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Tectonostratigraphic Evolution of the Blantyre Sub-basin and Adjacent Regions, New South Wales, Based on Integration of Seismic, Gravity and Well Data

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Abstract: This paper presents the principal tectonostratigraphic features within the Blantyre Sub-basin, a central part of the regional Darling Basin, that results from deformation of the latest Silurian to Devonian sequence. This case study shows that by integrating well data, seismic data and gravity data, conceptual geologic models in the Blantyre Sub-basin and surrounding area can be constructed. Integration of the gravity contour map with two-way time structure contour maps suggest that five major structural features can be identified: (a) the Mount Emu High that is interpreted as an anticlinal fold with an associated thrust fault, (b) the Wilcannia High, interpreted as an uplift, clearly identified on the northern margin of the Blantyre Sub-basin, (c) the Snake Flat High, interpreted as an asymmetric anticlinal fold with a number of high-angle reverse faults, (d) a structural low occurring in the central part of the Blantyre Sub-basin, interpreted as an elongate synclinal fold that covers an area of approximately 400 square kilometres, and (e) another small structural low, interpreted to be a synclinal fold. Structure and isochore maps reveal that faults profile the primary control on subsidence patterns. Understanding these structural features should help to decrease the risks for hydrocarbon exploration by applying better defined and up-to-date concepts throughout the Blantyre Sub-basin.

Keywords: Blantyre Sub-basin, latest Silurian-Devonian sequence, basin analysis, seismic data interpretation, gravity data, structure and isochore map, tectonostratigraphic model.

INTRODUCTION

The Darling Basin is potentially one of the most important areas in New South Wales for petroleum exploration, with over 8000 metres of sediment that range in age from Precambrian to Late Palaeozoic. The Darling Basin consists primarily of four sub-basins, the Pondie Range, Blantyre, Neckarboo and Nelyambo Sub-basins (Figure 1). It also includes three major troughs, the Bancannia, Menindee and Poopelloe Lake Troughs (Figure 1), (Byrnes 1985; Evans 1977; Encom Technology Pty Ltd 1994; Glen et al. 1996; Bembrick 1997a, b; Pearson 2003; Neef 2005; Khalifa 2005; Khalifa and Ward 2009). Data from geologic mapping, seismic profiles, gravity data, and wells are used here to describe the tectonostratigraphic history of the Blantyre Sub-basin, focusing on the latest Silurian-Devonian sequence.

Recently, Neef and Bottrill (1991), Neef (2005), Encom Technology Pty Ltd (1994), Bembrick (1997a,b), Alder et al. (1998), Willcox et al. (2003), Pearson (2003), Cooney and Mantaring (2007) provided further data that document the Winduck, Snake Cave and Ravendale Intervals as the principal latest Silurian-Devonian sequences in the Darling Basin. However, tectonostratigraphic units proposed in this study fundamentally differ from the physical stratigraphy and depositional models suggested by Bembrick (1997a, b), Alder et al. (1998).

The main focus of the present study is the Blantyre Sub-basin, which covers an area of approximately 14,000 square kilometres in the central part of the Darling Basin shown on Figure 1. The stratigraphy and structural geology of the Blantyre Sub-basin is based on an interpretation of seismic profiles, well logs and gravimetric anomalies. The Blantyre Sub-basin is bounded by the Wilcannia High in the north and northeast, by the Lake Wintlow High in the west, by the Neckarboo Sub-basin in the southeast, and the Neckarboo High in the south (Figure 1).

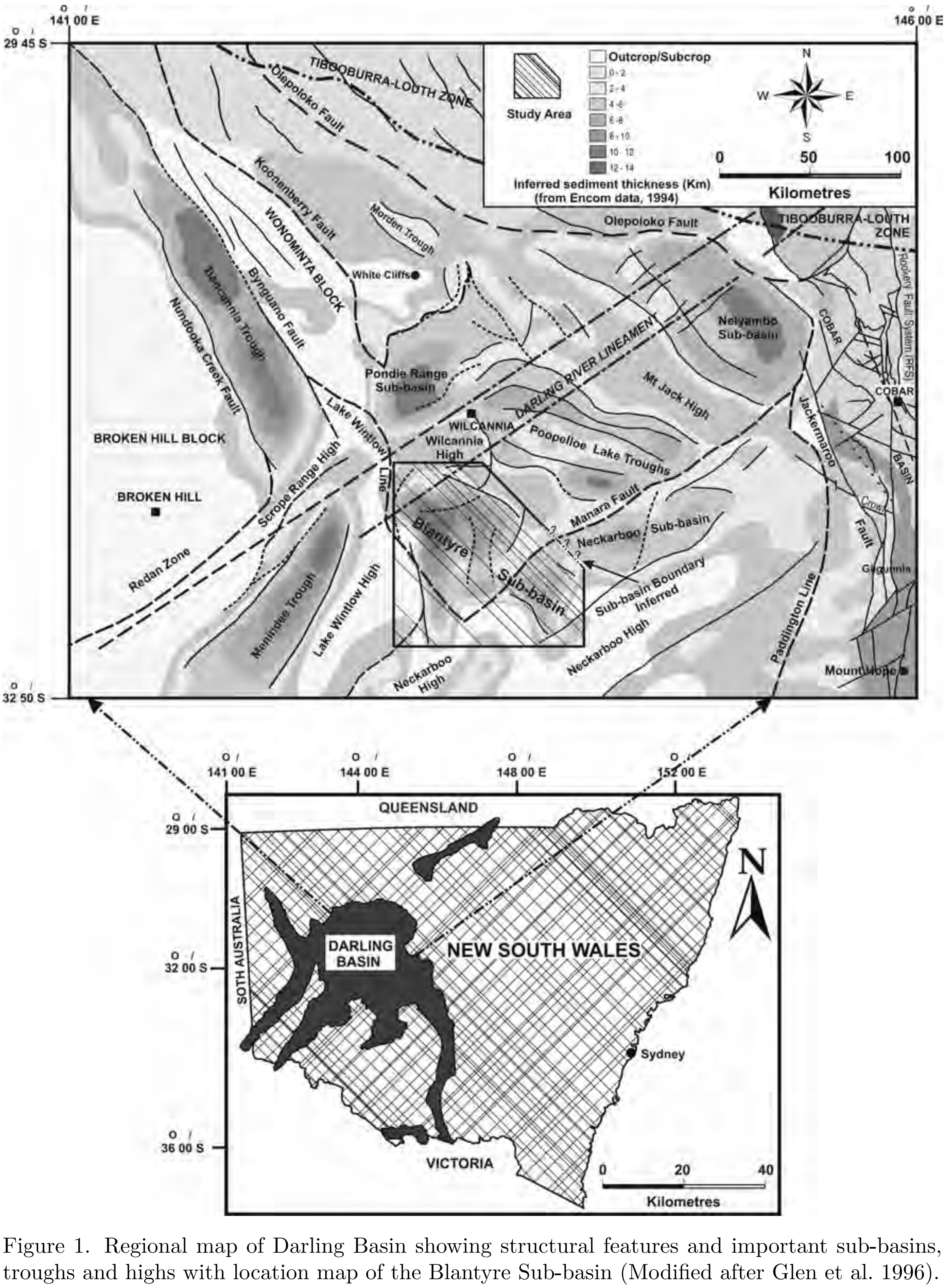

Figure 1. Regional map of Darling Basin showing structural features and important sub-basins, troughs and highs with location map of the Blantyre Sub-basin (Modified after Glen et al. 1996).

