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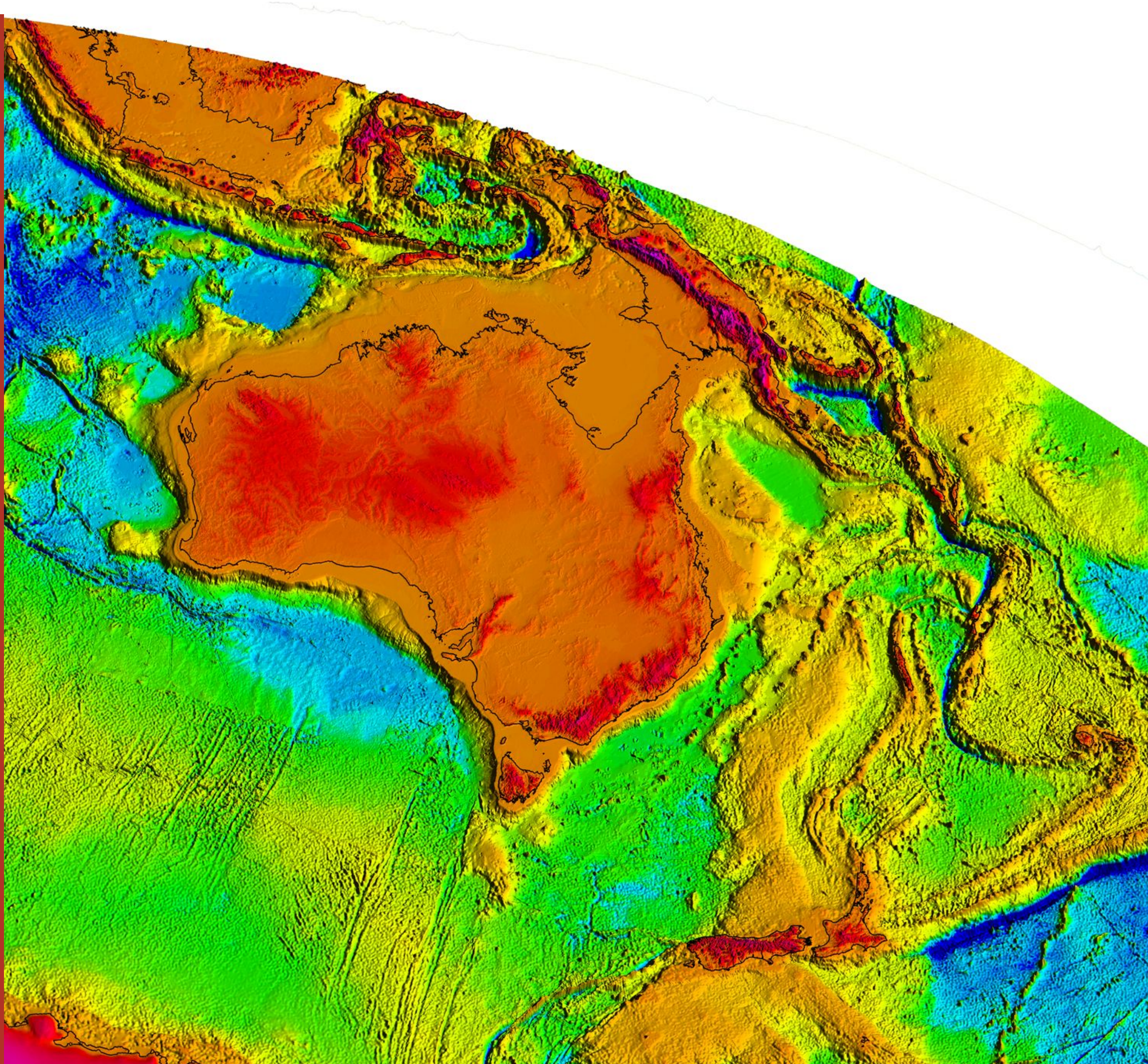

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STRUCTURAL EVOLUTION AND POTENTIAL PETROLEUM PLAYS IN THE DARLING BASIN
(PONDIE RANGE TROUGH – MOUNT JACK AREA)

Based on a seismic sequence analysis

by

J.B. Willcox[1], A.N. Yeates[1],
A.J. Meixner[1] & R.D. Shaw[2]

in consultation with

J.D. Alder[3]

[1]Geoscience Australia
GPO Box 378
Canberra ACT 2601

[2]Exploration Consultant
5A Mulbring Street
Mosman NSW 2088

[3] formerly NSW Department of
Mineral Resources
PO Box 536
St Leonards NSW 2065

Department of Industry, Tourism & Resources

Minister for Industry, Tourism & Resources: The Hon. Ian Macfarlane, MP
Parliamentary Secretary: The Hon. Warren Entsch, MP
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FOREWORD

This report stems from a joint project by Geoscience Australia (previously the Australian Geological Survey Organisation, AGSO) and the New South Wales Department of Mineral Resources (NSWDMR) that aimed to enhance perceptions of the petroleum prospectivity of parts of the Darling Basin in western New South Wales. It focusses on the Pondie Range Trough area near Wilcannia.

The interpretation of the 1980s vintage seismic data was undertaken by J.B. Willcox and was completed in the year 2000.

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Abstract

The Darling Basin is a Late Silurian to Early Carboniferous feature occupying approximately 100 000 km^2 of western New South Wales. In the area of the Pondie Range Trough, near the town of Wilcannia, it comprises up to 12 000 m of sediments, interpreted to have been deposited as syn-rift, thermal sag, and foreland basin phases of basin development, overlain by a veneer of Murray Basin and underlying infrabasin sediments.

Twelve megasequences (including basement) have been recognised from seismic profiles. Megasequences 9-11 form the presumed syn-rift and late rift fill stages, correlate with the latest Silurian to Early Devonian Amphitheatre Group and the Early Devonian Winduck Interval, and have seismic characteristics that indicate a component of marginal marine to deepening marine deposition. As such these units are considered to have the greatest source-rock potential.

The interpreted rift fill phase was terminated by an inversion event and ensuing planation in the late Early Devonian (401-384 Ma) that relates to the Tabberabberan Orogeny. Megasequence 8 represents a short-lived thermal sag phase that correlates with the late Lower to Middle Devonian Snake Cave Interval, and comprises a red-bed facies with a possible brackish-marine incursion.

Megasequences 2-7 correspond to the Ravendale Interval, and are principally red-bed facies (alluvial fan, braided stream and lacustrine) with possible minor marine influence at a time when marine deposits were being laid down in the related Adavale Basin of Queensland. They comprise mid Devonian to Early Carboniferous units deposited as the region came under the influence of a largely compressional or transpressional stress field, with the azimuth of shortening probably directed in a northeast-southwest sense. The overall regime is interpreted as attributable to a foreland basin, with plate convergence taking place to the east or northeast of the Darling Basin. A suite of north-northwest to northwest-trending thrust faults, and associated northeast trending wrench faults created mild inversion, reversal on the main Pondie Range normal fault and elevated the Mount Jack area as a 'positive regional flower structure'. This situation culminated in the Middle Carboniferous with extensive inversion and erosion during the Kanimblan or Alice Springs Orogeny.

Six hydrocarbon plays/leads are postulated. The most obvious are associated with trapping mechanisms involving fault propagation anticlines such as the Pondie Range Structure. Although this structure has been drilled, without success, there was inadequate seismic control to verify that the well, Pondie Range-1, tested a valid closed trap. The most promising structures are considered to be low-relief compaction drape anticlines (Play/lead Type IV) that are unaffected by faulting, and lie over the flank, in close proximity to the Pondie Range Trough with its potential source rocks. These leads lie at depths of 1300 to 4000 m and potentially could have sufficient gas reserves to make them viable stand-alone targets.

Introduction

The Darling Basin occupies a large portion (approximately 100,000 km^2) of western New South Wales, ringed in the north by the towns of Broken Hill, Wilcannia and Cobar, and stretching southward to the region of the Murray River (Figure 1). It is generally a region of plains, broken by low relief 'ranges'. The Darling Basin is a thick sequence of largely Devonian sediments (greater than 8000 metres) partially overlain by relicts of Late Palaeozoic and Mesozoic infrabasins, beneath the extensive cover of the Cainozoic Murray Basin. This veneer covers the region and restricts geological mapping to fault-bounded ranges. Although structurally complex, the planation of the basin since the Carboniferous has left little evidence in the present-day landscape of the underlying structural features.

The basin is prospective for petroleum, especially deep dry gas, but no occurrences are known. The Moomba to Sydney pipeline crosses the basin, making it an attractive place to find gas for the burgeoning eastern seaboard markets (NSWMR, 1993).

The region has been sparsely explored; an early phase of potential-field mapping and seismic exploration having taken place in the 1960's and 70's, with some renewed interest, largely in the form of two seismic surveys by BHP Petroleum Pty Ltd, in the mid 1980s. Most recently, Geoscience Australia (then AGSO) recorded an AGSO/NSWDMR jointly funded deep seismic profile across the western boundary of the Basin, the line extending from the Broken Hill area northeastwards into the basin ('CABGAS' Line AGS99-C1; Willcox & others, 2000; Direen & others, 2000). Exploration drilling in the Darling Basin commenced with Mount Jack-1 in 1963, and has continued sporadically with about a dozen wells having been located largely in the western part of the Basin. Most of these wells were sited on the basis of potential-field anomalies, or on poorly understood and poorly defined structures, and few penetrated below Late Devonian rocks of continental origin. Several of the sites appear to have been on invalid closures and none have been demonstrated to have tested valid closures. To date, the drilling results have been disappointing, with only two minor gas shows, and bitumen traces in Bancannia South-1. In its initial phase, petroleum exploration waned though a lack of shows, the likelihood of a gas-prone source, and the presence of a thick red-bed dominated and organically lean, Late Devonian sequence.

However, the "Discovery 2000" initiative by the NSWDMR which included the drilling of Kewell East-1 in the Neckarboo Trough (farther east of the study area) sparked some renewed industry interest (Mullard, 1995; Alder & others, 1998). Kewell East-1, a fully-cored stratigraphic well reached a total depth of 1224 metres and penetrated a Late Silurian - earliest Devonian section containing microfossils that provide unequivocal evidence of a marine depositional environment in the region and hence scope for marine source rocks (Playford, 1997). This finding, together with a currently projected shortfall in gas supplies to the Sydney market, and the basin's proximity to the Moomba - Sydney pipeline infrastructure, has led to renewed appeal for exploration in the Darling Basin.

This report describes an interpretation of the Pondie Range Trough – Mount Jack area (142° 30' 00" - 144° 00' 00"E; 30°30' 00" - 31° 50' 00"S) using part of a regional seismic data set recorded for BHP Petroleum Pty Ltd in 1983 and 1985. These data are of reasonable quality despite lack of 'migration' on some lines. The main objective has been to identify major reflection 'packages' on the seismic profiles and in some cases to use them to infer depositional environments, and to deduce the tectonic evolution of the region.

The study was carried out by Geoscience Australia (then AGSO) and NSWDMR under the auspices of the 'National Geoscience Mapping Accord'. The Darling Basin interpretation formed a part of the AGSO 'Central Australian Basins Gas Project' ("CABGAS").

Background Geology

The Darling Basin is a Late Silurian to Early Carboniferous sedimentary basin within the Tasman Fold Belt System of eastern Australia (Figure 2). It overlies basement disjunctions coinciding with boundaries between the Kanmantoo, Lachlan and southern Thomson Fold Belts (Glen, 1992; Scheibner & Basden, 1996; Shaw & others, 1996).

Strata are largely Devonian with a known thickness of up to 8 km. Latest Silurian to Early Devonian fossiliferous marine shales (and outliers of equivalent, mainly paralic and non-marine strata) are succeeded by latest Early Devonian to earliest Carboniferous coarse fluvial quartzose clastics. Several unconformities are present in the succession (Alder & others, 1998; Bembrick, 1997; Brown & others, 1982; Evans, 1977).

Indications of the possible presence of petroleum include gas of unknown origin seeping from water bores (Sharpe & McLaughlin, 1986), potential source rocks in sparsely sampled Early Devonian shales (Brown & others, 1982), and a few "shows" reported from wells. Reservoir units have good porosity and permeability. Cambrian to Ordovician carbonates and shales, where present beneath the basin, could also be potential source rocks (Alder & others, 1998).

Location

Located mainly in western New South Wales, the Darling Basin has subsurface edges which extend into western Victoria and eastern South Australia (Fig. 2). The basin is largely concealed beneath thin cover sequences of the Cainozoic Murray Basin and its underlying infrabasins (Brown & Stephenson, 1991) and by the southern part of the Mesozoic Eromanga Basin (Scheibner, 1976).

Basin Limits

Outcrop mapping (Rose & Brunker, 1969; Pogson, 1972; Glen, 1991; Mills, 1992; Neef & others, 1995) geophysical data (eg Pitt Research Pty. Ltd., 1995; Wyatt &

others., 1980) and subsurface interpretations (Glen & others, 1994; Scheibner & Basden, 1996; Murray & Parker, 1998; Shaw & others, 1996) have been analysed to compile the basin limits and their nature as shown in Figure 2. Apparent complexity of the outline is due to major faulting and to substantial erosion, both consequences of significant tectonism in the basin's history (Scheibner & Basden, 1996; Olissoff, 1989).

Early Devonian strata of the Darling Basin are unmetamorphosed and gently deformed. They are faulted against time-equivalent, highly deformed and mineralised turbiditic metasediments of the Cobar Basin. Faulting of the western boundary of the Cobar Basin occurred during Laclan Fold Belt inversion in latest Early Devonian time (Glen, 1991).

Mapping and facies analysis (Glen & others, 1985; Webby, 1972) suggest a pre-inversion gradational boundary between the two basins. In the present interpretation of the basin boundaries (Figure 2), it would appear that the latest Silurian to Early Devonian fossiliferous shales of the Darling Basin may represent marginal marine deposits that remained in a stable environment, unaffected by the volcanic, hydrothermal and tectonic activity which accompanied turbidite deposition in the Cobar Basin.

Outliers

Correlations and palaeogeographic reconstructions (Walley & others, 1990; BMR Palaeogeographic Group, 1990) suggest the mainly non-marine Grampians Group (western Victoria) and Mount Daubeny Formation (faulted against the Wonominta Block) may formerly have been part of the early Darling Basin. Outcrops are now structurally separate from the basin (Cayley & Taylor, 1997; Neef & others, 1996). The paralic to non-marine character of the outliers allows reconstruction of the approximate limits to the latest Silurian to Early Devonian sea (BMR Palaeogeographic Group, 1990).

Stratigraphy and Correlations

Darling Basin stratigraphy is comprehensively reviewed by Bembrick (1997) and this section is simply a summary of the salient features pertinent to the Pondie Range Trough. The stratigraphy intersected in the Pondie Range-1 and Mount Jack-1 exploration wells, which lie within the area of this study, is given in Figures 3 & 4.

