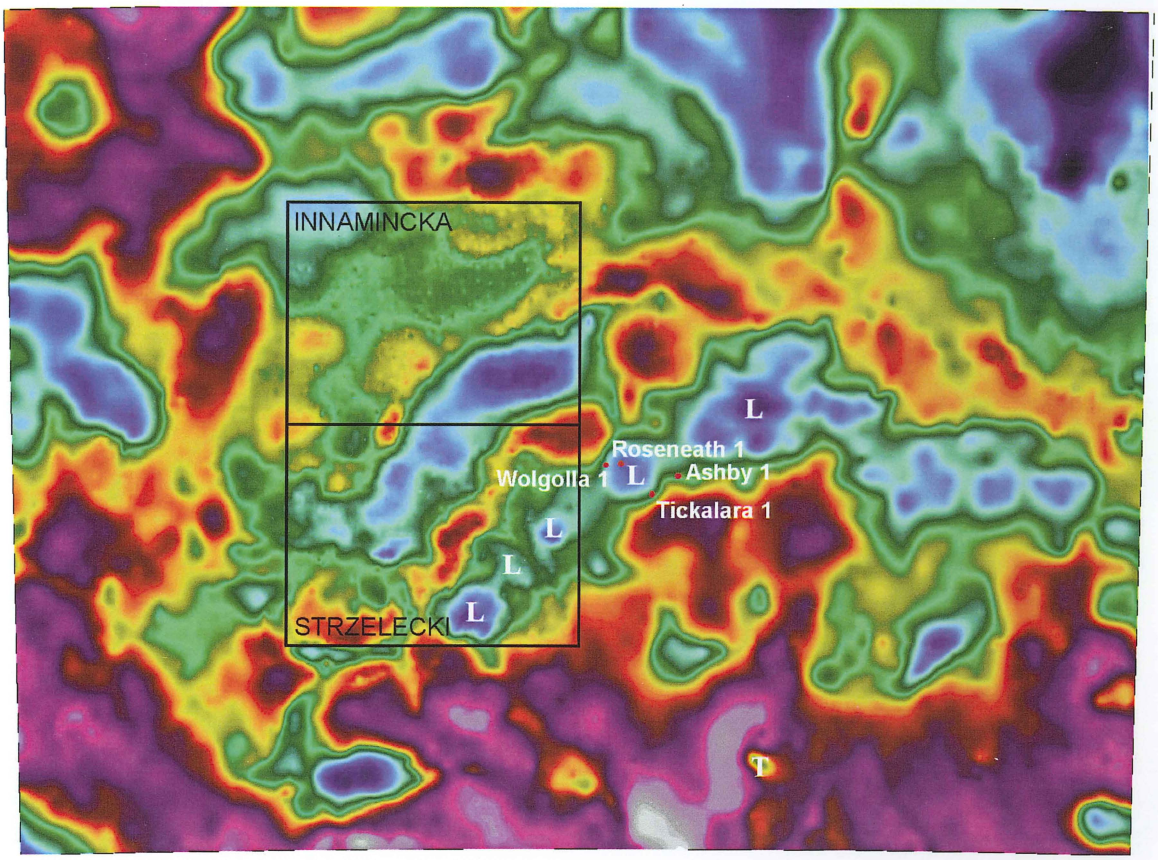


Figure 15. Regional gravity image of the Cooper Basin area. The position of the Early Devonian Roseneath 1 granite well intersection is shown. The location of the associated north-east trending gravity lows (L), and the Early Devonian Tibooburra Granite (T) are also shown.

Figure 16. Tectonic elements of the Eastern Warburton Basin. The Warburton basement-detached depocentre (after Roberts et al 1990) developed adjacent to the Birdsville Track Ridge. The Warburton Rift Trough elements are established from drill hole, aeromagnetic and seismic data. The location of Kalladeina 1 well is shown. Sediment transport directions are for the Kalladeina Formation (W, X; after Sun 1996), Innamincka Formation (Y; Zang 1993b) and Pando Formation (Z; Gravestock at al 1995). The location of the Birdsville Track Ridge is from the outcropping Cretaceous and Tertiary sediments of the Gason Dome and Sturt Stony Desert (Cowley & Freeman, 1993) which indicates a mild reactivation of the ridge (Moussavi-Harami & Alexander, 1998). Note: the Birdsville Track Ridge cannot be clearly seen on the 'Z' horizon (Fig 4) because the structural movements were mostly prior to this time (cf. Fig. 13).