According to Encom Technology Pty Ltd (1994), the Blantyre Sub-basin has a basement depth estimated from seismic data near Blantyre-1 well that indicates a sediment thickness of 11–12 kilometers. The amplitude of the Bouguer gravity anomaly from the basement on the western flank of the Blantyre Sub-basin to the basement in the centre of the area is 57 mgal. The gravity data, obtained from the Australian Geological Survey Organization base, were acquired from ground gravity methods; a very tight grid has been recorded in the vicinity of the Snake Flat-1 well in the Blantyre Sub-basin with an average station spacing of approximately 700 metres (NSW Department of Mineral Resources, 1993).

The aim of this paper is to discuss the geometry and structure of the three main conceptual tectonostratigraphic packages of latest Silurian-Devonian sequences in the Blantyre Sub-basin using reflection seismic profiles, well data and the Bouguer gravity map. Recent advances in our understanding of three-dimensional geological models have also been compared to information from detailed gravity surveys in the area, and interpreted in the light of the regional tectonic setting to develop a better understanding of the relationship between the structural development and the depositional processes in the latest Silurian-Devonian sequences (e.g. Winduck, Snake Cave and Ravendale Intervals). In addition, many of the key well penetrations of the latest Silurian-Devonian sequence were tied to regional seismic profiles (e.g. Blantyre-1, Mount Emu-1, Booligal Creek-1, Booligal Creek-2, Snake Flat-1 and Kewell East-1) (Table 1). Additional regional seismic sections were also constructed to assist the analysis process, further clarifying the relation between the stratigraphy, sub-basin geometry, history and the regional structural style (e.g. major faults and folds).

STRATIGRAPHIC SUMMARY

A summary of the latest Silurian to Early Permian stratigraphic succession of the Darling Basin and surrounding region is given below.

Latest Silurian and Devonian Sequence

The latest Silurian to Devonian succession in the Darling Basin is summarized in Table 2. Using terminology for the central part of the basin as described by Rose (1968) and Packham (1969), the succession in these areas is subdivided on the basis of regional unconformities into three major intervals as follows: (1) Latest Silurian to Early Devonian (Pragian) Winduck Group and equivalents, (2) Early Devonian (Emsian) to Middle Devonian (Eifelian) Snake Cave Sandstone and equivalents, and (3) Middle Devonian (Givetian) to Late Devonian (Famenian) Ravendale Formation and equivalents. The uppermost two units in this sequence, the Snake Cave Sandstone and the Ravendale Formation, are generally correlated with the Mulga Downs Group, a unit originally defined on the basis of outcropping strata in the area west of Cobar (Rayner 1962).

Bembrick (1997a, b) and Alder et al. (1998) used three seismic horizons, originally described by Evans (1977), to divide the stratigraphic sequence of the Darling Basin into three informally named ‘Intervals’, as an initial reference framework to describe the strata within this poorly exposed and sparsely drilled area. These intervals (Table 2) are broadly equivalent to the main lithostratigraphic units identified from outcrop studies, but are defined on the basis of seismic marker horizons rather than lithologic criteria. Bembrick (1997a, b) and Alder et al. (1998) related the unconformities associated with the seismic markers to significant tectonic events in the geological history of the region. Horizon A was considered to mark the Bowning event, an angular unconformity of latest Silurian age; Horizon B was taken as representing the Bindian event, a regional unconformity of late Early Devonian age; and Horizon C was considered to mark the Tabberabberan event, a regional unconformity of late middle Devonian age (Table 2).

Well name	**KB. (metres)**	**TD. (metres)**	**Informal stratigraphy**	**Unit top (metres)**	**Thickness (metres)**	**References**
Blantyre-1	77	2289	Lower Permian	235.61	66.14	Bembrick 1997b
			Upper Carboniferous?	301.75	103.55	
			Ravendale Interval	405.3	1784.7	
			Snake Cave Interval	2190	99	
Mount Emu-1	80.2	1450.5	Snake Cave Interval	368.9	243.1	Khalifa 2005 and Khalifa & Ward 2009
			Winduck Interval	612	838.5	
Booligal Creek-1	80.2	409.5	Winduck Interval	260	149.5	Khalifa 2005 and Khalifa & Ward 2009
Booligal Creek-2	80.2	761.4	Winduck Interval	238	523.4	
Kewell East-1	79.9	1224	Snake Cave Interval	88	290	Clark et al. 2001
			Winduck Interval	378	846	
Snake Flat-1	4	353.5	No Mulga Downs Group and Winduck Interval	–	–	Maple Oil N.L. 1994

Table 1. Generalized informal stratigraphy, top and thickness of the lithostratigraphic units drilled within Blantyre Sub-basin.