Conodonts, palynomorphs and brachiopods reveal that marine shales from early Darling Basin deposits are of latest Silurian to earliest Devonian age (Jones & others, 1981; Strusz, 1996; Foster, 1997; Playford, 1997).

Dating of the coarser clastic, non-marine and paralic outliers is less convincing but stratigraphic ages are anticipated to be similar. The long-ranging inarticulate brachiopod *Lingula* and the trace fossil *Skolithos* are present in the Silverband Formation at the Grampians (Cayley & Taylor, 1997), the Wonominta Block (Neef &

others, 1996; Warris, 1969) and the Cobar region (Glen, 1987), inviting broad comparisons (Bembrick, 1997).

Fish fragments in the Silverband Formation have been dated at about the Silurian-Devonian boundary (Turner, 1986). *Baragwanathia* floral elements in the upper Mount Daubeny formation (Neef & others, 1996) have a similar stratigraphic age, comparable to the well dated flora at Yea in central Victoria (White, 1986). Therefore, time equivalences of the Grampians Group, Mount Daubeny Formation and early Darling Basin shales appear reasonable assumptions.

A comparative tectono-stratigraphic framework for the Darling Basin and Adavale Basin has been presented by Alder & others (1998; Figure 5). This incorporates the stratigraphic scheme of Bembrick (1997) with the results of NSW-DMR's stratigraphic drilling in the region, together with seismic horizons identified by Evans (1977). Due to a scarcity of adequate well control identifications of megasequence picks on seismic sections are largely interpretive.

Seismic sections reveal the oldest sequences are of Late Silurian to earliest Devonian age and have a rift-fill character, comparable to marine fill in exposed troughs farther east. Overlying strata in the basin are interpreted on the basis of their seismic character to be shale dominated. They become progressively more widespread until truncated at a widespread unconformity. From latest Early Devonian times, the succession is dominated by thick coarse quartzose sandstones and conglomerates. Redbeds are widespread in this succession which continued until the earliest Carboniferous (Evans, 1977; Bembrick, 1997).

Potential Fields Data

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

Figure 6 is a reprocessed image of the total magnetic intensity field, derived from the NSWDMR 'Discovery 2000' grid of NSW. A major portion of the study region is covered by high resolution regional airborne surveys flown at 250 m and 400 m line spacing, while the northeastern portion (bounded by latitude 31^{o} S and longitude 143^{o} E), consists of an older lower resolution airborne survey with a line spacing of

3000 m. The lower resolution survey lacks subtle high frequency anomalies that result from shallow magnetic bodies.

Figure 7 is an image of the Bouguer gravity field, using values from the Australian national gravity database (Murray, 1997). The location of the Darling Basin troughs and basement highs were defined by Alder & others (1998) using a synthesis of gravity, magnetic, seismic and outcrop data. Gravity lows that relate to structural troughs, are caused by thick sections of relatively low-density Darling Basin sediments, more specifically Late Devonian to Carboniferous sediments. Recent work in the Paka-Tank and Booligal Trough areas by NSWDMR suggests that the Amphitheatre Group may not be particularly mass deficient and that magnetics is a better means of determining Late Silurian to Early Devonian depocentres.

The extent of Darling Basin sediments in the Pondie Range region (Figures 6 & 7) is limited by the unexposed Thomson Fold Belt in the north, and the Wonominta Block and the Scopes Range High in the west. These features comprise shallow basement, and are characterised by high frequency shallow-sourced linear anomalies in the west, and a series of moderate amplitude east-west trending anomalies in the north. Positive gravity anomalies reflect the shallow basement. The area that adjoins the Pondie Range Trough and the Bancannia Trough to the west, is characterised by high frequency short-wavelength anomalies, corresponding with the known thin section of Darling Basin sediments underlain by shallow basement. In particular, this is consistent with a continuation of a gravity high through the area, and by minimal broadening of the magnetic anomaly frequency of the north-south trending anomalies. In the far west, the Proterozoic basement crops out.

The magnetic field within the basin region (Figure 6) is dominated by a large broad amplitude anomaly with a depth to magnetic source estimate of 7900 m. The lack of an associated gravity anomaly (Figure 7) indicates that there is no significant density contrast with the surrounding crust. The large depth to the source body places it below the base of the Darling Basin sediments, and thus it is interpreted to be an intrusive igneous body probably of mafic composition, with a large depth extent and a high magnetite content. The broad magnetic low directly to the south of the anomaly is due to the non-vertical inclination of the magnetic field at these latitudes.

The remaining magnetic features within the Darling Basin region, consist of a limited number of broad, deeply sourced anomalies and a series of higher frequency shallower sourced anomalies. The depth to magnetic source estimates of 4100 m in the south and 3300 m in the northeast are considered to be derived from the relatively shallow basement of the Wilcannia High and the Mt Jack High. The lack of further discrete magnetic anomalies, suggests that the basement is deep in the Pondie Range Trough and consists of sparsely magnetised rock.

The higher frequency anomalies are considered to be sourced from intra-sedimentary units. A series of northwest trending anomalies with depth to source estimates of 550 m, 600 m and 840 m are interpreted as intrusive dykes and sills. A series of north-west trending continuous anomalies above the Pondie Range and Poopelloe Lake Troughs are interpreted as thrust faults within the Darling Basin sediments. The magnitude of these anomalies is less than 3 nT and they are probably due to subtle variations in magnetite content of the various sediment layers. These anomalies provide a useful tool in mapping of the major thrust faults through the region.

Seismic Interpretation of the Pondie Range – Mount Jack Area

Data

The Darling Basin region has been covered with clusters of seismic lines, concentrated over areas of perceived structural interest, often on the basis of the potential field data (Figure 8, Plate 1). In places, these lines form simple grids which have been used to site petroleum exploration wells. Most seismic lines are of old vintage and poor quality by modern standards, having been recorded and processed using relatively basic seismic techniques. The interpretation herein is based on a more modern, a higher quality, sub-set of these seismic profiles recorded for BHP Petroleum Limited (as part of the Darling Seismic Survey) in 1983 by Seiscom Delta United Inc. The lines, HD-100 and HD101, and HD-103 to HD-107, lie within the northern part of the Darling Basin, in the Pondie Range – Mount Jack area, near the town of Wilcannia (Figure 9). These data comprise a mix of 12-fold stacked and migrated profiles displayed to 4 seconds two-way time (twt).

Acquisition and processing details are tabulated below:

Table 1. Seismic Acquisition and Processing Parameters

Acquisition -

Energy Source	Type	Vibroseis Mertz Y-12
	Source interval	160 m
	Sweep length	6 seconds
	Sweep frequency	16 – 96 Hz upsweep
	Source array	16 sweeps per station
	Number of vibrators	4
Recording Geometry	Fold	1200%
	Spread	1980 – 100 – SP – 100 – 1980 m
	Number of groups	96 at 40 m intervals
	Geophone group length	33 m
Instrumentation	Geophones	GSC HS 20D (10 Hz); 12/group
	Recording system	DFS V
	Gain	IFP
	Filters: Low cut	Out
	High cut	128 Hz; Slope = 22 dB/octave
	Format	SEGY
	Record length	6 seconds
	Sample interval	2 milliseconds

Processing –

Initial Process	Resample	4 milliseconds
	Trace edit	
Trace Equilisation	Gate length	800 milliseconds
	FK-filter	
Pulse Compression	Wavelet shaping	
Datum Statics	Corrections	Source/receiver elevations
	Datum	100 m
	Replacement velocity	3500 m/s
	Refraction statics	1800 m/s weathering velocity
CDP Gather		
Velocity Analysis		
Surface statics	(ANSAC)	
Stack		Standard 12-fold
Trace Equilisation	Gate length	800 milliseconds
Filter	0.0 – 4.0 seconds	16–50 Hz; Slope 24–60 dB/oct.
Wave Equation Mig.	Operator	Koehler
Display	Type	Trace equilised
	Vertical scale	10 cm/s
	Horizontal scale	10 traces/cm
	Peaks	Increased impedance

In general, the profiles are of fairly good quality and exhibit reasonable signal/noise ratios throughout the 4 seconds of display. Sub-parallel, fairly continuous reflectors occur above the basement complex, the most prominent of these often defining the interpreted sequence boundaries. In places the dips steepen abruptly, usually in association with what appear to be thrust zones, and the stratigraphy is not resolvable. At the surface, some of these zones form low-elevation ranges.

Seismic Sequences & Bounding Unconformities

In most basins, the largest-scale sequences (first-order megasequences of Hubbard *et al*. 1985; Haq *et al*. 1988) are formed by basin-wide tectonic events (eg. extension, cooling, flexural loading etc). Twelve widespread major ‘reflection packages’/seismic sequences (including the ‘basement’ complex) can be recognised within the Darling Basin area and are interpreted herein: additional lesser sequences that are not as clearly defined are also present. For convenience these twelve sequences have been referred to as ‘megasequences’ though some of them may strictly be sequences of lower order.

The twelve megasequences, that are numbered ‘1 to12’ downwards, are bounded by unconformities labelled downwards from ‘A to L’ in Plates 1 & 2. It should be noted that in a previous seismic study (Evans, 1977) the three main reflectors were categorised as ‘A-C’ in the opposite sense. The geometrical characteristics of the twelve megasequences, surmised structural and depositional setting, and age identification, are described below (Table 2).

Table 2. Seismic Sequences

Mega- -sequence*	Bounding U/c	Reflection Character			External Shape	Max. thickness estimate (m)	Interpretation (from seismic character & other sources)
		Upper Boundary	Lower Boundary	Internal			
	Surface						
1		Surface	Mild onlap	Within ground noise	Sheet	100	Fluvial veneer sediments.
	A						Middle Carboniferous Kanimblan or Alice Springs Orogeny. Folding, uplift and planation of Darling Basin.
2		Erosional truncation	Mild onlap	Within ground noise	Sheet	160-200	Probably red-bed facies of Late Devonian Ravendale Interval (Mulga Downs Group).
	B						
3		Largely concordant	Mild onlap	Low amplitude, discontinuous	Sheet	1000	Red-beds: alluvial fans, braided streams, and lacustrine Late Devonian Ravendale Interval (Mulga Downs Group).
	C						
4-6		Concordant/mild truncation	Concordant/mild bottomlap	Low amplitude, largely continuous. Discontinuous/chaotic in structural highs. Some high amplitude/high continuity reflections.	Sheets with compaction drape.	2800	Red-bed facies with lacustrine components more likely than in Megasequence 3. ?Limestone/oolite mentioned in Alder & others (1998) could be calcrete. Late Devonian (?Famennian) Ravendale Interval (Mulga Downs Group).
	F						
7		Mild truncation	Concordant/bottomlap	Low amplitude, discontinuous. High amplitude,continuous in places	Sheet/wedge over/ infilling topography; Lenses/build-up structures	300 NE – 1300 SW	Fluvial red-bed facies with possible minor marine influence in places. Build-ups could be carbonates, volcanics or wrench 'flower structures. Additional sequence SW of Pondie Range Structure. ?Foreland loading. Late Devonian (?Frasnian) Lower Ravendale Interval (Mulga Downs Group).
	G						Initial development of fault propagation anticlines; NE-SW crustal shortening/transtension; erosion in the mid Devonian. Horizon 'C' of Evans (1977).

***Table 2** (continued)*. **Seismic Sequences**

Mega- -sequence*	Bounding U/c	Reflection Character			External Shape	Max. thickness estimate (m)	Interpretation (from seismic character & other sources)
		Upper Boundary	Lower Boundary	Internal			
8		Erosional truncation	Mild bottomlap	Low ampl/discontinuous. Some high amplitude/continuous.	Wedge over/infilling earlier topography	1500	Fairly uniform lithology; probably fluvial red-bed facies. Commencement of basin 'sag' phase. Early Middle Devonian (Eifelian) Snake Cave Interval (Mulga Downs Group).
	H						Extensive erosion of basement and rift-related megasequences. Horizon 'B' of Evans (1977).
9		Erosional truncation	Onlap	High amplitude/continuous	Basin SW thickening wedge	1200 SW –3000 NE	Probably marine; deposited following relative fall in sea level. Late syn-rift or rift fill phase. Early Devonian (Pragian), upper Winduck Interval, Winduck Group equivalent.
	I						
10		Erosional truncation	Onlap	Moderate amplitude continuous/semi - continuous	Basin SW thickening wedge; basin margin lens	1900	Marginal marine – deepening marine. Syn-rift phase. Early Devonian (Pragian) Winduck Interval, and upper Amphitheatre Group equivqlent.
	K						Alternative (uppermost) level for seismic Horizon 'A' of Evans (1977).
11		?Concordant	Onlap/basinward downlap	Largely low amplitude; high amplitude/ continuous near top	Lens/wedge	1300	Possible earliest syn-rift within regional extensional setting. Traditional models would consider this as alluvial fan, though a marginal marine facies seems likely in this case. Carbonates, volcanics, or a thrust plane may overlie the megasequence. Latest Silurian – earliest Devonian (Pragian), lower Amphitheatre Group equivalent.
	L						Strong erosional unconformity, probably corresponding to the seismic Horizon 'A' of Evans (1977).
12		At depth	Strong erosional truncation	Variable amplitude/ sub-parallel – discontinuous and arcuate reflections	'Basement'	8000+	Basement complex with numerous folds and thrust planes. Pre-Darling Basin section. Proterozoic and Early Palaeozoic rocks of the Kanmantoo Fold Belt, Broken Hill Block and Lachlan Fold Belt.

* The term 'megasequence' is used for convenience to cover major basin-wide sequences. While many of these correspond to the major basin phases and are thus true megasequences re the terminology of Hubbard et al., 1985 & Haq et al., 1988, some may strictly be sequences of lower order.

Basement Complex

Megasequence 12:
The bottom-most sequence on the seismic reflection profiles comprises a thick zone of sub-parallel, but often discontinuous, reflections of variable amplitude. Its upper boundary (Horizon L) generally lies between 1 second to 3.5 seconds twt, a depth range of about 2000 to 10 000 metres. Its discernible thickness is about 8 000+ metres. The boundary of this zone and the overlying megasequence is for the most part clearly defined and indicates a strong erosional unconformity. Variability in amplitude and signature, created largely by impedance changes across the boundary, indicate that the 'basement complex' comprises, and is overlain by, rocks of varying lithology and age. Broad arcuate reflections within the complex are largely indicative of folds. Discontinuities and dip reversals associated with these structures are interpreted to signify major fault zones, many of which appear to be ancient thrusts and reverse faults. Younger, post-basement, thrust faults are also present and are considered to have grown during the upper Early Devonian (Tabberaberran) and Early Carboniferous (Kanimblan/Alice Springs) orogenies. As such the basement boundary was presumably formed during an earlier (Silurian) orogeny. The large thrust anticline on which Pondie Range-1 was drilled (Line HD-106, see Plate 1) is bounded by a thrust fault that appears to detach within the basement complex, as indicated by its convergence with a clearly defined sub-horizontal reflection.