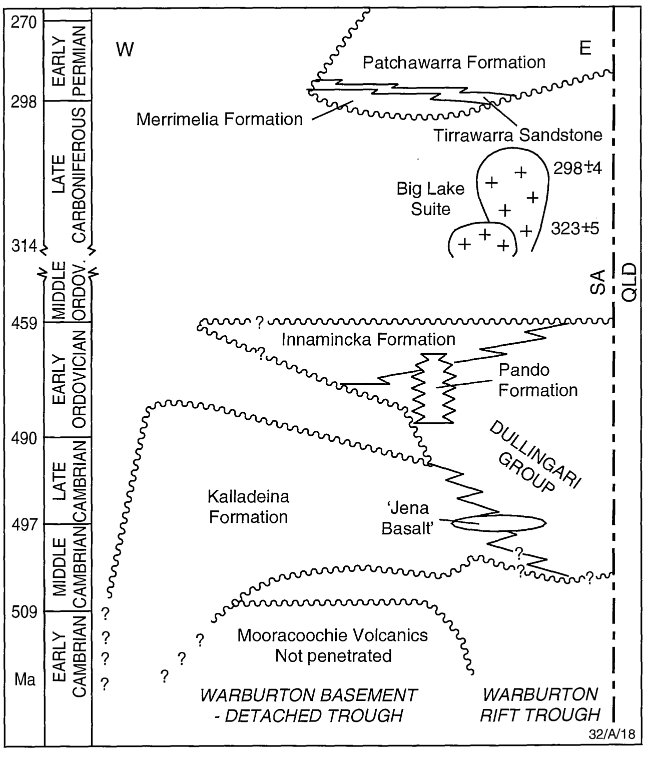


Figure 17. Tectonostratigraphic diagram of the Eastern Warburton Basin indicating two troughs.

Figure 18. Granodiorite at Pyramid Hill, northeast Victoria outcropping beneath Murray Basin sediments. This is somewhat analogous to the Moomba palaeo-high during the early Permian.

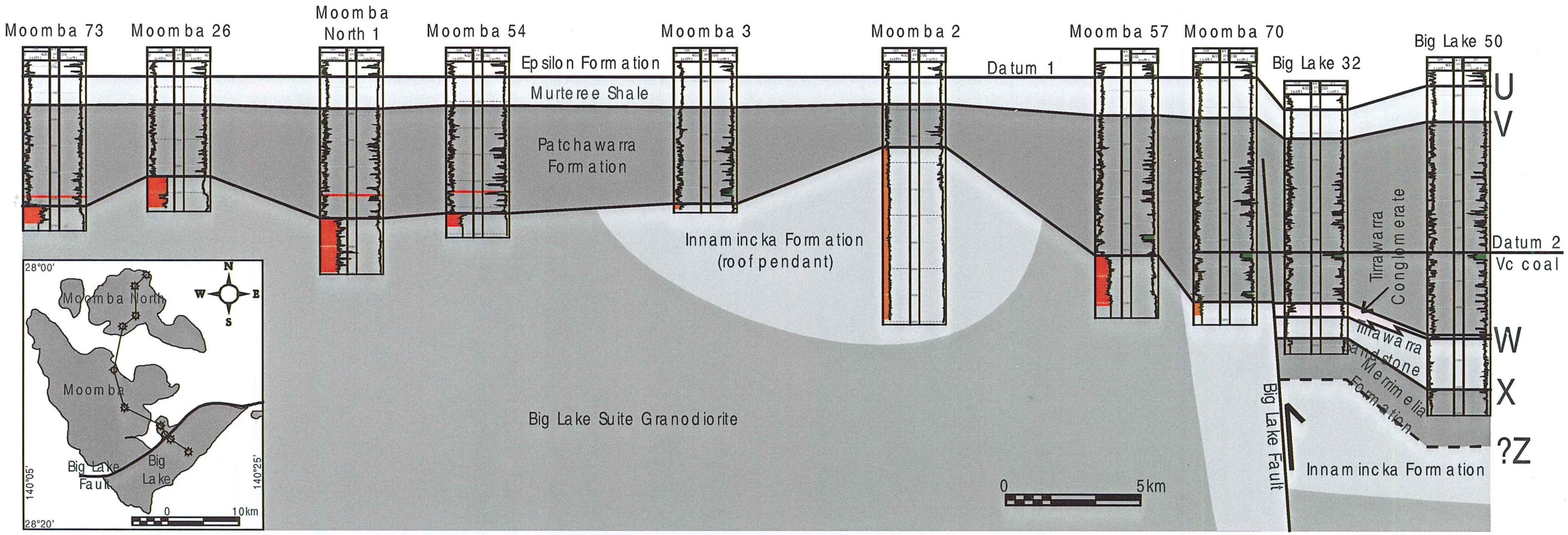


Figure 19. Cross-section through the Moomba and Big Lake fields. Gamma ray log scales are 0-600 API to indicate the high values for the Big Lake Suite. The entire area is underlain by the Big Lake Suite as determined from drilling and gravity (Figs. 1 & 9). Contact metamorphosed Innamincka Formation sediments in Moomba 2 are proposed to form part of a roof pendant above the granodiorite. Two datum levels are used, the top Murteree Shale for the Moomba area and the Vc coal in the Big Lake area to demonstrate the amount of movement on the Big Lake fault (also refer fig. 13). The Tirrawarra Sandstone gives way to the high gamma-ray 'Tirrawarra Conglomerate' of granodiorite provenance and relates to the unroofing of the pluton at Moomba. Each of the lower Cooper Basin formations onlaps the granitoid palaeo-high until it is completely covered. By Murteree Shale time the formation is of uniform thickness except in Big Lake 32 which has recently been uplifted.