Period	Epoch	Age	Generalised Lithostratigraphic Units *West* ---------- *Central* ---------- *East*					
LATE CARBONIFEROUS/ EARLY PERMIAN			---------- Unnamed unit ---------- ***Kaninmblan Event~Regional Unconformity ~Seismic Marker Reflector (Horizon-D)***					
DEVONIAN	LATE	FAMENNIAN FAASNIAN	--- Ravendale Interval --- --- Bembrick (1997a,b) ---	Nundooka Sandstone (1070 m) Ward *et al* (1969)	Ravendale Formation (800 m) Rose (1968) Packham (1969)	Unit-C (375 m) Unit-B (120 m) Uint-A (600 m) Carroll (1982)	Crowl Creek Formation (2000 m) Bundycoola Formation (300 m) Glen (1982a)	--- Mulga Downs Group --- --- Mulholland (1940) and Rayner (1962) ---
	MIDDLE	GIVETIAN	***Tabberabberan Event~Regional Unconformity ~Seismic Marker Reflector (Horizon-C)***					
		EIFELIAN	--- Snake Cave Interval --- --- Bembrick (1997a,b) ---	Coco Range Beds (760 m) Ward *et al* (1969)	Snake Cave Sandstone Rose (1968) (120 m) Packham (1969) (2285 m)	Unit (5, 6 & 7) (100-900 m) Unit (1, 2, 3 & 4) (250-550 m) Carroll (1982)	Bulgoo Formation (2600 m) Merrimerriwa Formation (200-300 m) Meadow Tank Formation Glen (1982a)	
	EARLY	EMSIAN	***Bindian Event~Regional Unconformity ~Seismic Marker Reflector (Horizon-B)***					
		PRAGIAN LOCHKOVIAN	Mt Daubeny Formation Neef *et al* (1989) and Neef and Bottrill (1991)	Winduck Group	---------- Glen (1979, 1982b) ---------- Gundaroo Sandstone (90 m) / Unit-A1 (40 m) / Unit-A2 (50 m) Sawmill Tank Siltstone (500 m) Buckambool Sandstone (1000 m)		Amphitheatre Group Andrews (1913) and Rayner (1962)	--- Winduck Interval --- --- Bembrick (1997a,b) ---
LATEST		SILURIAN	***Bowning Event~Angular Unconformity ~Seismic Marker Reflector (Horizon-A)***					

Table 2. Lithostratigraphic units nomenclature correlation of the latest Silurian to Devonian sequence in the Darling Basin. Seismic marker unconformities (A, B, C, D) from Evans (1977) are correlated with the three informally named 'Intervals' described by Bembrick (1997a, b).

The Mulga Downs Group, which is the main focal point of this study, is one of the major thick clastic successions of late Early Devonian to Late Devonian age in western New South Wales. This Devonian sequence, originally referred to as the Mulga Downs Stage (Mulholland 1940) but re-defined as the Mulga Downs Group by Rayner (1962, cited in Conolly et al. 1969), has been subdivided into several formations and mapped by authors such as Conolly (1962), Rose (1968), Ward et al. (1969) and Glen (1979, 1982a, 1986). Bembrick (1997a, b) also suggested that the Mulga Downs Group required re-definition based, among other aspects, on regional mapping by Glen (1986), and avoided using the term in his discussion. Such a framework, based on mapping and correlation of seismically defined units, also provide a useful stratigraphic framework for the present study.

Winduck Interval and Equivalents

The Winduck Interval is widespread throughout the Darling Basin, both in outcrop and in the subsurface. These strata are represented by the Mt Daubeny Formation in the western part of the basin (Neef et al. 1989), the Winduck Group in the central to eastern part (Glen 1982a, b; Scheibner 1987), and the Amphitheatre Group in the eastern part of the basin (Andrews 1913; Rayner 1962) (Table 2).

The depositional environment of the Winduck Interval shows an overall regressive nature from west to east across the Darling Basin. It generally ranges from alluvial/fluvial in the Mt Daubeny Formation through fluvial to deltaic/shoreline in Winduck Group (Glen 1982a,b; Neef 2005; Neef et al. 1989; Neef and Bottill 1991) and deeper marine within Amphitheatre Group in the east (Glen 1982b, 1986).

Snake Cave Interval and Equivalents

The lower part of the Mulga Downs Group was formally proposed as the Snake Cave Interval by Bembrick (1997a, b). This interval is equivalent to the Snake Cave Sandstone in the Mt Wright area (Rose 1968), and in the eastern part of the Bancannia Trough (Packham 1969; Carroll 1982). It also includes the Coco Range Beds (now Coco Range Sandstone, Neef et al. 1995) on the western flank of the Bancannia Trough (Ward et al. 1969). In the east the interval has been subdivided into a lower part, the Meadows Tank Formation, a middle part, the Merrimerriwa Formation, and an upper part, the Bulgoo Formation, in the Buckambool area (Glen 1979, 1982a) (Table 2).

The depositional sequence of the Snake Cave Interval was initiated by braided and alluvial fan input from the west within the Valley Tank Member in the western part of the basin and from the south-west for the Meadows Tank Formation in the eastern and central parts of the basin (Glen 1979, 1982a). At this time, the central parts of the Darling Basin were relatively free of coarse siliciclastic sediments and minor carbonates were developed locally (Rose 1968; Conolly et al. 1969; Carroll 1982; Neef and Larsen 2003).

Ravendale Interval and Equivalents

The upper part of the Mulga Downs Group is equivalent to the subsurface Ravendale Interval proposed by Bembrick (1997a, b). The interval is equivalent to the Ravendale Formation named by Rose (1968). Conolly et al. (1969) has described the Ravendale Formation near the Bancannia Trough. The unit is synonymous with Units A, B and C mapped by Carroll (1982) on the eastern side of the Bancannia Trough. The Ravendale Formation is equivalent to the Nundooka Sandstone, mapped on the western flank of the Bancannia Trough by Ward et al. (1969). The lower part is also equivalent to the Bundycoola Formation and the upper part to the Crowl Creek Formation in the Buckambool area, west of Cobar (Glen 1982a), as shown in Table 2.

In general the Ravendale Interval is initiated by an influx of coarse siliciclastic sediments in both the western and eastern parts of the basin (Ward et al. 1969; Conolly et al. 1969; Neef et al. 1995, 1996). Few coarse clastic types of sediment reached the central regions of the basin (Neef et al., 1995; Bembrick 1997a, b). The depositional environment of the Ravendale Interval is dominantly fluvial, but closes with a Famennian marine episode encountered in the structural troughs where the thicker Late Devonian section is preserved (Neef and Larsen 2003; Bembrick 1997b).

Late Carboniferous to Early Permian Sequence

In the southern part of the Darling Basin, rocks of Late Carboniferous to Early Permian age have been recognized in several different studies (Byrnes 1985; Bembrick 1997b). Horizon D was considered to mark the Kanimblan event, a regional unconformity of Late Carboniferous age (Evans 1977) (Table 2). Areas in which such beds have been noted include the Blantyre Sub-basin. The lithology of these strata is dominated by interbedded siltstones and sandstones, which are variably micaceous and carbonaceous. Thick sections of Late Carboniferous to Early Permian strata have also been encountered in wells drilled in the Wentworth and Tararra Troughs (Evans 1977). Evans (1969) and Veevers and Evans (1975) considered from microfloras in the sequence that the rocks are mainly Late Carboniferous in age. However, rocks of Early Cretaceous age are known in the subsurface of the northern Bancannia Trough, and have also been encountered in wells to the south near Wentworth and Mildura (Evans and Hawkins 1967).