The Basement Complex represents a pre-basinal phase with respect to Darling Basin formation. The elements that make up this basement are poorly known but are probably similar to those underlying the Murray Basin as discussed by Brown & Stephenson (1991). Syn-basinal (possibly syn-rift) sediments making up Megasequences 9, 10 & 11 lie directly over this complex in the Pondie Range Trough area (Plate 2). As discussed above, the dating of the Basement Complex is poorly constrained; however, on balance it is thought to comprise an indurated block of pre-Late Silurian sediments overlying Precambrian rocks equivalent to the Broken Hill Block and metamorphosed units of the Kanmantoo and Lachlan Fold Belts. On this basis, the unconformity that floors the basin and delineates to top of the Basement Complex is predicted to be Late Silurian, probably no older than about 420 Ma.

Latest Silurian/Earliest Devonian ?Syn-rift Section

Megasequence 11 (bounding unconformites K-L):
Megasequence 11 occurs along the northeastern margin of the Pondie Range Trough (HD-101, 106). It comprises a lens of largely low amplitude reflections that onlap basement updip, and downlap basement in the developing basin to the southwest. The megasequence is bounded above by a band of high-amplitude continuous reflections. Its maximum thickness is of the order of 1300 metres, based on the stacking velocities. The extent to which this package may have been present in other troughs is unclear, however, its characteristics have not been identified on other lines from the northern part of the basin.

This sediment package is considered to represent the earliest ?syn-rift phase within the developing basin. In the traditional interpretation of syn-rift environments, Megasequence 11 would be a lens of probable alluvial-fan type deposits, derived from erosion of the basement along the rotational edge of a developing ?half-graben, and probably giving way to more lacustrine and fluvial deposits within the main depocentre. An alternative interpretation, based on the relationship of the package to the underlying basement, is that it could comprise sediments deposited in a marginal marine environment. The high amplitude, continuously layered nature in the upper part of the sediment package could be due to a number of causes; namely, a switch from largely continental to marine deposition; high impedance contrast created by the presence of carbonates or volcanic sills; or the possible presence of a low angle thrust plane sub-parallel to the bedding.

Megasequence 11 was clearly deposited during the initial subsidence of the Pondie Trough area, and marks the commencement of the Darling Basin's depositional history. The relationship of this package to the dated sequences of the Darling Basin is unclear as it would underlie the oldest dated unit. The package may be an incipient rift, perhaps similar to the early deposits of the Cobar Basin (see Glen & others, 1996).

Early Devonian ?Syn-rift and Late Rift

Megasequences 9 & 10 span the unconformities H, I, (J) & K. They appear to have been deposited during the structural phase of basin development (largely Pondie Range Trough) and could be described as syn-rift and late rift fill, though their association with an extensional pulse of tectonic development cannot be conclusively demonstrated from the available data. Compared to Megasequence 11, they have wider distributions denoting enlargement of the depositional environment.

<u>Megasequence 10</u> (I-K):
This is made up of moderate amplitude reflectors that range from continuous to semi-continuous. Its lower boundary onlaps unconformity K, and its upper boundary shows erosional truncation. Along the northeastern side of the Pondie Range Trough this megasequence has been reduced in thickness by erosion at the time of unconformity H. Its maximum observed thickness is of the order of 1900 metres. This megasequence exibits a 'mound-like' structure along the northeastern edge of the Pondie Range Trough (Line HD-106). Although this mound-like feature has been accentuated by mid-Devonian thrusting, it seems to be at least in part depositional in origin. The megasequence appears to thicken to the southwest and probably bore a syn-rift relationship to an early extensional fault that was later reactivated and reversed to create the structure on which Pondie Range-1 was drilled.

The moderate continuity of reflections and the marginal build-up indicate that Megasequence 10 could be envisaged as a marginal marine deposit grading into deeper marine sediments within a developing trough. It may correlate with the deep shelf and basin facies, including turbidite fans, of the type that have been described in the Cobar Basin and to its west (Webby, 1972; Glen, 1987). On the basis of conodont assemblages and shelly macrofauna the age of equivalent facies was deduced as

Pragian. It thus seems probable that Megasequence 10 could correlate with the earliest part of the Winduck Interval (Early Devonian portion of the Amphitheatre Group) implying a Lochkovian or Late Silurian age for Megasequence 11.

Megasequence 9 (H-I):
This is a basin-thickening wedge that shows onlap at its lower boundary and erosional truncation at its upper boundary. Reflection amplitude and continuity are relatively high. The profiles show evidence that this megasequence was probably much more widespread and Glen (1987) described it overlying basement in the Cobar region. If correlations are correct, a large trough would have been present to the northeast of Mount Jack (Line HD-101), and residual deposits are also preserved in depressions within basement. This megasequence has a maximum thickness of around 1200 m in the Pondie Range area, but may be up to 3000 m thick at Mount Jack. As with Megasequence 10, it was also deposited during active formation of the trough or ?half-graben; in the latter case it could best be described as syn-rift fill with respect to a half-graben that extended southwestwards to the Pondie Range-1 structure.

This megasequence could also be marine in origin and, if so, would seem to have been deposited following a relative fall in sea level and offlap in the Pondie Range Trough of at least 10 km. The overlying unconformity H represents an extensive period of erosion, truncating the underlying megasequences and probably planating large areas of the basement (Seismic 'B' Horizon of Evans, 1977). Compressional structuring and reverse faulting are interpreted, and it is possible that some of the major anticlinoria within the basement were developed or reactivated at this time. On the basis of the movements known to have occurred in the Devonian, it seems probable that such major erosion would best correspond to the Bindian/Bowning Movement, and the Tabberabberan Orogeny. If this supposition is correct, Megasequence 9 would relate to the upper part of the Winduck Interval and be no younger than latest Pragian.

Correlation of Megasequences 9-11 with Early Devonian Winduck Interval:
The Megasequences 9-11 that are likely to represent a syn-rift phase in development of the Darling Basin, are interpreted to be equivalent to the Early Devonian of the Winduck Interval including the Amphithreatre Group (as per Alder & others, 1998, fig. 8). Some latest Silurian sediments may also be present.

In general terms, the Winduck Interval comprises the Amphitheatre and Winduck Groups in the eastern part of the Basin and the Mount Daubeny Formation in the western Wonominta Block (Neef & others, 1989) (see for example the rock relations diagram of Bembrick, 1997, redrawn in Alder & others, 1998). The Winduck Interval equivalent is known to reach a thickness of up to 6000 m in the west, but where it crops out in the McCullochs Range southeast of the Pondie Range Trough it is 3500 m thick. This corresponds well with an estimated thickness of up to 3250 m for the combination of Megasequences 9-11.

Where penetrated in wells, and in outcrop, the Winduck Interval ranges from alluvial/fluvial in the west to fluvial-deltaic and shelfal in the east (Alder & others, 1998). In the Pondie Range Trough, the seismic data indicate what are probably shelfal deposits in the northeast, grading to deeper marine deposits in the southwest.

The erosional truncation observed on the seismic profiles, corresponding to Evans (1977) Horizon 'B' overlying the Winduck Interval, appears to have created isolated areas in which Winduck sediments are preserved. Whether or not the Winduck Interval was at one time more widespread cannot be determined, but indications at Cobar (Glen, 1987) suggest it probably was.

Middle Devonian Thermal Sag Phase

In broad terms, Megasequence 8 results largely from 'layer cake' strata deposited during the period when Darling Basin subsidence was driven by thermal relaxation. At Cobar, Perkins & others (1994) dated this at 384 Ma. It appears to make up a relatively short-lived phase that existed in the Middle Devonian, before the basin moved into a foreland basin tectonic setting. For the most part, the Middle and Late Devonian sequences are made up of red-bed facies with sandstones predominant. They are equivalent to the Mulga Downs Group mapped by Glen (1987) in the Cobar region.

<u>Megasequence 8</u> (G-H):
This interval is characterised by mild bottomlap and erosional truncation at its upper boundary. Internally, it comprises low amplitude discontinuous reflections, though in the presumed deeper part of the basin, in the vicinity of the Pondie Range-1 structure, it incorporates some continuous high amplitude events. The megasequence appears to have infilled irregularities in the underlying topography. It reaches a maximum thickness of about 1500 m.

In the Pondie Range Trough, it forms a southwestward thickening wedge that extends to the main fault in the Pondie Range-1 structure: it then appears to thin abruptly to the southwest (by 500+ m) across this same fault. This indicates that the main fault in the Pondie Range-1 structure was an active extensional fault during deposition of the megasequence.

The character of this megasequence indicates that through most of the area it relates to rocks of a uniform lithology. The lack of continuity of reflections make it unlikely that it corresponds to a further marine section - a fluvial deposit being the more probable. The widespread nature of Megasequence 8, together with its thickness and position in the stratigraphic succession, indicate that it corresponds with the Snake Cave Interval (Eifelian, lower Middle Devonian). This interval has been described by Neef & others (1996) as being made up of braided stream, low angle alluvial fan, and some meandering stream deposits. The dominant lithology is of quartzose sandstone with minor siltstone. In the Scopes Range area, Alder & others (1998) have stated that there is evidence for a brief but possibly widespread brackish to marine incursion that terminated the interval.

<u>Mid Devonian Unconformity</u>:
The upper boundary of Megasequence 8 (Unconformity G; Horizon 'C' of Evans, 1977) marks the first period of structural shortening across the Darling Basin. Several

large asymmetric anticlines, principally with northwest-southeast trending axes (for example, that bounding the Pondie Range-1 structure) started to form at about this time. These anticlines are essentially fault-propagation folds, with bounding thrust faults that are in most cases associated with reversal on the major faults that had previously formed the half-grabens. As noted above, most of these faults tend to ‘sole-out’ (flatten) to the northeast into sub-horizontal detachment surfaces within basement, approximately at 3.5 to 4 seconds twt, that is at about 12 km depth.

There are, however, some major faults with planes that sole-out to the south or southwest. Whether or not they are all related to the mid Devonian shortening event is difficult to determine, as the high dip in these regions often make sequence correlation uncertain. The most notable of these occur within the complex thrust zone that lies to the south of Pondie Range (Line HD-107). There is also a triplet of southwest-dipping thrust planes along the northeastern side of the Mount Jack structure (HD-101) that are interpreted to have been active from the mid Devonian. Antithetic faults and tensional faults are common within the anticlinal structures. In most cases, the bedding shows little offset across the thrust faults, indicating either; that the fault reversals were of similar magnitude to the original downthrow into the half-grabens; or more probably, that there was a significant element of ‘transpression’ through the region, with little vertical displacement.

The truncation at the unconformity shows that at least 300 m of erosion occurred over the anticlinal crests in the mid Devonian. Attendant deposition seems to have taken place in localised downflank positions, probably mainly as alluvial fans and braided stream deposits.

It should be noted that the Pondie Range-1 exploration well, which reached a total depth of 3148.5 m sub-sea (?zero metres datum), penetrated Unconformity G at about 2861.9 m (NSWMR, 1993). The underlying unit was composed of sandstone and was at that time assumed to be “Proterozoic”, based purely on a slow rate of drilling penetration. On the basis of this seismic interpretation such a conclusion is not possible.

Late Devonian Foreland Basin Setting

<u>Megasequence 7</u> (F-G):

Megaseqence 7 exhibits a concordant to bottomlap lower boundary and mild truncation at its upper boundary. Its internal reflection characteristics are more varied than for the underlying megasequence; ranging from low amplitude/discontinuous over much of its extent; to high amplitude/continuous in its upper part on the northeastern side of the Pondie Range Trough, and on the southwestern flank of the Pondie Range-1 structure. This megasequence is widespread and infills the topography created by development of the mid Devonian thrust anticlines, thus having a large range in thickness, from about 300 m in the northeast to about 1300 m in the southwest. The infilling deposits tend to show chaotic reflection configuration, possibly indicative of alluvium. On the crest and southwestern flank of the Mount Jack structure (HD-101) there appear to be ‘build-ups’ within this interval, however it is not clear if these result from carbonates or volcanics, or if they are ‘positive flower-type structures’ created by complex wrench faulting.

On the southwest flank of the Pondie Range-1 structure, the sedimentary configuration within Megasequence 7 indicates that the thrust anticline was growing at least through the first part of the interval. Beyond this flank (HD-106, SSW) the interval bounded by unconformities F-G is over 600 m thicker than elsewhere. Essentially, the section incorporates what could be regarded as an additional megasequence. Its provenance was presumably from the west and/or southwest, with sedimentation extending to the northeast as far as the developing anticline.

There are indications that the Mount Jack structure was also being uplifted at this stage, probably as a large 'positive flower structure' flanked by wrench faults.

Megasequence 7 is interpreted to correspond with the early part of the Ravendale Interval (Frasnian – Famennian). In the Bancannia Trough to the west, and around Cobar to the east, these sediments are typically red-bed facies with alluvial fans and braided stream deposits. Areas of higher reflection amplitude and continuity could indicate lacustrine deposits. It is not impossible, however, that the bands of high continuity reflections in its upper part, together with the build-ups at Mound Jack, are the result of some marine influence, presumably from the northeast. The presence of marine carbonates and shales of this age is documented in the related Adavale Basin (see Figure 5), and it is possible that the marine transgression across the mid Devonian surface (equivalent to Unconformity F; Evan's Horizon 'C' seismic marker) in the Adavale Basin may also have extended southwestwards into the Darling Basin.

Structural considerations indicate that Megasequences 7 to 2 were probably deposited within a foreland basin setting and underwent periodic compression from the northeast, together with associated wrenching.

<u>Megasequences 4-6</u> (C-D, D-E, E-F):
Megasequences 4-6 show similar characteristics; concordance/poorly-defined bottomlap at their lower boundaries and concordance/poorly-defined truncation at their upper boundaries. Internally, they comprise medium/low amplitude events that are largely continuous, but tend to become discontinuous or chaotic over more elevated areas, possibly due to energy dispersion and/or tensional fracturing. However, several higher amplitude/high continuity reflectors are present in each of these megasequences. The combined thickness of these megasequences is of the order of 2800 m.

These megasequences are also a part of the Ravendale Interval, described above. Their associated depositional environments are assumed to be alluvial fans, braided streams and lakes. The higher amplitude/high continuity reflectors that are much more common than in the overlying Megasequence 3 suggests that lacustrine deposits may have been more common in this interval. It is noted that Alder & others (1998, fig.9) show limestone/oolites within the upper part of the Ravendale Interval, implying the possibilities of short-lived marine environments.

Each of the megasequences show slight thinning over features such as that drilled by Pondie Range-1, indicating that major structures were continuing to grow through the Late Devonian, though at a lesser rate than during the time of the mid Devonian unconformity. There was probably also a small component of compaction drape within the section, created by differential compaction between the predominantly sand-prone lithology and areas with greater argillaceous deposition. There appears to be a thickening in the basal part of each of Megasequences 4-6 on the southwest flank of the structure on which Pondie Range-1 was drilled. The chaotic nature of these deposits indicates alluvial fan/braided stream-type sedimentation, downdip from the eroding crests of the growing anticlines.