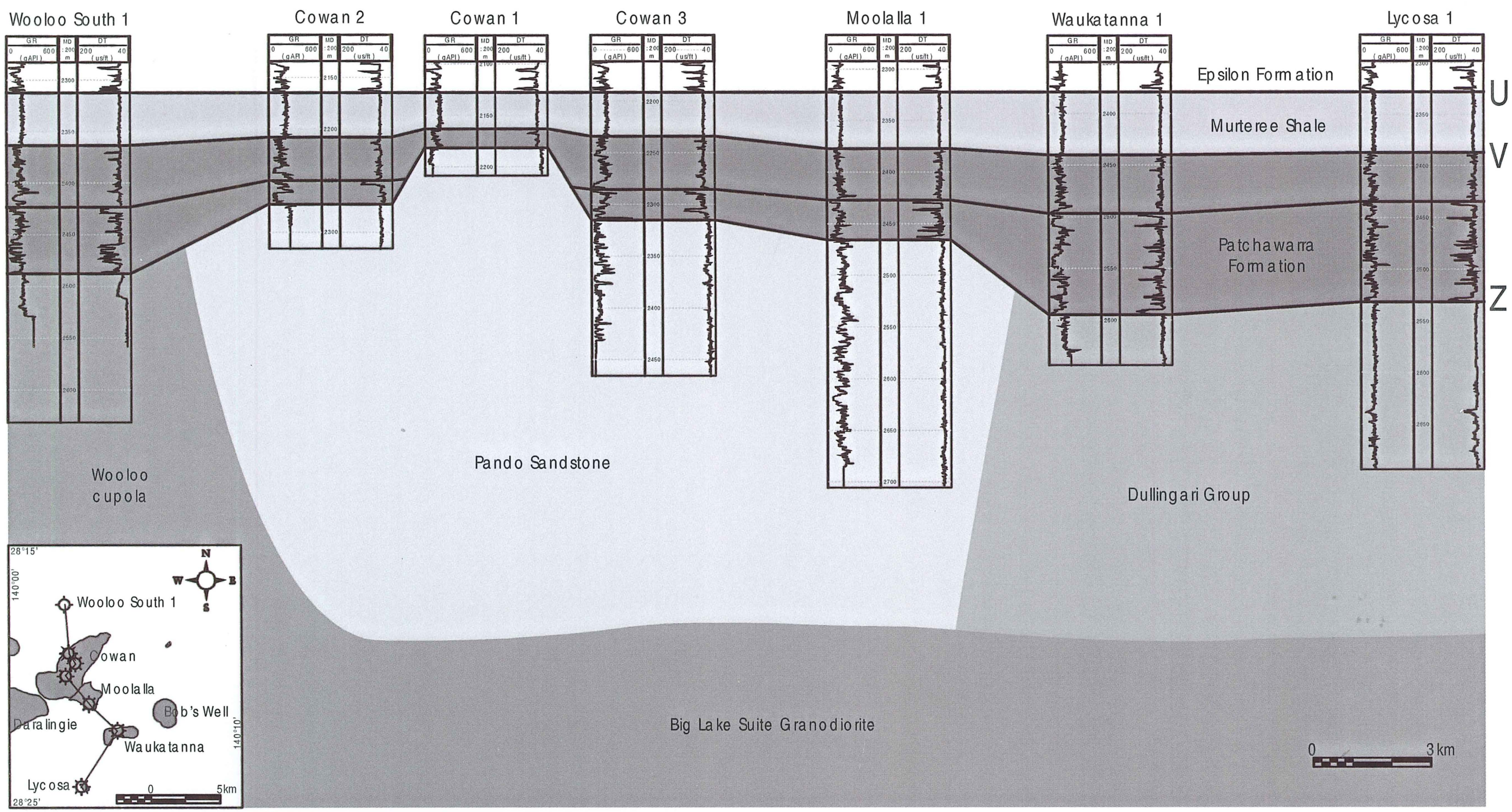


Figure 20. Cross section through the Cowan area. Gravity data (Fig. 9) indicates the Big Lake Suite occurs beneath steeply dipping Warburton Basin sediments except where the Wooloo cupola projects upwards from the main batholith. As in the Moomba area, the lower Cooper Basin sediments lap onto pre-existing, glaciated 'basement' topography. Subtle thickness variations in the Muerteree Shale reflect compactional differences in the recently deposited Permian sediments.