STRUCTURAL FRAMEWORK

Integration of lineament data within the Darling Basin shows that the boundaries are marked by a complex of major structural features as shown in Figure 1. The basin can be divided into six structural zones and one sub-zone, each representing distinct fault-bounded blocks (Scheibner 1993), and perhaps into several less distinct geologic terranes (Scheibner 1972, 1976; Evans, 1977; Glen et al. 1996; Glen and Walshe 1999; Pearson 2003; Neef 2005; Cooney and Mantaring 2007).

The basin appears to be bounded in the north and east by the Tibooburra-Louth Zone (Scheibner 1989; Scheibner and Basden 1996, 1998), the Olepoloko Fault (Stevens and Crawford 1992) and the Paddington Line (Glen et al. 1996) (Figure 1). The western margin, against the Broken Hill Block, is represented by the NW-trending Nundooka Fault in the Bancannia Zone, and by the southwest trending southern margin of the Redan Zone (Scheibner 1993) (Figure 1).

Significant faults and other features within the basin include the NW-SE trending Koonenberry Fault (Rose and Brunker 1969; Leitch et al. 1987; Neef and Larsen 2003; Neef 2005), the prominent ENE-trending Darling River Lineament (Hills 1956), and the Bynguano Fault (Buckley 2001) on the eastern side of the Bancannia Trough. The Lake Wintlow Line separates the Bancannia Trough and the Pondie Range Sub-basin in the north and the Menindee Trough and Blantyre Sub-basin in the southwestern part of the basin.

The structural features of the Blantyre Sub-basin were described by Glen et al. (1996). The Manara Fault changes from NW trending in the SE part of the sub-basin to NW-trending near the Nelyambo Sub-basin. Uplift of the Wilcannia High, as defined by Evans (1977), appears to indicate the development of another major structural feature within the sub-basin. The Lake Wintlow Line provides a well-defined feature separating the Blantyre Sub-basin from the Menindee Sub-basin (Encom Technology Pty Ltd 1994; Glen et al. 1996; Alder et al. 1998). The Neckarboo High, along the southeastern margin of the Neckarboo Sub-basin and the southern margin of the Blantyre Sub-basin, is a narrow, elongate feature, which is approximately 60 kilometres long (Alder et al. 1998; Pearson 2003) (Figure 1).

DATA COLLECTION AND METHODOLOGY

Database

The database used for this study consists of data from five exploratory petroleum wells and approximately 800 km of conventional two-dimensional seismic reflection profiles drawn from four different data sets (Figure 2). The Appendices summarize seismic data acquisition and processing parameters. This seismic data set was then integrated with Bouguer gravity data in order to identify and map the major structural features within the Blantyre Sub-basin (Figure 2).

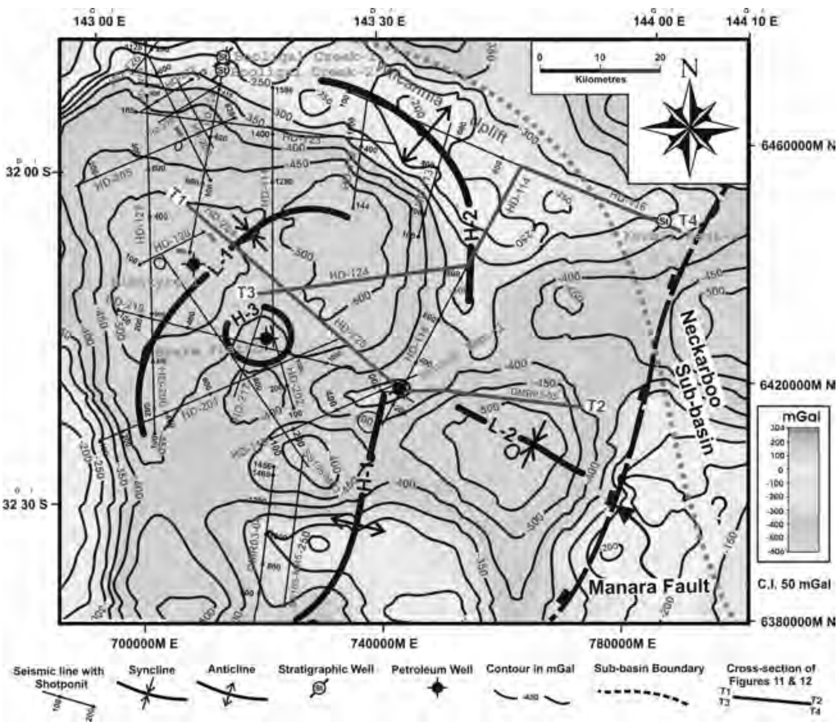

Figure 2. Map showing gravity anomaly with distribution of two-dimensional (2-D) seismic profiles. Location of wells drilled within the Blantyre Sub-basin (modified after NSW Department of Mineral Resources, 2003). Also shown are hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as determined in Figures 3, 4 and 5.

The two-dimensional seismic reflection data sets were integrated and re-interpreted using a range of computer-based techniques, particularly the Kingdom® processing suite. Information from the seismic and well studies was integrated using CorelDraw® 11 (e.g. for preparation of seismic cross-sections) and Surfer 8 for preparation of contour maps and three-dimensional geologic evaluations.

The two-way travel time at selected shot points, about 100 metres apart on each of the seismic sections, was estimated for each reflector. The resulting data (the eastings and northings of each shot point and the two-way travel time to the reflector at that shot point) were input to the Surfer 8 graphic modelling package, to develop contour maps of the individual horizons. Areas where the relevant horizons were not present, especially in modelling the base of the Ravendale Interval, were excluded from the modelling process.

Interpretation Methods

The data were interpreted in four steps. It should be noted, however, that tectonostratigraphic modelling is very much an iterative process between the different steps, and hence the succession of processes was repeated several times in developing the final output of the study area. The first step was to describe the major structural features of the sub-basin, based on time-structure contour maps of the bases of the Winduck, Snake Cave and Ravendale Intervals. The second step involved comparison of the time-structure maps with the most recently available gravity data of the area, compiled by the New South Wales Department of Mineral Resources in 2003 (Figure 2). A good correlation was observed between the gravity data and the two-way travel time contours to the key horizons, especially those on the base of the Winduck Interval. This indicates that the gravity data mainly reflect the sub-basin structure, and do not appear to be significantly affected by variations in basement density or rock type. The third step was to compare the isochore map for each lithostratigraphic unit (in terms of two-way travel time) to the time-structure patterns, especially for the Winduck and Snake Cave Intervals. The fourth step was to interpret the tectonostratigraphic evolution of the area, as indicated by a study of the contour maps and a closer look at the individual seismic cross-sections. This suggested a history involving three separate phases of tectonic activity.