Fault propagation does not seem to extend significantly above Unconformity E within most structures.

<u>Megasequence 3</u> (B-C):
This unit is characterised by low amplitude/ discontinuous reflections, is largely featureless, and with mild basal onlap evident in some locations. The megasequence is up to 1000 m thick but is absent on the crests of the main anticlines due to their deep erosion.

Megasequence 3 may correspond with the upper part of the Mulga Downs Group as mapped west of Cobar. In that area it comprises a conglomeratic unit, interpreted as a braided stream and alluvial fan deposit.

<u>Megasequence 2</u> (A-B):
Megasequence 2 lies within the noise train generated on the 'near traces' (ie. those closest to the vibration point) of the seismic records. It has a maximum thickness of 160-200 m but has been eroded from the crests of the anticlines. It is considered to be the uppermost preserved part of the Ravendale Interval.

Kanimblan Orogeny and Post-depositional Darling Basin History

<u>Late Devonian/Carboniferous Unconformity</u>:
Unconformity A separates the Late Devonian (Famennian) or earliest Carbonifeorous strata from a veneer of younger sediments that are no more than 100 m thick in the study area. It probably marks the cessation of deposition in the Darling Basin. Importantly, it was a major period of crustal shortening and 'transpression' within the Darling Basin region, followed by extensive planation of the topography.

The seismic profiles show that major fault-propagation anticlines such as the Pondie Range-1 structure, continued to grow through a period of broad basin-wide folding that occurred after the Devonian. Wrench-related features such as the Mount Jack High, were also preferentially uplifted at about this time. In the region under consideration, folds with amplitudes of 1000-1500 m were commonplace, and subsequent erosion was of similar magnitude. Whether or not faulting reached to the surface is unclear, as few faults can be resolved within the acoustically transparent Megasequences 3 & 4; however, faulting propagated upwards through the section at least as far as the 'D' unconformity.

Unconformity 'A' can best be equated to the Middle Carboniferous regional transpressional movements that were part of the coeval Kanimblan and Alice Springs

Orogenies. Following these events, renewed deposition was confined to depressions across pre-existing troughs in which Late Carboniferous to Early Permian sediments have been encountered (O'Brien, 1986; Alder & others, 1998). These sediments, which are restricted in area, include interbedded mudstones, siltstones and sandstones, diamictites of glacial origin, and marginal marine shales. There is no clear evidence that these sediments are represented in the area under consideration, though they were intersected in the Ivanhoe-1, Blantyre-1 and Wentworth –1 wells.

<u>Megasequence 1</u>:
This sediment veneer is just detectable on the seismic profiles and seems to be about 100 m thick. Penetration of this unit in Pondie Range-1 indicates that it comprises about 70 m of Cainozoic sands, gravel and clay, lying directly over the Late Devonian. Neither the Early Carboniferous to Early Permian mentioned above, nor outliers of marine Cretaceous sediments from the Eromanga Basin to the south, appear to be represented in seismic data from the Pondie Range area. This sediment veneer is north of the Murray Basin proper (Brown & Stephenson, 1991) but may reflect deposition within the ancient Darling River floodplain.

Summary of Structural Evolution

The Pondie Range Trough – Mount Jack area is underlain by a basement complex that probably comprises Proterozoic to Early Palaeozoic rocks related to either the Kanmantoo and Broken Hill Blocks, and/or Lachlan Fold Belt. The extent to which each of these terranes occur under that part of the Darling Basin cannot readily be determined from this study; however, recent seismic imaging on a 160 km transect through the northern part of the basin may help to resolve the issue. In the study area, these basement rocks show clear evidence that they were extensively folded and faulted during an extended history, prior to formation of the Darling Basin.

The Pondie Range Trough is one of several extensional features that formed in the latest Silurian and Early Devonian. It appears to have been a southwest or southward deepening half-graben with its primary bounding fault coinciding with what is now the master fault of the Pondie Range Structure. This fault appears to flatten out into a detachment plane, interpreted within the basement at about 12 km depth (Plate 1). The extensional regime was predominant through the early part of the Devonian when the half-grabens deepened and filled with sediments that may have included marine source rocks. The northeast trending Darling River lineament which cuts through the region may have acted as transfer fault offset at about this time. The syn-rift phase of basin formation was followed in the late Early Devonian (from 401-384 Ma) by extensive erosion and planation of the half-graben deposits and the flanking basement. It coincides with Cobar Basin inversion (Glen, 1991) and milder inversion of early Darling Basin troughs at this time (Glen & others, 1996). This widespread event correlates with the Bindian/Bowning Movement and the Tabberabberan Orogeny which may represent a continuum in this region.

A thermal 'sag phase' of basin development ensued during the early Middle Devonian (Perkins & others, 1994). This age is based on the timescale of Young & Laurie (1996).

A set of north-northwest to northwest-trending thrust faults (NSWMR, 1994) and associated northeast trending wrench faults, started to form in the mid Devonian, creating minor inversion of the basin's 'layer cake' sag phase geology. From this time, the stress field was largely compressional or transpressional, with the azimuth of shortening probably in a northeast-southwest sense. This event led to reversal on the main Pondie Range normal fault and elevated the Mount Jack area as a 'positive regional flower structure'. Again, the Darling River Lineament may have been an active transfer fault, but during this phase would have separated compressional rather than extensional compartments. This style of tectonics persisted through the Late Devonian and into the Early Carboniferous, and compressional pulses can be recognised by further inversion, erosion, and flank deposition on features such as the Pondie Range Structure.

The overall regime, following the thermal subsidence phase, is interpreted as attributable to a foreland basin, with plate convergence taking place to the east or northeast of the Darling Basin. This situation culminated in the Middle Carboniferous with extensive inversion and erosion coeval with the Kanimblan or Alice Springs Orogenies. From that time on, there appears to have been only residual local subsidence and compaction, with deposition of younger sediments in reactivated troughs, preceding deposition of a widespread veneer of Murray Basin and equivalent age sediments.

Geological History (Table 3)

Age	Event	Environment	Correlation	Megasequence	Comment
Precambrian & Early Palaeozoic	Pre-Darling Basin	Cratonised basement with folding and thrust faulting	Broken Hill Block, Kanmantoo & Lachlan Fold Belts	12	Basement complex of various ages.
				Unconformity L	Appears to correspond to the 'A' Horizon of Evans (1977).
Latest Silurian – earliest Devonian (Pragian)	Initiation of Darling Basin/ ?Early syn-rift extension	Alluvial fan deposition predicted in traditional models, but possibly marginal marine in this case		11	The widespread initiation of half-grabens cannot be proven conclusively from the seismic profiles but the Pondie Range & Tilba-Nelyambo Troughs appear extensional.
Earliest Devonian	Extensive faulting and erosion of basement			Unconformity K	
Early Devonian (Pragian)	Syn-rift phase	Marginal marine – marine wedge	Winduck Interval (Amphitheatre Group)	10	Mound-like structure along NE edge of Pondie Range Trough.
				Unconformity I	
Late Early Devonian (?latest Pragian)	Syn-rift/ late rift fill	Probably marine	Upper Winduck Interval	9	Probably remnants of a marine transgression that covered the entire Devonian basin region.
Late Early Devonian (~Emsian) 401-384 Ma	Extensive erosion and planation of extensional rift phase		Cobar Basin inversion to relaxation	Unconformity H	Corresponds to the 'B' Horizon of Evans (1977). Probably Bindian/Bowning Movement and also including Tabberabberan Orogeny. Duration: Perkins & others, 1994.
Early Middle Devonian (Eifelian)	Commencement of thermal sag phase	Probably red-bed: braided streams and alluvial fans	Snake Cave Interval (Mulga Downs Group)	8	?Brackish – marine incursion in Scopes Range area (Alder & others, 1998). Some continued normal fault movement on Pondie Range Structure.
Mid Devonian	Crustal shortening/probable 'transpression', initiation of fault propagation anticlines			Unconformity G	'C' Horizon of Evans (1977). Pondie Range Anticline and fault reversal. Development of Mount Jack Structure. Erosion of the structurally elevated areas.
Late Devonian (?Frasnian)	?Foreland basin, some continued growth on anticlines etc	Fluvial red-bed facies, but possible minor marine influence in places	Lower part of Ravendale Interval (Mulga Downs Group)	7	Marine carbonates and shales of this age occur in Adavale Basin. 600 m thickening SW of Pondie Range fault. 'Build-up' observed on seismic profiles in Mount Jack area.
Late Devonian (?Famennian)	Largely layer-cake with some differential compaction	Red-bed facies: alluvial fans, braided streams and lacustrine.	Upper part of Ravendale Interval (Mulga Downs Group)	2-6	Alder & others (1998) show limestone/oolites in upper part of Ravendale Interval, but these could possibly be calcretes. Fault propagation to Unconformity E.
Middle Carboniferous	'Transpression' and broad folding, uplift and planation, within ?foreland setting			Unconformity A	Kanimblan or Alice Springs Orogeny. Main phase of structural development of Darling Basin section.
Early Permian	Residual local subsidence and compaction	Glaciomarine and marginal marine			Post-Darling Basin. Restricted deposition in reactivated troughs that may not be represented in Pondie Range area.
Cretaceous	Widespread transgression	Marine			Limited Eromanga Basin deposition.
Cainozoic		Fluvial sands, gravels and clay		1	Murray Basin and equivalent veneer.

Hydrocarbon Plays and Leads

There have been only a few hydrocarbon shows stemming from exploration in the Darling Basin. The most notable of these have been in the Bancannia Trough to the west of the area considered herein. Gas shows and bitumen traces were reported in Bancannia South-1 by Planet Oil Company, from Late Devonian sandstones that are equivalent in age to the Mulga Downs Group. Minor gas shows were also encountered in Jupiter-1 and Bancannia North-1, and methane of unknown origin has been detected in several water bores around the flanks of the basin (Sharpe & McLaughlin, 1986).

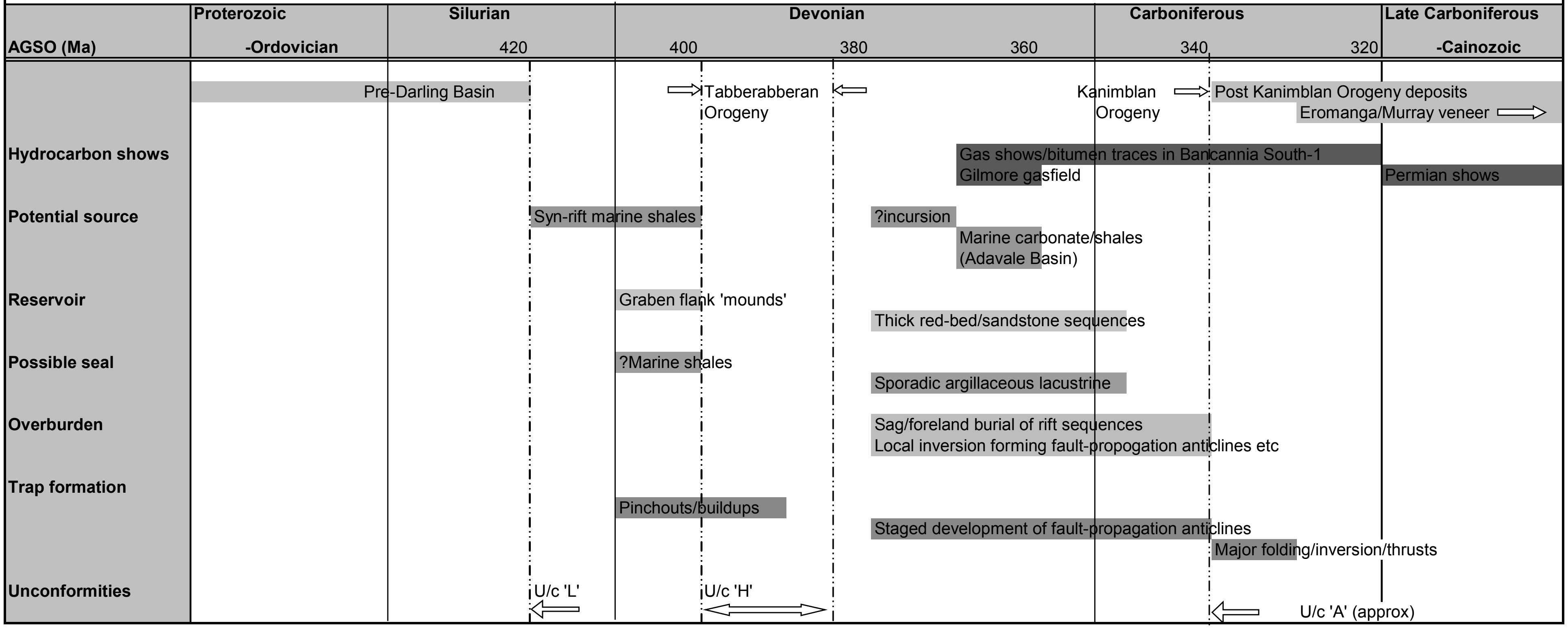
The impetus for continued gas exploration in the Darling Basin comes from an analogy of the Darling Basin stratigraphy with that of the Adavale Basin in Queensland, and the likelihood that the Devonian sequences now preserved in eastern Australia are largely structural remnants of a much more extensive Devonian basin. In the Adavale Basin, commercial quantities of gas have been discovered in the Gilmore Gas Field, reservoired in the Bury Limestone, a unit within a mid-Devonian transgressive sequence (Shaw, 1995; Boreham & De Boer, 1998). Gas with similar isotopic composition to that in the Adavale Basin is known from water bores in the Darling Basin region (Alder & others, 1998).

Potential source rocks in the Pondie Range Trough and nearby areas are most likely to occur in the latest Silurian and Early Devonian sequences that make up the syn-rift and rift-fill phases of basin development (Megasequences 9-11; Table 4). Seismically, these sediments have many of the characteristics of a marginal marine to deepening marine section, in that they are basin thickening wedges with high reflection continuity and with possible build-ups along the margin of the depocentre. Some additional source rocks could be present in the early Middle Devonian (~Eifelian) during the beginnings of what appears to have been the start of the basin's 'sag phase': these being indicated by a brackish to marine incursion reported from the Scopes Range area (Alder & others, 1998) (Megasequence 8). Darling Basin rocks of Late Devonian (?Frasnian) age that make up Megasequence 7, are approximately time equivalent to those that produce gas in the Gilmore field. They form part of what may constitute a foreland loading episode in the Darling Basin's history. A minor marine incursion may have occurred at this time, and the presence of possible build-ups within Megasequence 7 may be indicative carbonate deposits associated with such a transgression.

In general, the largely Early Devonian marine sediments appear to be equivalent to sediments penetrated in the Berangabah-1, Kewell East-1 and BMR Ivanhoe-1 exploration wells, the last having TOC values of up to 0.98 per cent.

Potential sandstone reservoirs in the basin are plentiful, and porosities and permeabilities encountered in several exploration wells have been remarkably high (Alder & others, 1998), even in view of the high seismic velocities and the relatively great age of the rocks. In Blantyre-1 for example, porosities of 18-19 per cent, and permeabilities of over 1000 mD, were encountered at the 2000 metre (near TD) level.

Table 4. Darling Basin Event Chart for Potential Hydrocarbon Accumulation



The presence of suitable 'seal rocks' is likely to be a significant problem in the Darling Basin. Much of the Devonian section, particularly the Middle and Late Devonian, is composed of a sand-prone red-bed facies with high permeability. Effective seals would most likely have to come from argillaceous/carbonate layers associated with any short-lived marine transgressions or areally restricted lacustrine deposits.

There are numerous structures in the region that appear to have the potential to form hydrocarbon traps. In general, the most obvious are the large ?wrench-related fault-propagation anticlines of the type on which Pondie Range-1 exploration well was drilled (Plate 1, Line HD-106). Another major feature is the Mount Jack thrust complex that appears to be a regional 'positive flower structure' resulting from wrenching. Although the major faults that bound these structures may have provided suitable conduits for any migrating hydrocarbons, the continual development of many of the structures through the Devonian and Early Carboniferous, and the propagating nature of the fault systems, means that there is a high probability that traps have been breached and that hydrocarbons have leaked out. This scenario, together with reports that in the early stages of exploration many prospects were drilled off-structure, could account for the lack of exploration success. Assuming that there is a viable source in the area and adequate migration pathways, the more subtle structures that show no evidence of late faulting are recommended.

Six potential hydrocarbon plays and leads have been recognised within the northern part of the Darling Basin (Pondie Range Trough area) based on this seismic interpretation (Plate 2). Whether or not these are viable plays will depend to a large extent on the presence of a generative source and timely migration of any hydrocarbons into the traps. The gas shows and bitumen traces are encouraging aspects, but source and timing are the most critical unknown factors in further exploration of the Darling Basin.

Play/Lead Type I (fault-propagation anticlines)

Trap style:	Major wrench-related fault-propagation anticlines (yellow on Plate 2).
Example:	Pondie Range Structure (Line HD-106, SW end).
Source:	Largely latest Silurian – Early Devonian syn-rift /rift-fill marine sequences in the Pondie Range Trough (Megasequences 9-11). Possible contribution from any Middle Devonian marine incursion sequences (Megasequence 8) Adavale Basin equivalents.
Reservoir:	Sandstones within Late Devonian red-bed facies.
Seal:	Unknown: possible argillaceous lacustrine layers.
Trap timing:	Mid Devonian – Early Carboniferous.
Migration paths:	Up-dip intrabedding; main boundary fault; antithetic faults.
Assessment:	No success in drilling on this type of structure so far, possibly due to progressive trap breaching and hydrocarbon leakage to surface.

Play/Lead Type II (anticlines unaffected by faulting)

Trap style:	Anticlines that appear to be uneffected by faulting (brown on Plate 2).
Example:	(Line HD-104, SSE end).
Source:	Possible latest Silurian – Early Devonian syn-rift /rift-fill marine sequences (Megasequences 9-11). Possible contribution from any Middle Devonian marine incursion sequences (Megasequence 8) and Late Devonian Adavale Basin equivalents (Megasequence 7).
Reservoir:	Sandstones within Late Devonian red-bed facies.
Seal:	Unknown: possible argillaceous lacustrine layers.
Trap timing:	Mid Devonian – Early Carboniferous.
Migration paths:	Possible lateral migration within Megasequences 7 and 8. Remote chance of lateral migration from Pondie Range Trough.
Assessment:	The specific lead identified (Line HD-104), is a relatively large structure, with little possibility of breaching by faults. However, the potential source is more remote than for Type I, and the migration pathways are more tenuous.

Play/Lead Type III (regional 'flower structures)

Trap style:	Complex regional 'positive flower structure' incorporating pinchouts, anticlinal features, wrench-related 'pop-ups', and possible overthrusts (red on Plate 2).
Example:	Mount Jack thrust complex (eg. Line HD-101, ENE half).
Source:	Possible thick section of latest Silurian – Early Devonian syn-rift /rift-fill marine in depocentre to the ?north. Possible contribution from any Middle Devonian marine incursion sequences (Megasequence 8) and Late Devonian Adavale Basin equivalents (Megasequence 7).
Reservoir:	Sandstones within Late Devonian red-bed facies; pinchout beds within Early Devonian; ?build-ups within Megasequences 7 and 8.
Seal:	Unknown: possible argillaceous lacustrine layers.
Trap timing:	Mid Devonian – Early Carboniferous.
Migration paths:	Up-dip from ?northern depocentre; thrust faults; wrench faults.
Assessment:	This is a highly complex area that would require detailed mapping to isolate the individual structures. No success in drilling this feature with Mount Jack-1 (offset), possibly due to trap breaching and potential hydrocarbon leakage to surface.

Play/Lead Type IV (low-relief compaction anticlines)

Trap style:	Small low-relief anticlinal closures possibly created by differential compaction (blue-green on Plate 2).
Example:	Over ENE end of Pondie Range Trough (Line HD-106).
Source:	Largely latest Silurian – Early Devonian syn-rift /rift-fill marine sequences in the Pondie Range Trough (Megasequences 9-11). Possible contribution from any Middle Devonian marine incursion sequences (Megasequence 8) and Late Devonian Adavale Basin equivalents (Megasequence 7).
Reservoir:	Sandstones within mid Devonian ?marine incursion, and Late Devonian red-bed facies.
Seal:	Unknown: possible argillaceous lacustrine layers.
Trap timing:	?mid to Late Devonian.
Migration paths:	Updip through syn-rift section, into mid Devonian thrust and antithetic faults.
Assessment:	This type of play is promising, although the structures appear to be relatively small in vertical closure and are probably also areally small. Structural traps are postulated at levels ranging from the 'C' to 'G' unconformities, and these are not likely to be breached by faults. Further, these structures lie above the pinchout edge of the syn-rift ?marine section and short-range migration pathways can be envisaged. Leads lie within a drillable depth range of approximately 1300 to 4000 m.

Play/Lead Type V (sedimentary build-ups)

Trap style:	Possible sedimentary 'build-ups' along (i) the updip pinchout edge of the syn-rift ?marine section under the 'H' unconformity, and (ii) on the flank of the Mount Jack structure within Megasequences 7 and 8 (purple on Plate 2).
Example:	(i) Line HD-106, NNE end and (ii) Line HD-101.
Source:	(i) Possible latest Silurian – Early Devonian syn-rift /rift-fill marine sequences (Megasequences 9-11), (ii) Late Devonian (?Frasnian) marine incursion.
Reservoir:	Possibility of carbonate build-ups.
Seal:	Unknown: possible argillaceous lacustrine layers.
Trap timing:	(i) late Early Devonian at later stages of syn-rift deposition and, (ii) Late Devonian (?Frasnian).
Migration paths:	Lateral/updip along respective bedding.
Assessment:	These build-up structures are worthy of further investigation, particularly the shallower ones at Mount Jack, as carbonates are known from the Adavale Basin. The build-up on the edge of the Pondie Range Trough syn-rift section is at about 5000 m and is probably beyond economically drillable depths.

Play/Lead Type VI (pinchouts)

Trap style:	Fault dependant and pinchout traps along the NNE side of the Pondie Range Trough (green on Plate 2).
Example:	(Line HD-106, NNE end).
Source:	Possible latest Silurian – Early Devonian syn-rift /rift-fill marine sequences (Megasequences 9-11).
Reservoir:	Sandstones within Late Devonian red-bed facies.
Seal:	?Marine shales or argillaceous lacustrine layers.
Trap timing:	Early Devonian.
Migration paths:	Updip/interbed within syn-rift section of Pondie Range Trough.
Assessment:	These traps seem to be favourably positioned with respect to any hydrocarbon migration from the ?marine syn-rift section. The main disincentive is their considerable depths that range from about 4500 to 5000 m.

Exploration on Type II and IV Plays

The lack of exploration success may result directly from the sparsity of seismic control. This has given rise to well locations that, in many instances, seem to be outside of structural closure. However, it is also speculated that the larger and more obvious structures on which the wells have been drilled, principally the fault-propagation anticlines (Type I play/leads), could have been subject to leakage. Hence, it is considered that other plays/leads that are less fault-dependent and less likely to have leaked potential hydrocarbons, may make more viable exploration targets.

Given the great thickness of Middle to Late Devonian strata, any petroleum generation is most likely to have taken place during the foreland depositional phase. Structures were being formed during that period, prior to major deformation resulting from the Kanimblan and Alice Springs Orogenies. Petroleum is most likely to have been preserved in places distant from the Kanimblan (largely fault-breached) structures. In the related Adavale Basin, the presence of the Gilmore field demonstrates that mid-Devonian petroleum can survive Kanimblan deformation (Boreham and De Boer, 1998). It would thus appear that any structures not reactivated during the Kanimblan event would probably provide the best potential in terms of entrapment timing and generation/migration.

The largest of these plays is the Type II anticline/rollover on Line HD-104 (shown in brown on Plate 2). If this lead were proven to be a closed structure with seal, any hydrocarbons trapped within it are unlikely to have leaked to surface, as it appears to be uncomplicated by faulting. Also, in terms of the cost of drilling, it has the advantage of lying at relatively shallow depths (extending from near surface to about 4000 m). Its major disadvantage is the tenuous nature of potential migration pathways from any marine section in the Pondie Range Trough.

It is considered that the compaction closures designated as Type IV plays/leads (blue-green in Plate 2) may provide a lower risk alternative, since potential migration pathways appear more favourable. However, since these tend to be somewhat deeper in the section (depths of 1300 to 4000 m) the economic feasibility of drilling them will be strongly dependent on estimated reserves. A basic estimate, using what are considered to be conservative input parameters and the following assumptions, is provided below:

- The length of the observed structures are assumed to be twice their width as indicated on 'dip lines',
- They are assumed to be rectangular in area,
- Vertical closures are estimated from amplitudes in twt, together with the associated stacking velocity,
- Porosity is taken to be 15% which is typical of that in many of the existing exploration wells,
- Other assumptions made were:
    - water saturation of 50%,
    - gas flow volume factor (GFVF) of 128,
    - a recovery factor of about 70% for gas.

Table 5. Reserve Estimate for Type IV Leads

Structure	Width km	Length 2 x width	Area km^2	Net Pay m	ϕ	$1-S_w$	GFVF	Recovery	Reserves $10^6 m^3$ (BCF)
Upper Type IV U/c C	3	6	18	4	15	0.50	128	0.7	484 (17 BCF)
Lower Type IV U/c G	7.5	15	112	12.5	15	0.50	128	0.7	9450 (334 BCF)

The above calculation indicates that Type IV structures as interpreted on Line HD-106 could theoretically produce from about 484 – 9450 x $10^6 m^3$ (that is, 17 – 334 BCF) of gas based on fairly conservative assumptions. On this basis, they could probably be considered as viable exploration targets.

Conclusion

A coherent evolutionary history of the Darling Basin, in the Pondie Range Trough – Mount Jack area near Wilcannia, has been deduced from the seismic interpretation. In general, the interpreted seismic megasequences are consistent with pre-basinal, syn-rift/rift fill, thermal sag phase, foreland loading, and post-Darling Basin veneer, phases of basin development. Their reflection characteristics and external form allow depositional environments to be predicted in a broad sense. These include marine deposition and the presence of potential source units in a latest Silurian – Early Devonian syn-rift half-graben, the Pondie Range Trough. The megasequences have been correlated with the previously recognised Amphitheatre Group and Winduck, Snake Cave, and Ravendale Intervals.

Major structural breaks that correlate with the Early Devonian Tabberabberan and Middle Carboniferous Kanimblan/Alice Springs Orogenies are clearly present. This has allowed the structural history, particularly the growth of major fault propogation anticlines such as the Pondie Range Structure, to be deduced.

Of the six hydrocarbon plays/leads that have been envisaged, it is the leads that are least affected by faulting that are considered the most promising for exploration. Of these, low-relief compaction drape anticlines (Play/lead Type IV) that lie over the flank of the Pondie Range Trough, with its potential source rocks, are highly rated. These leads lie at depths of 1300 to 4000 m and potentially could have sufficient gas reserves to make them viable targets.

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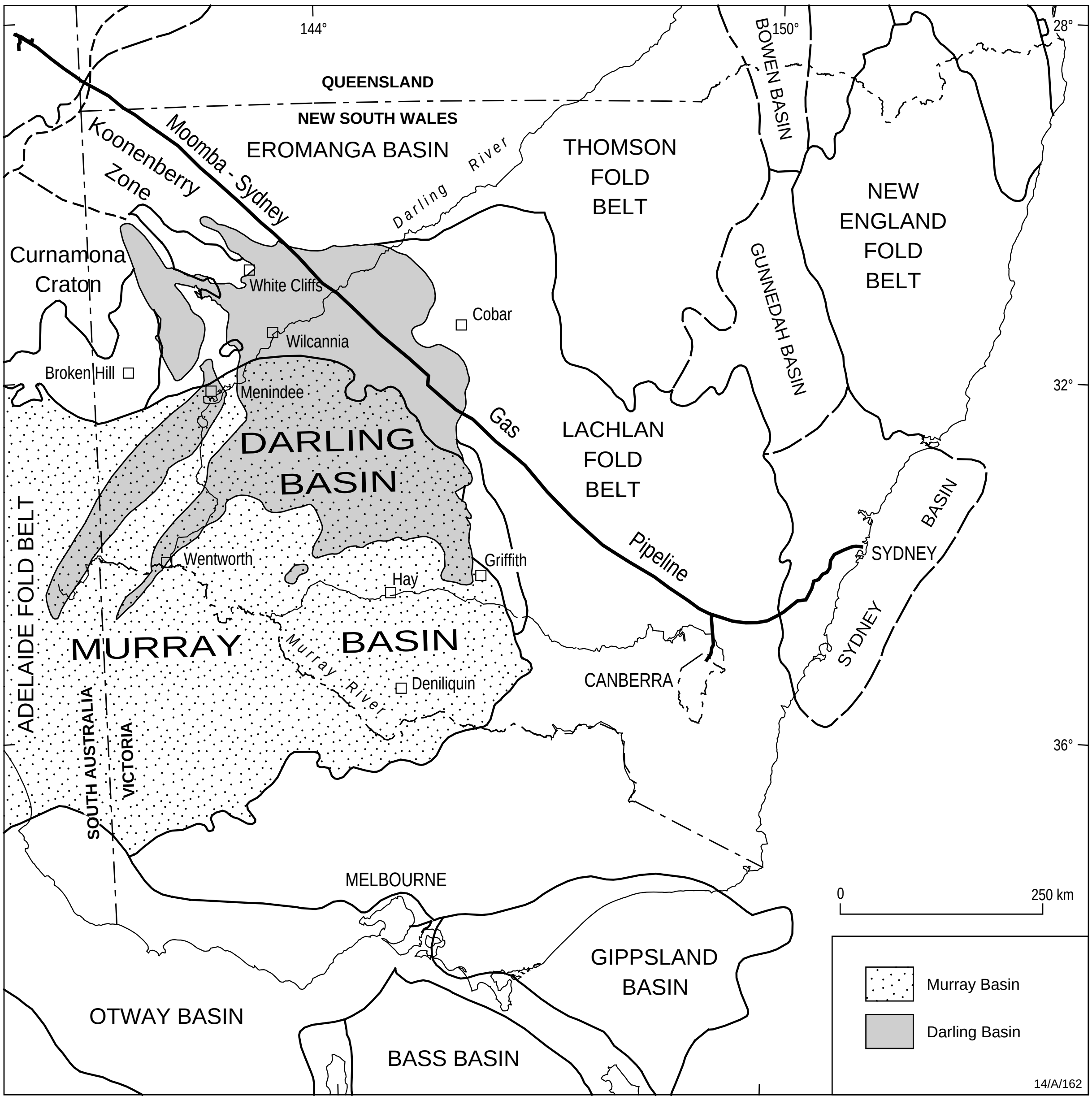


Figure 1. Darling Basin location map showing relationship to surrounding geological provinces.