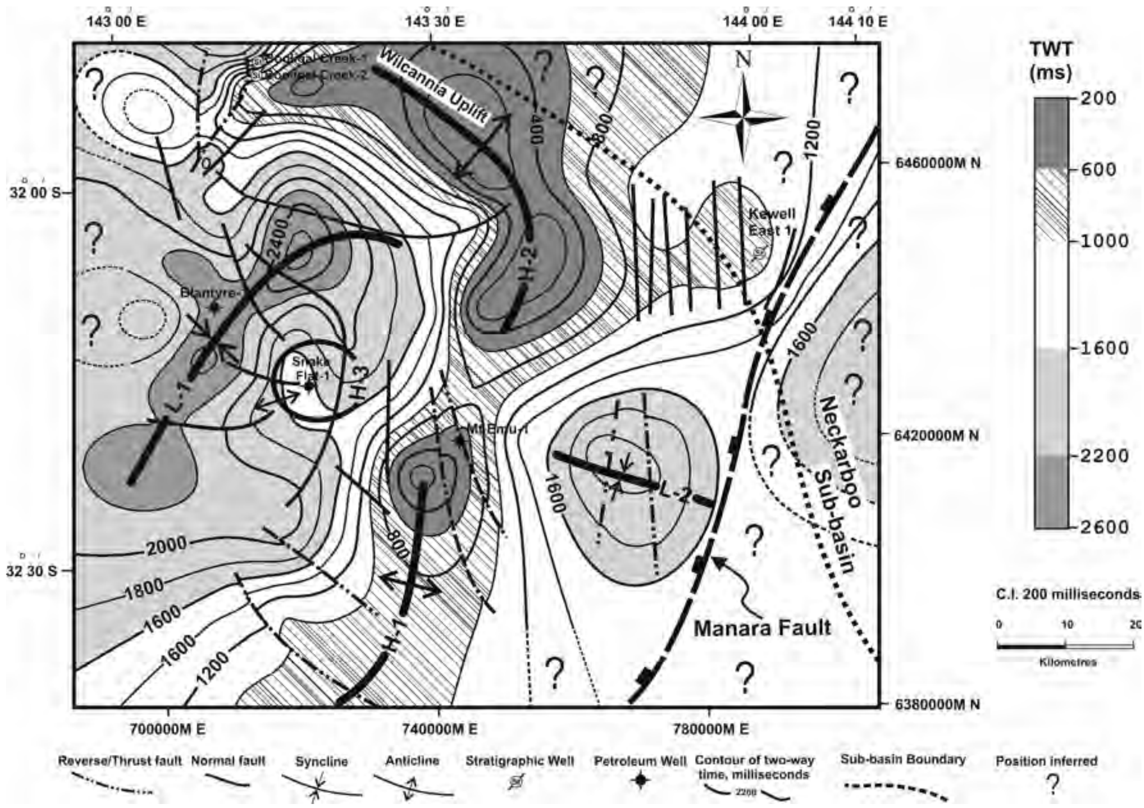

Figure 3. Two-way time structure map of the base of the Winduck Interval within the Blantyre Sub-basin showing hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as discussed in the text.

RESULTS AND DISCUSSION

Subsurface Map Construction

On the basis of the interpretation of the newly acquired data, the Blantyre Sub-basin can now be divided into a number of distinct structural provinces; these provinces are shown in the three two-way time structure maps (Figures 3, 4 and 5), supplemented by the two isochore maps (Figures 6 and 7).

Structure Map Interpretation

The data analysed includes both stratigraphic and seismic data. The three two-way time structure map interpretations in Figures 3, 4 and 5 are consistent with a reconstructed pattern of sub-basin evolution.

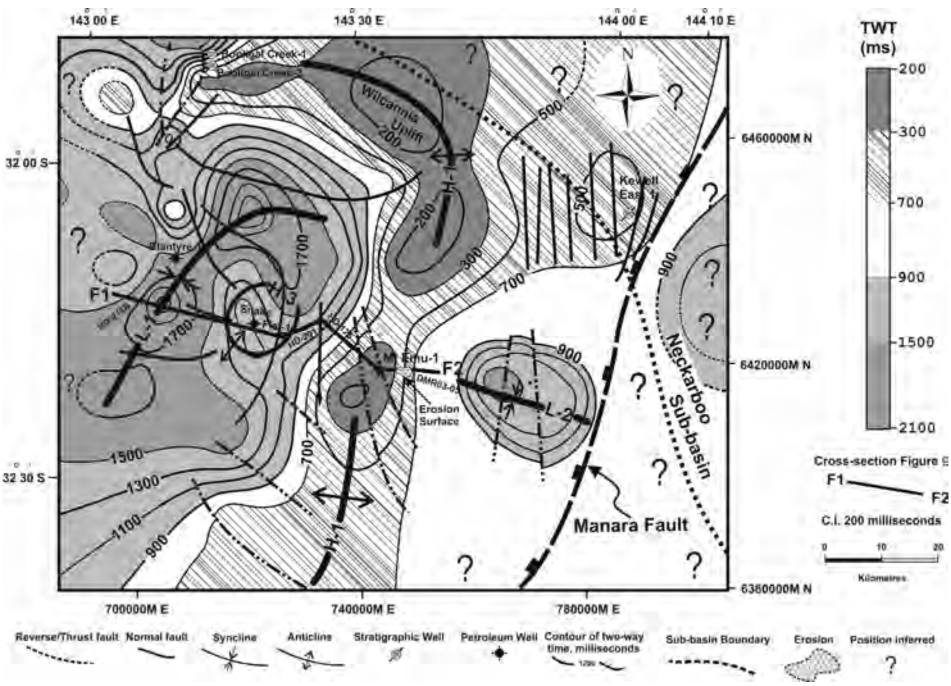

Figure 4. Two-way time structure map of the base of the Snake Cave Interval within the Blantyre Sub-basin showing hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as discussed in the text.