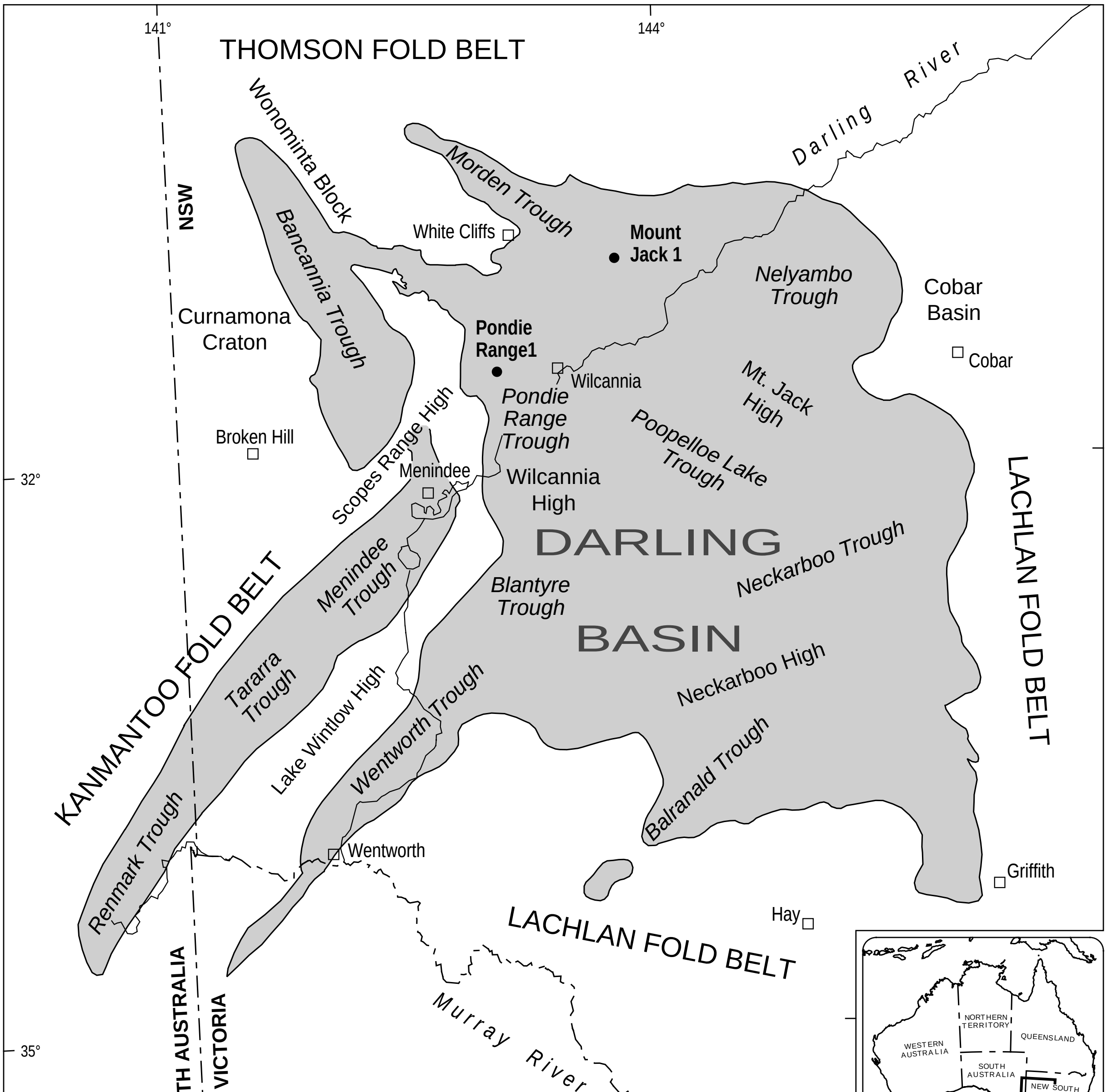
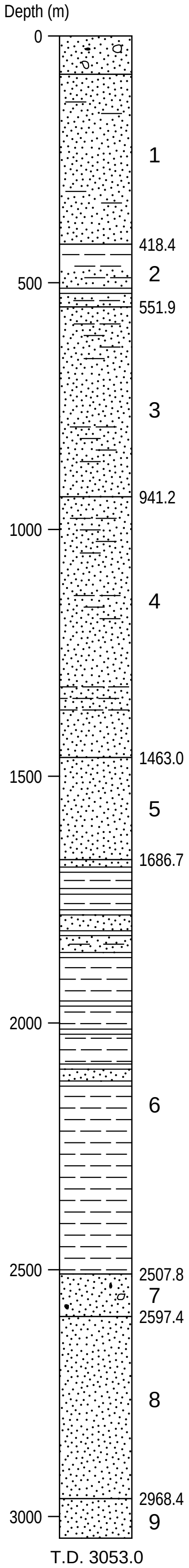


Figure 2. Darling Basin structural elements.



PONDIE RANGE 1

143° 06' 46" E
31° 28' 35" S
K.B. 94.5m - G.L. 90.5ma.m.s.l.

Age	Rock Unit	Tops (m) KB.	Tops (m) Sub-sea	Thickness (m)
TERTIARY	Un-named sands, minor gravel and clay	10.6	+ 83.9	69.9
UPPER DEVONIAN	UNIT 1 Sandstone, minor siltstone, claystone	80.5	+ 14.0	334.9
	UNIT 2 Siltstone, minor sandstone, claystone	415.4	- 320.9	136.5
	UNIT 3 Sandstone, minor siltstone	551.9	- 457.4	289.3
	UNIT 4 Sandstone, conglomerate, minor siltstone	841.2	- 746.7	621.8
	UNIT 5 Sandstone	1463.0	- 1368.5	223.7
	UNIT 6 Siltstone, shale	1686.7	- 1592.2	821.1
	UNIT 7 Conglomeratic sandstone	2507.8	- 2413.3	89.6
	UNIT 8 Sandstone, rare siltstone	2597.4	- 2502.9	359.0
PROTEROZOIC	UNIT 9 Sandstone	2956.4	- 2861.9	96.6 +

Status: Plugged and abandoned
Hydrocarbons: Nil
Drill Stem Tests: 4, Open hole
DST 1, 593.0 - 611.4m (porosity test) — Rec 33.5 m mud muddy water
DST 2, 731.8 - 746.8m (porosity test) — Rec 54.8 mud 393.1 m muddy water Formation water : 14830 ppm
DST3, 2144.2 - 2165.6m (test of increased drilling rate interval) — Rec 256.0m mud (packer failed)
DST3A, 2142.7 - 2165.6m — Rec 192.0m mud (packer failed)
DST4, 2173.8 - 2182.3m (test of interval of rapid drilling) — Rec. nil (packer failed)
Temperature Survey 152.4 - 1332.5m

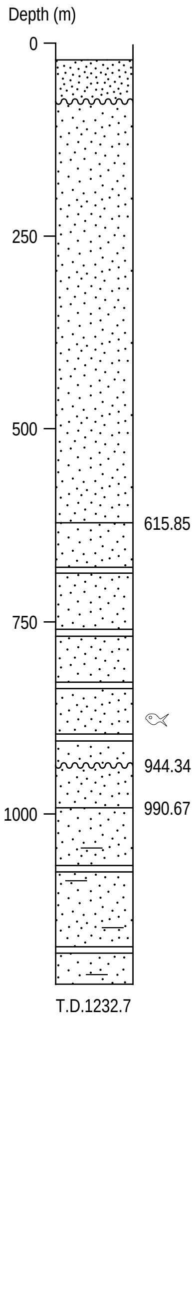
Cores: 24 cut
Fossils: Spores (Du or Cl)
Fish (Du) at 449.2 and 450.3m, in core No.3
Fish (Du) at 903.7m in Core No.5
No other fossils
Sidewall Cores: 79, recoveries in 33
E - Logs: IES, Microlog - Caliper, Gamma - Sonic, Dipmeter

14/A/209

Figure 3. Pondie Range-1 exploration well stratigraphic table (after Department of Mineral Resources, New South Wales, 1993).

MT. JACK No. 1

143° 45' 02"
30° 51' 03"
G.L. 183 m (approx.).

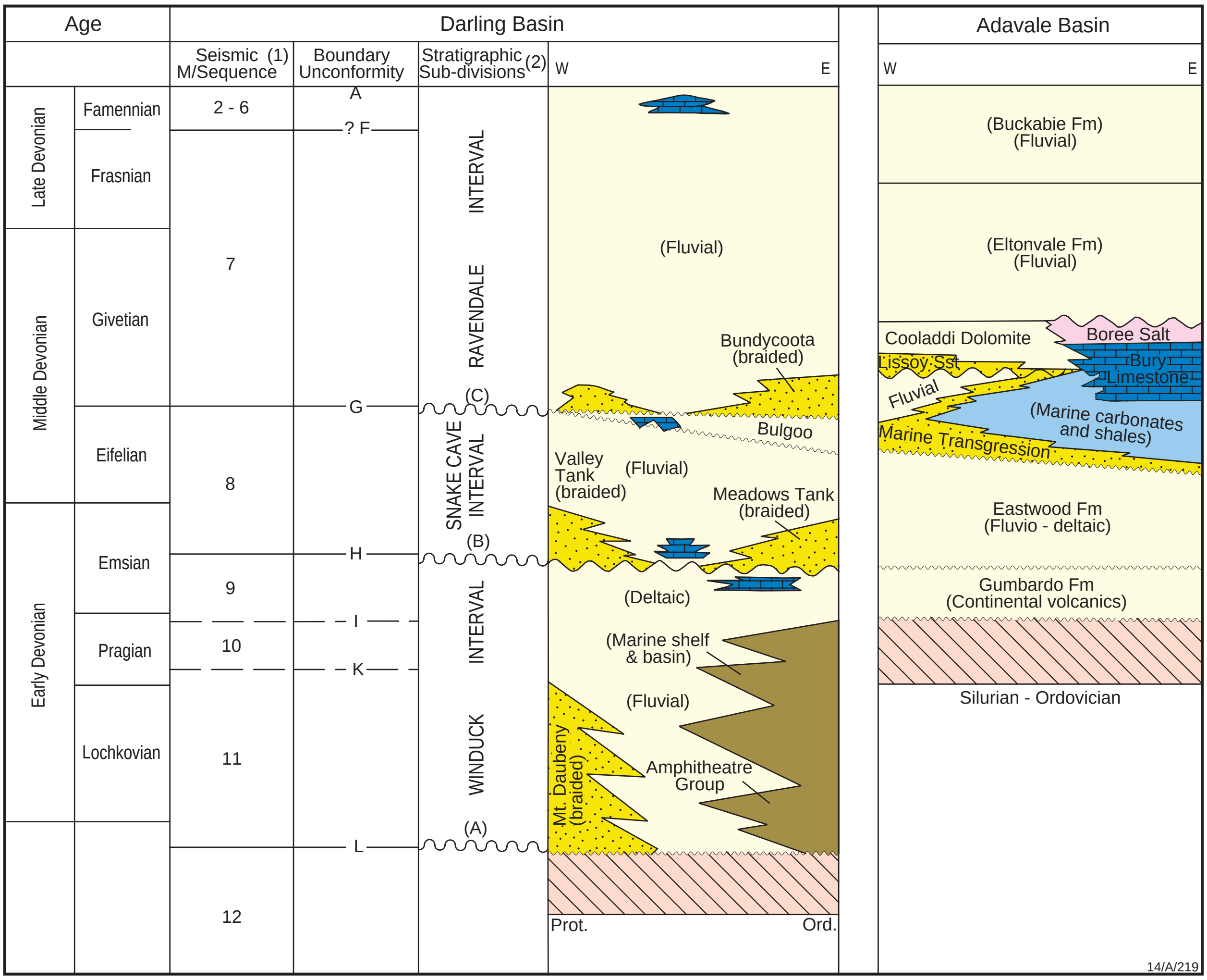


Age	INTERVAL (m)	THICKNESS (m)	LITHOLOGY
	sfc - 4.5	4.5	Sand
	4.5 - 615.8	611.3	Red - brown, fine to medium grained quartzite with interbedded dark - brown shale
	615.8 - 944.3	328.5	Red - brown, fine to medium - grained quartzite and sandstone with inclusions and bands of dark - brown shale
	944.3 - 990.7	46.4	Red - brown, grey, whitish grey, fine to medium grained flaggy sandstone and quartzite; minor brown shale. Fish fragment at 895 m
	990.7 - 1232.7	242.0	Dark grey - brown fine to medium - grained hematitic tuffaceous quartzite. bands of dark - brown shale; siltstone (After Rade)

14/A/210

Hydrocarbons: Nil
Located on north flank of
Mt. Jack Anticline
Dips: 6° - 9° NNE in cores
35° - 85° near faults
Quartzite is diagenetic

Figure 4. Mt. Jack-1 exploration well stratigraphic table (after Department of Mineral Resources, New South Wales, 1993).



(1) *Approximate age of seismic sequences identified in this report*

(2) (A), (B) *and* (C) *are the original seismic horizons of Evans (1977)*

Figure 5. Darling Basin and Adavale Basin stratigraphy showing the approximate relationship to seismic sequences and bounding unconformities identified in this study (modified from Alder & others, 1998).

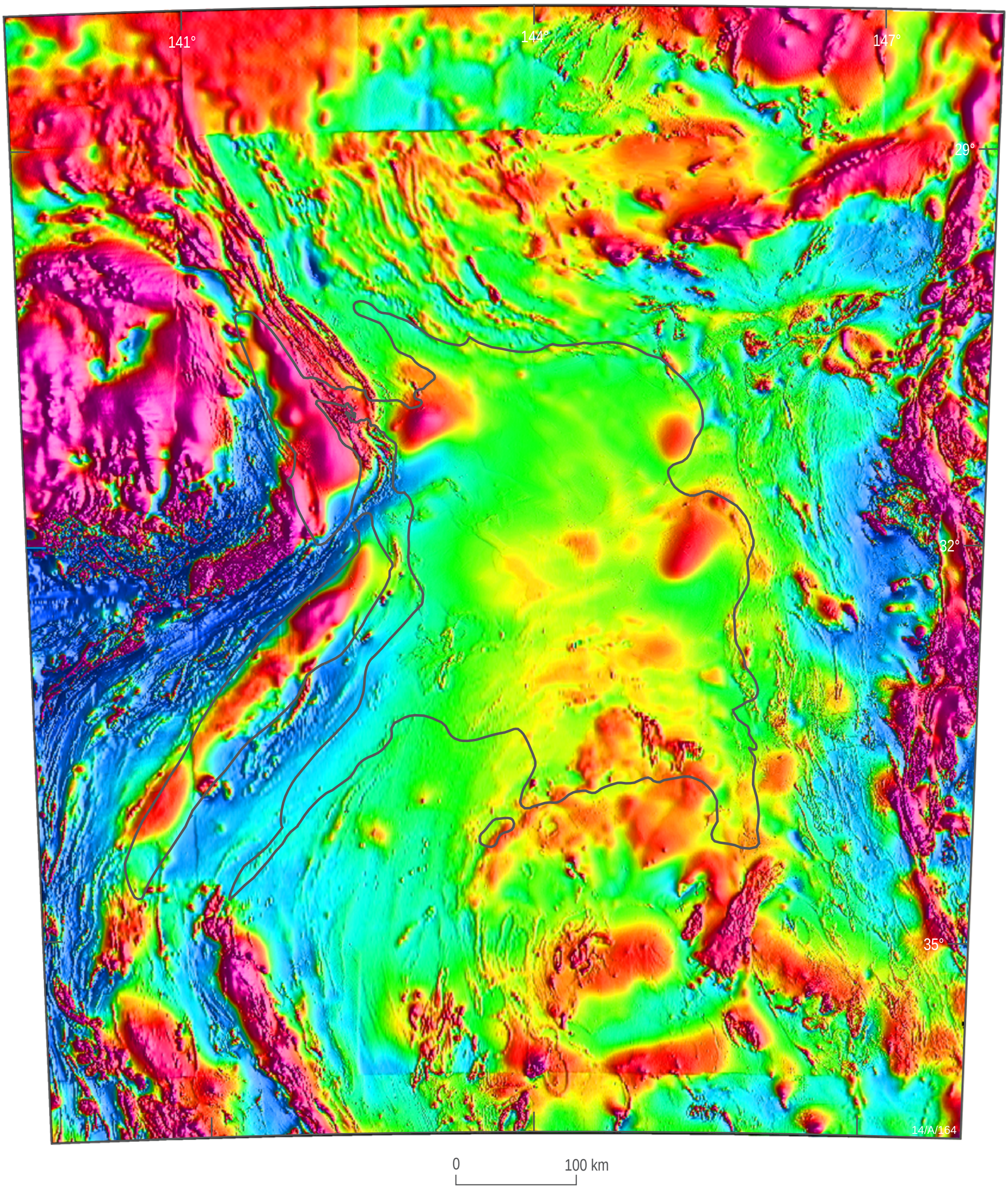


Figure 6. Image of the total magnetic intensity with a northeast illumination. The extent of Darling Basin sediments are shown (black line) as well as the positions of the depth to magnetic source estimates generated by the AutoMag process.

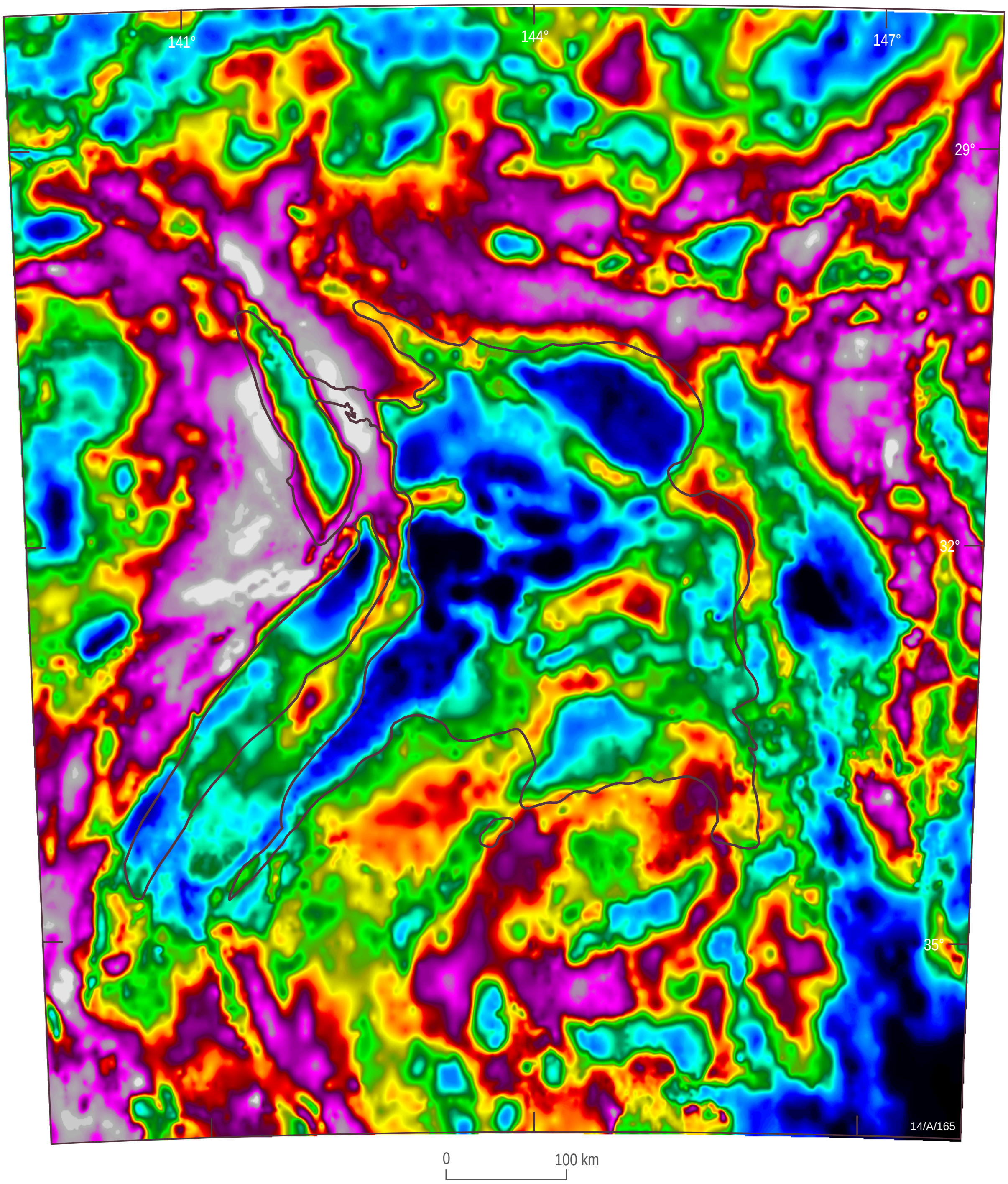


Figure 7. Image of the Bouguer Anomaly gravity field. The extent of the Darling Basin sediments are shown (black line) as well as the major structural elements.

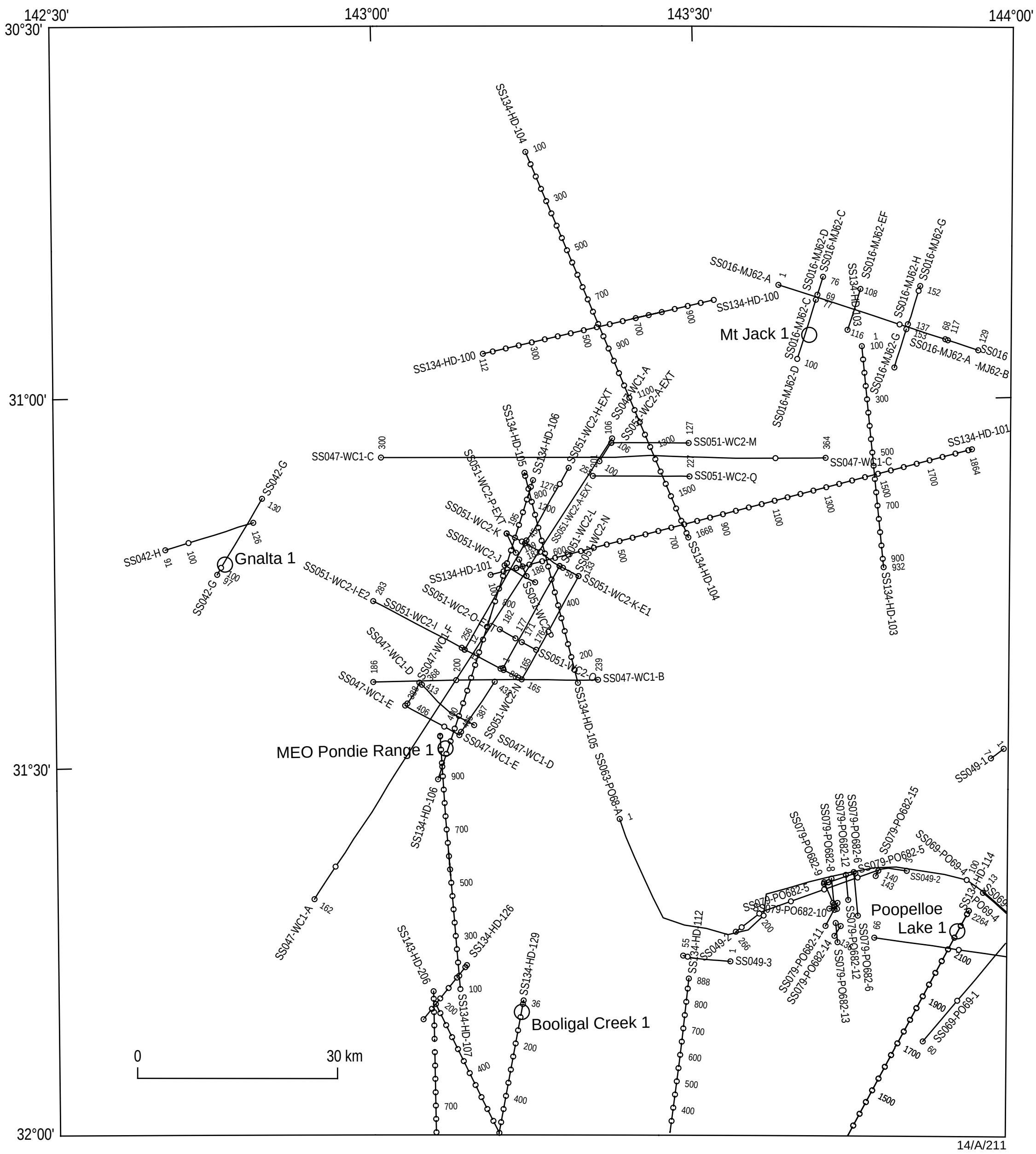


Figure 8. Location of all seismic reflection lines in the Pondie Range-Mount Jack area.