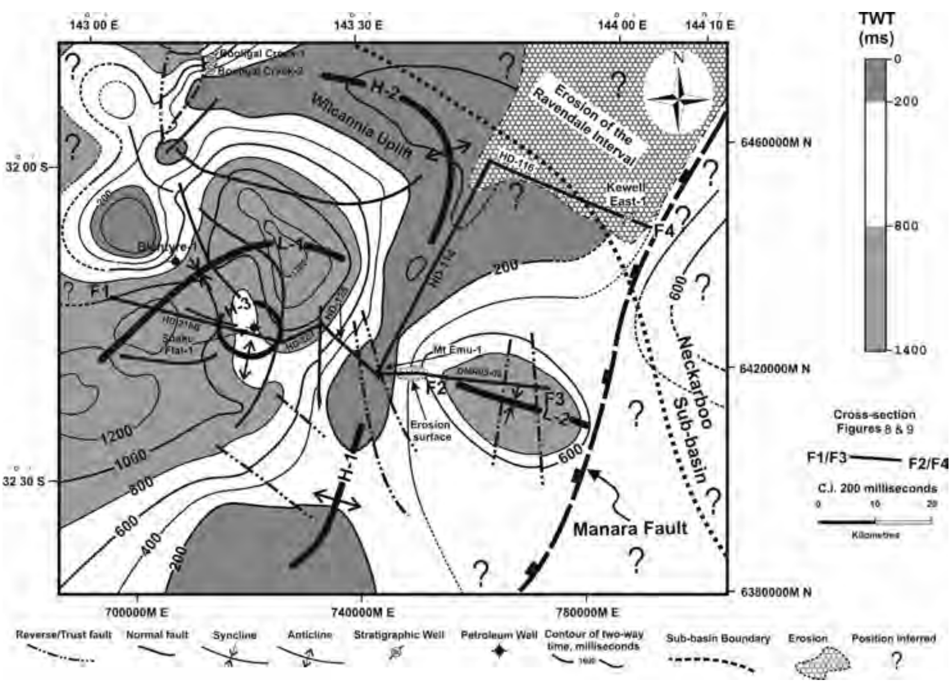

Figure 5. Two-way time structure map of the base of the Ravendale Interval within the Blantyre Sub-basin showing hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as discussed in the text.

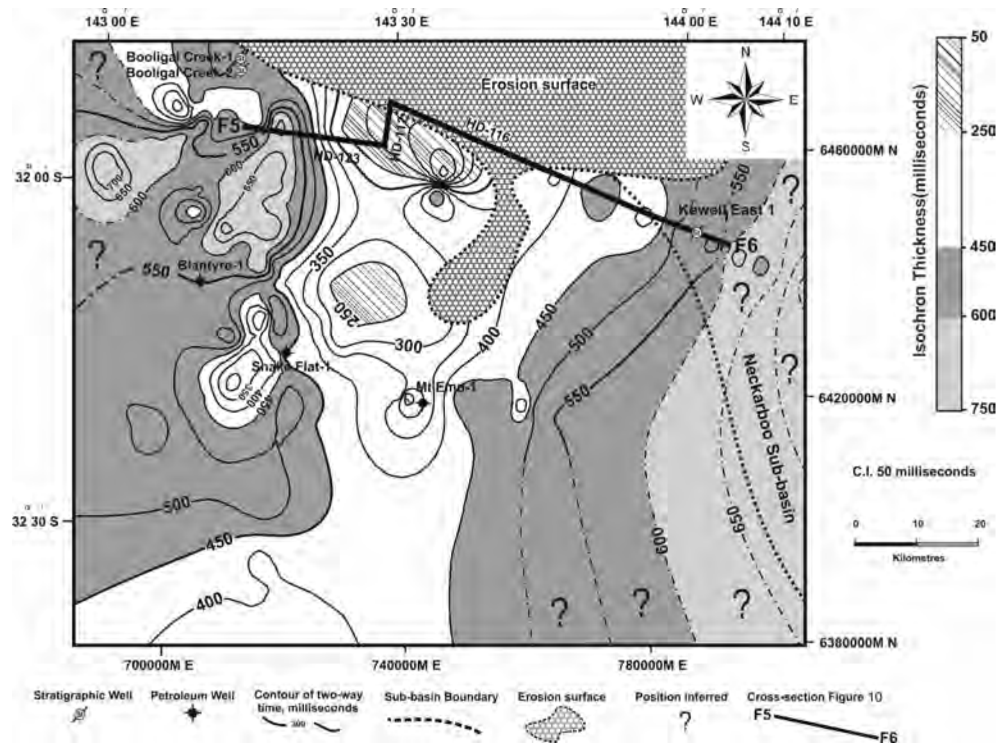

Figure 6. Isochore map of the Winduck Interval, showing the response of the latest Silurian to late Early Devonian sequence to subsidence within the Blantyre Sub-basin.

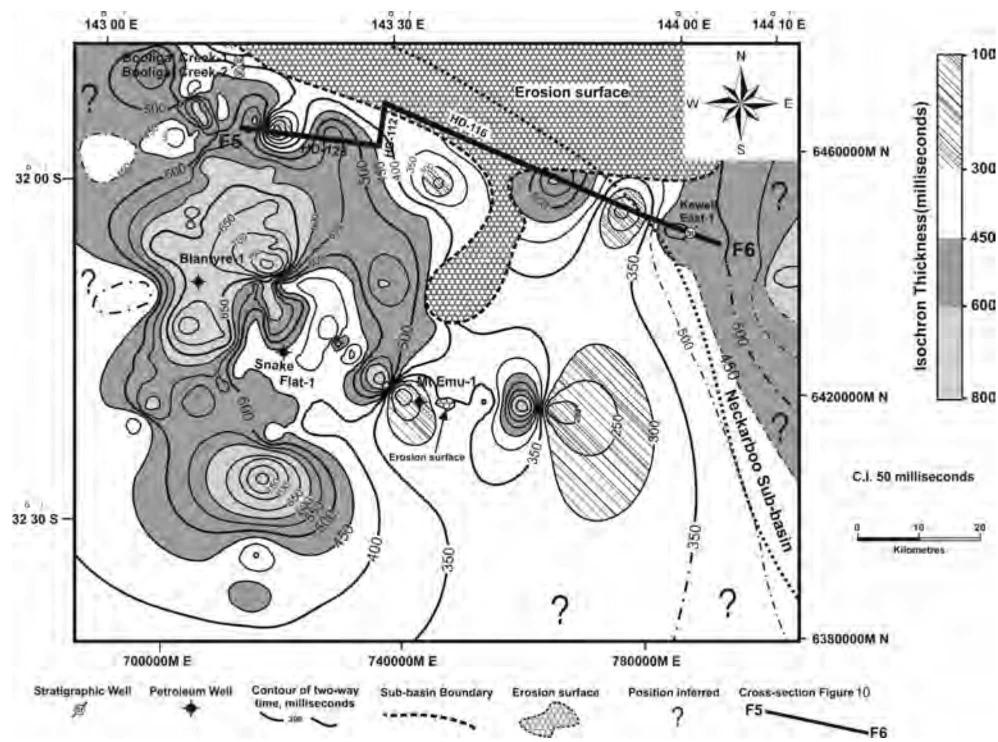

Figure 7. Isochore map of the Snake Cave Interval, showing the response of the late Early Devonian to early Middle Devonian sequence to subsidence within the Blantyre Sub-basin.