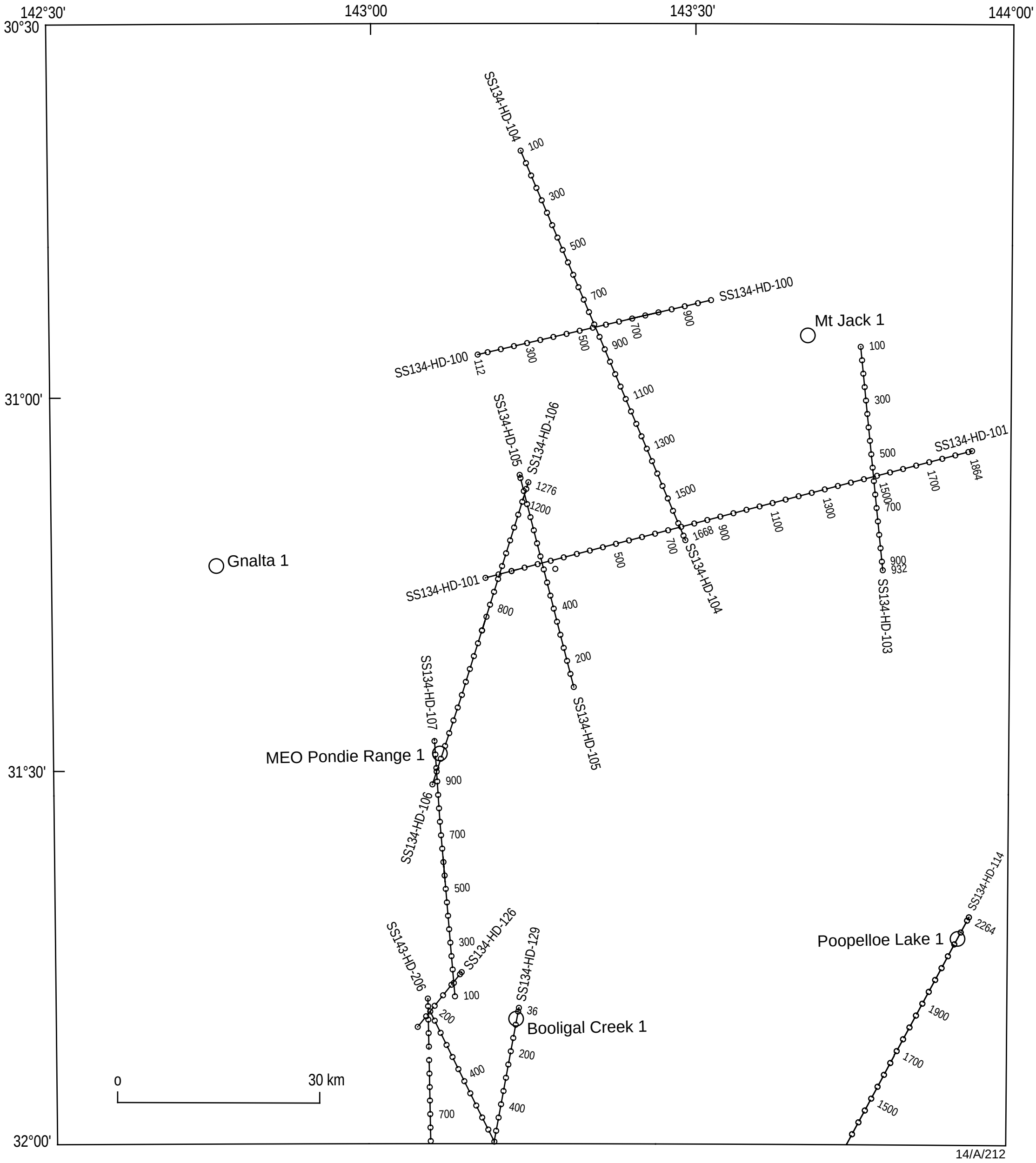
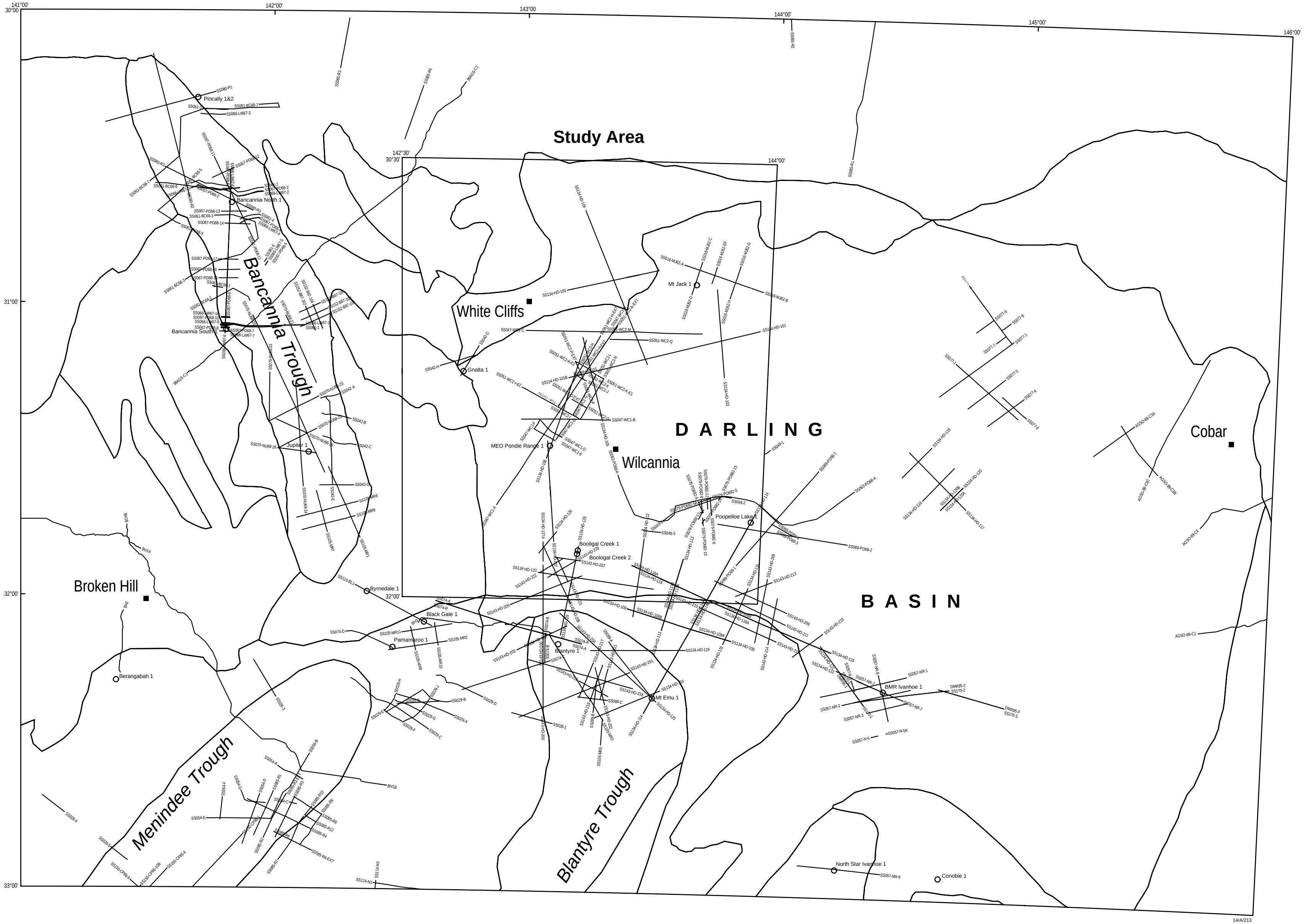


Figure 9. Location of BHP seismic reflection lines in the Pondie Range-Mount Jack area, interpreted herein.



Petroleum wells (depths in metres below K.B.)

Structural Elements (after A.N.Yeates)

HD-120 Seismic lines

0 20 40 60 80 100 km

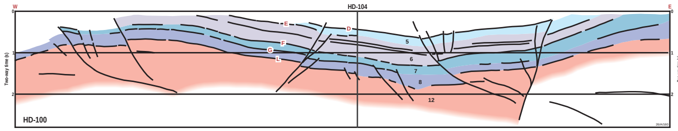
UNIVERSAL TRANSVERSE MERCATOR PROJECTION
AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 141 00 00 E

GEOSCIENCE AUSTRALIA

PLATE 1 : Map of the Darling Basin showing location of seismic lines, petroleum exploration wells and basin boundaries

J.B. Willcox, A.N. Yeates, A.J. Meixner & R.D. Shaw

Geoscience Australia Record, 2003/05

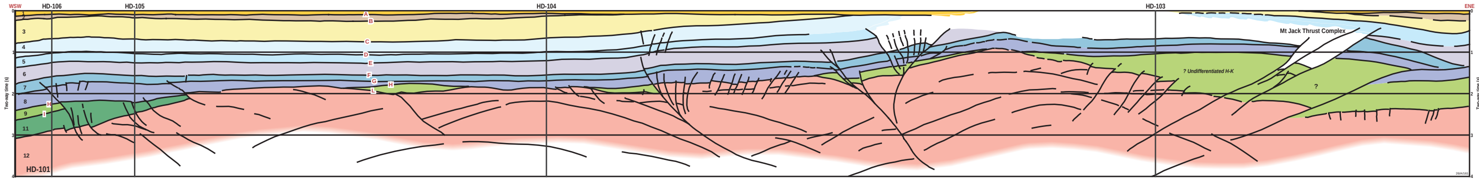


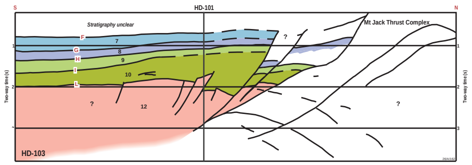
GEOSCIENCE AUSTRALIA

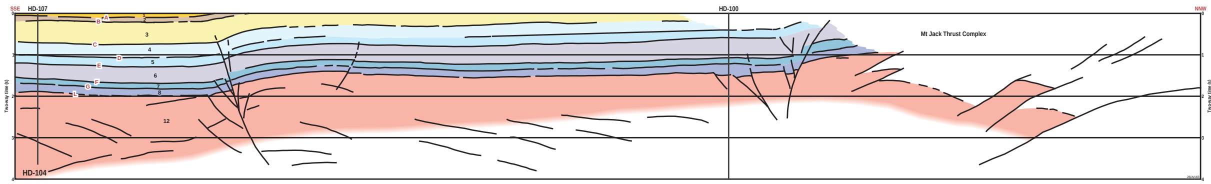
PLATE 2 : interpretation of seismic profiles in the Darling Basin
Pondie Range trough - Mt. Jack area

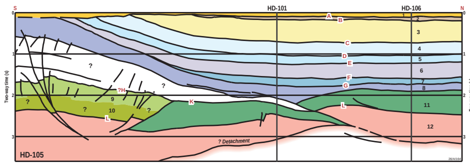
(BHP Lines HD100 - 107)

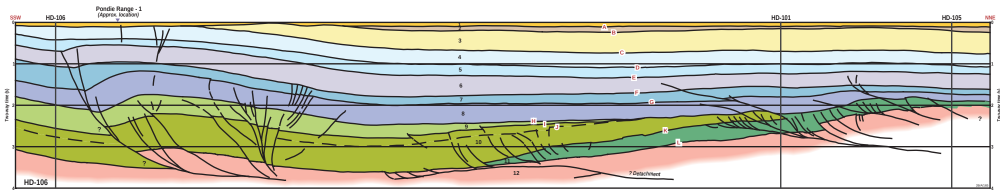
J.B. Willcox, A.N. Yeates, A.J. Meixner & R.D. Shaw
Geoscience Australia Record, 2003/05

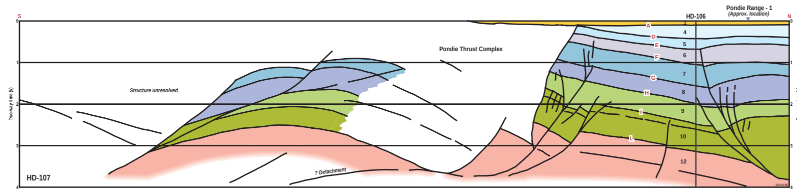


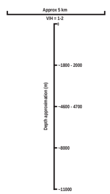






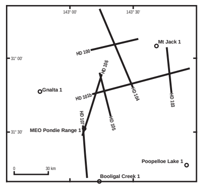


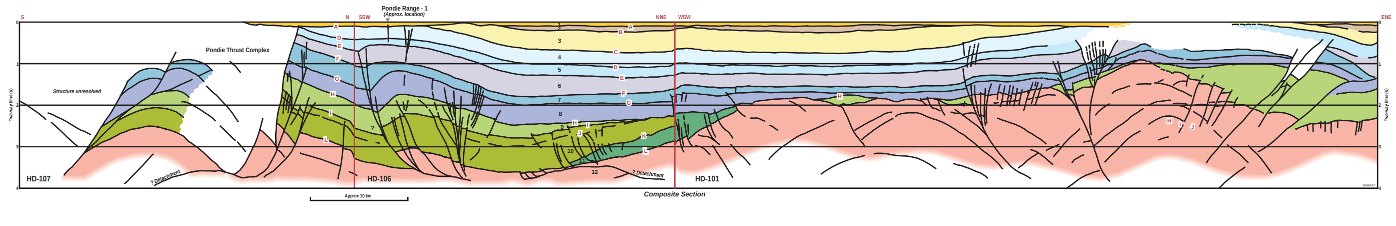




SEISMIC SEQUENCES

	1	Largely Cainozoic
A	2	? Largely Late Devonian continental
B	3	
C	4	
D	5	
E	6	
F	7	
G	8	
H	9	? Synrift Late Silurian - Early Devonian
I, J	10	
K	11	? Marginal marine
L	12	? L. Proterozoic - E. Palaeozoic





Composite Section

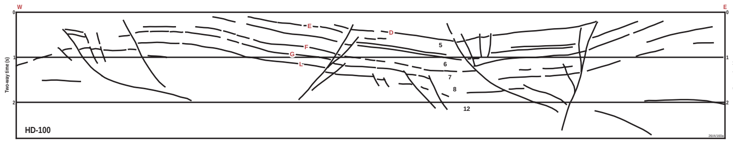
GEOSCIENCE AUSTRALIA

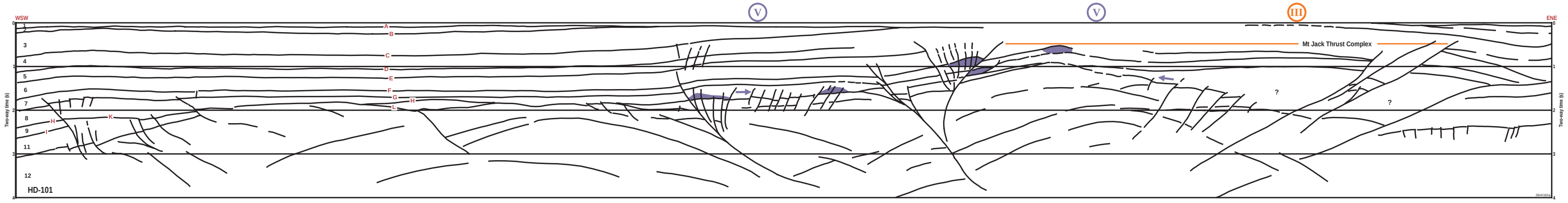
PLATE 3 : Potential petroleum plays and leads in the Darling Basin (Pondic Range Trough - Mt. Jack area)

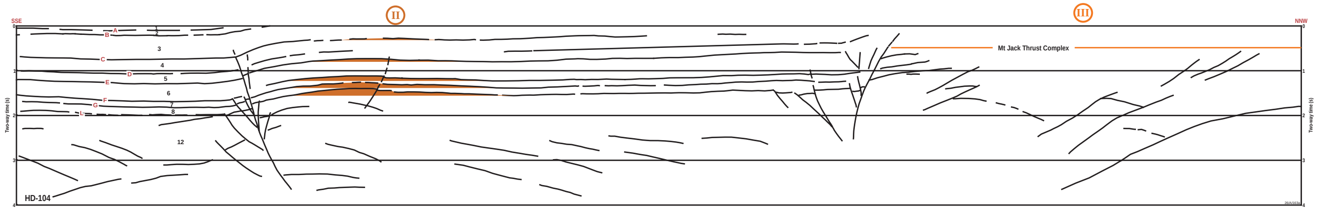
BHP Lines HD 100 - 107

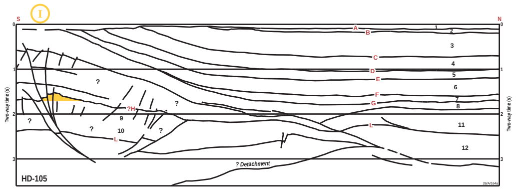
J.B. Willcox, A.N. Yeates, A.J. Meixner & R.D. Shaw

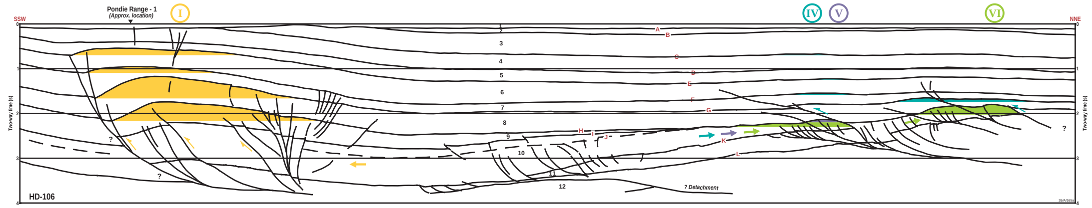
Geoscience Australia Record, 2003/05

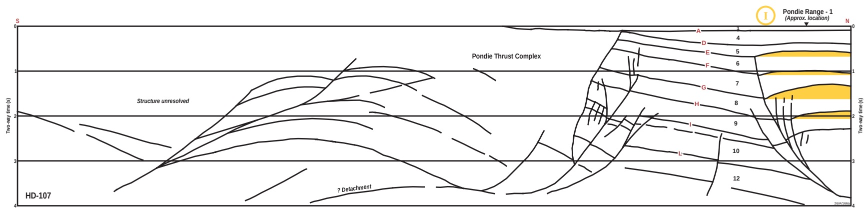


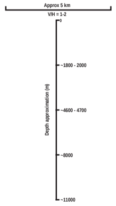


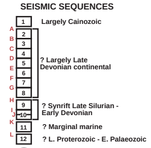












Play Identification