(A) Two-way time structure contours on base of Winduck Interval

The two-way time structure contours on the base of the Winduck Interval (Figure 3) shows a NE-SW oriented structural low (L-1) in the western part of the Blantyre Sub-basin, centred around the Blantyre-1 exploration well. To the east of this is a NE-SW trending high, lying approximately along seismic profile SS134>HD-114. This contains two smaller high areas, one of which (H-1) is immediately SW of the Mount Emu-1 site.

The base of the Winduck Interval is widespread throughout the Blantyre Sub-basin. Its depth ranges between 200 to 2600 milliseconds of two-way travel time, being shallowest near the northern margin and deepest in the faulted central part of the Blantyre Sub-basin (Figure 3). The strata of the Winduck Interval, as defined from seismic profile DMR03-05, have an estimated thickness in this area of approximately 1,400 metres (Figure 8).

Farther east again there is a second structural low (L-2), centred near the eastern end of seismic profile DMR03-05. The eastern part of this structure is poorly defined, due to a lack of seismic coverage. However at the eastern end of DMR03-05 there is an up-to-the-east high angle reverse fault (see Figure 9). A second structural high (H-2) is mapped in the northern part of the Blantyre Sub-basin, running east and then SE from Booligal Creek-1 and Booligal Creek-2 (Figure 2). This corresponds to the feature identified by Evans (1977), Alder et al. (1998), Pearson (2003), Neef (2005), Cooney and Mantaring (2007) Khalifa (2005) and Khalifa and Ward (2009) as the Wilcannia High. It curves southwards to link up with the NE-SW high (H-1) through the Mount Emu-1 well site. Smaller structural highs are noted west of the Booligal Creek wells, east of the Wilcannia High around the Kewell East well, and west of the main NE-SW high, around the Snake Flat well (H-3) (see Figures 2 and 3).

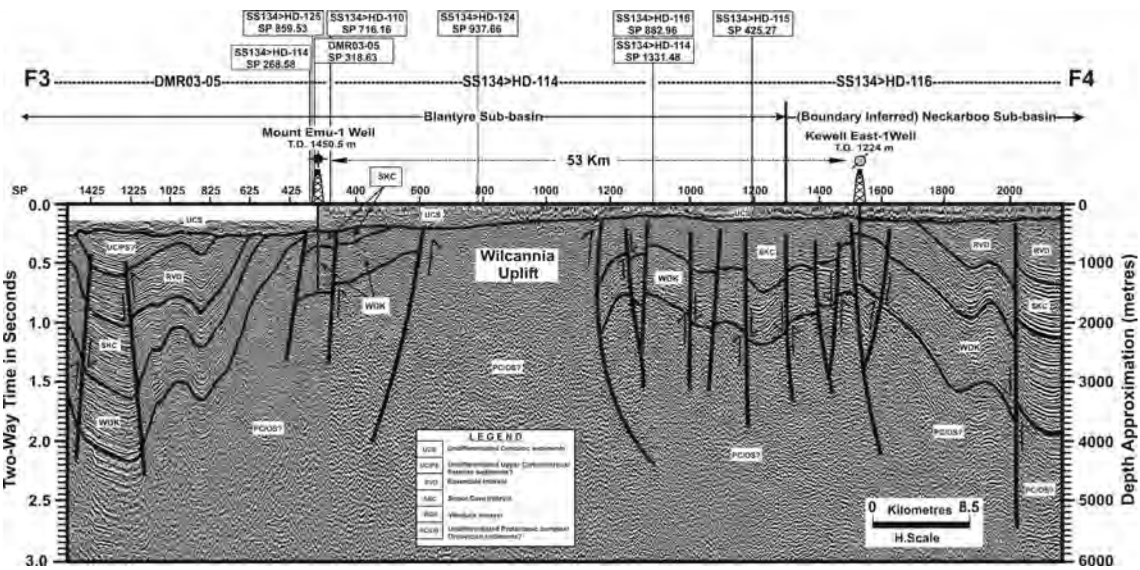

Figure 8. Interpreted seismic section F3-F4, through east part of the Blantyre Sub-basin linked to the Neckarboo Sub-basin showing how thickening of Winduck, Snake Cave and Ravendale Intervals is compartmentalized on either side of the Wilcannia Uplift by complex faults. Section is based on well data, gravity data, and seismic profiles SS134>HD-114, 116 and DMR03-05. Location of seismic section is shown in Figure 5.

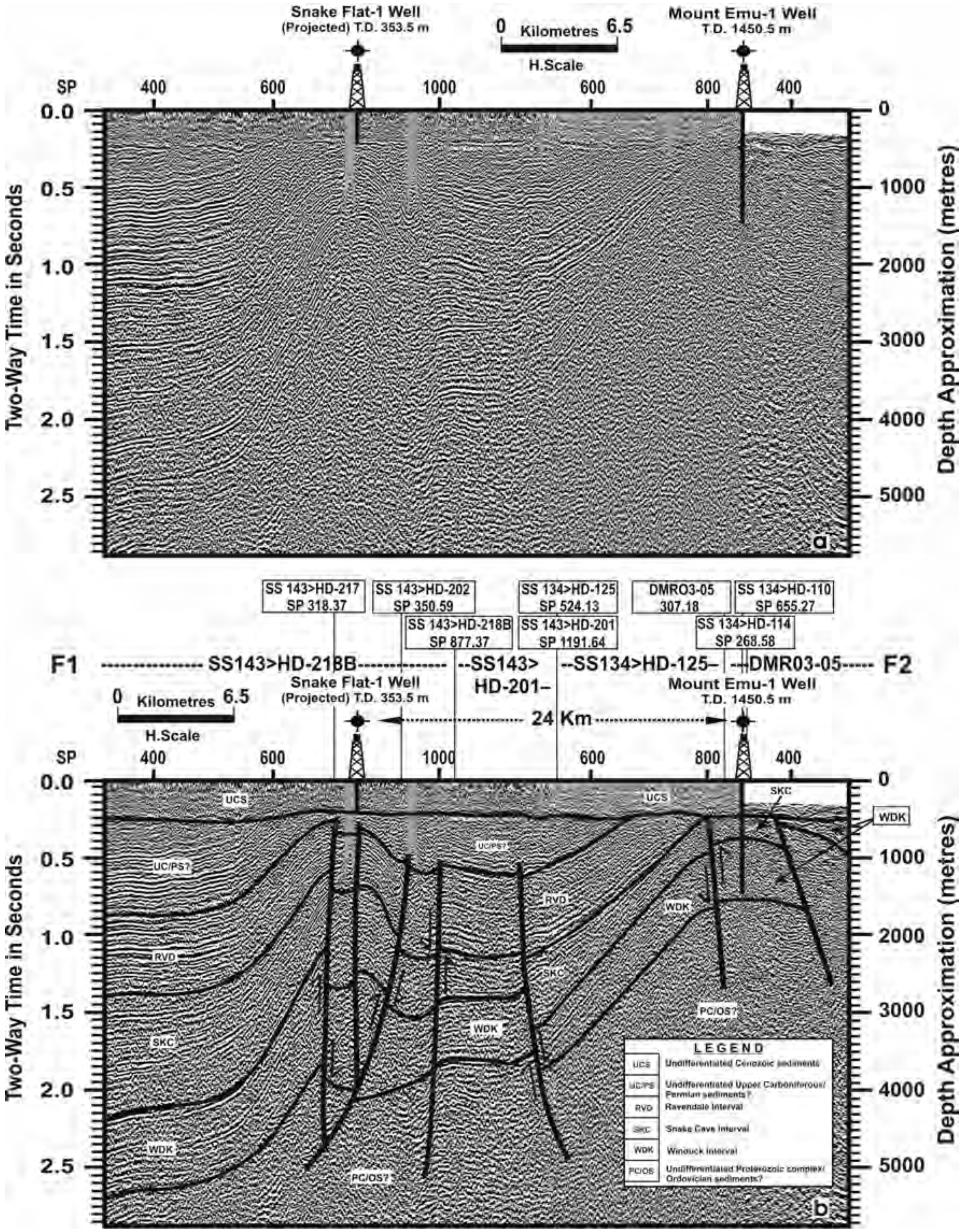

Figure 9. (a) Uninterpreted seismic section F1-F2 through the central part of the Blantyre Sub-basin, showing location of seismic section as shown in Figures 4 and 5 (b) Interpreted seismic profiles SS143>HD-218B and 201 showing the most deformed part of Snake Flat anticline with several high angle reverse faults. Also interpreted part of seismic profiles SS134>HD-125 and DMR03-05, showing anticlinal folding and a associated thrust fault, indicating stratigraphic geometry and absence of the Ravendale Interval in the Mount Emu-1 well.

(B) Two-way time structure contours on base of Snake Cave Interval

The two-way time structure contours on the base of the Snake Cave Interval (Figure 4) display a similar structural pattern to those on the base of the Winduck Interval (Figure 3). The surface for the base of the Snake Cave Interval has been mapped using data from all of the available shot points on the seismic profiles in Figure 2, except where the unit has been completely removed by erosion. Figure 9 displays a part of seismic profiles SS134>HD-125 and DMR03-05, which indicate in greater detail the setting of the anticlinal folding and associated thrust faulting close to the Mount Emu-1 Well. Figure 3 also shows a NE-SW oriented structural high (H-1) around the Mount Emu-1 Well, representing the Mount Emu Anticline (cf. Mullard 1995, Khalifa 2005).

The base of the Snake Cave Interval recognised in the two-way time structure contours within the Blantyre Sub-basin, ranges in depth between 200 and 2100 milliseconds of two-way time, being shallowest near the northern margin of the sub-basin and deepest in the faulted region in the central part of the study area (Figure 4).

The strata of the Snake Cave Interval, as shown in Figures 8 and 9, has been mapped by combining information from seismic profiles and well logs. In the wells, the greatest known thickness of the Snake Cave Interval (243.1 metres) has been recorded in Mount Emu-1 (cf. Khalifa 2005, Khalifa and Ward 2009), and the minimum thickness (about 100 metres) in Blantyre-1 (cf. Bembrick 1997b) is shown in Table 1, but thickness reaches an estimated 1,600 metres in the western Blantyre Sub-basin (e.g., at about 1.4–2.2 sec. TWT around SP 400 in seismic profile SS143>HD-218B; Figure 9).

(C) Two-way time structure contours on base of Ravendale Interval

The two-way time structure contours on the base of the Ravendale Interval (top of Snake Cave Interval) show a similar pattern to Winduck Interval and Snake Cave Interval although there are extensive areas where the Ravendale Interval is not present (Figure 5). The Wilcannia High in the northern part of the sub-basin clearly exposed the Ravendale Interval, running SE from the Booligal Creek-1 and Booligal Creek-2 wells. The Wilcannia High is also seen to curve southwards and link up with the NE-SW oriented structural high (H-1) controlled by the Mount Emu Anticline (Figure 9).

The base of the Ravendale Interval is widespread throughout the Blantyre Sub-basin, at a depth ranging from 250 to 1400 milliseconds of two-way travel time. It is shallowest in the southeastern and northern parts of the sub-basin, and deepest in the faulted region in the central part of the study area (Figure 5). The Ravendale Interval is absent in the Mount Emu-1, Snake Flat-1, Booligal Creek-1, and Booligal Creek-2 well sections (Table 1). The strata of the Ravendale Interval reach a maximum thickness of approximately 1200 metres in the western Blantyre Sub-basin (e.g., at about 0.6–1.1 sec. TWT between SP 600 and 1000 in seismic profile SS143>HD-201, Figure 9).

The base of the Ravendale Interval is missing in part of the area (Figure 5), especially in the north-east, due to erosion after deposition and uplift. This is also shown on seismic section F3-F4 (Figure 8).

Integration of Data from Structure Contour and Gravity Structure Maps

The gravity contours of the area can be compared with the two-way travel time contours on the base of the Winduck Interval (Figures 2 and 3). The gravity data also reflect the main structural features indicated on the two-way time structure contour maps. Two gravity lows, with NE-SW orientations are interpreted in the western part of the sub-basin, and a NW-SE oriented structural low occur near the eastern end of seismic profile DMR03-05. These correspond to positive structures on the travel-time contour map of the base of the Winduck Interval (Figure 3).

A positive gravity anomaly, corresponding to the Wilcannia High, is clearly identified on the northern margin of the Blantyre Sub-basin, around the Booligal Creek-1 and Booligal Creek-2 wells. This appears to link with gravity high (H-1) through the Mount Emu-1 well (equivalent to the Mount Emu anticline in Figure 9). The NE-SW oriented structural high around the Snake Flat-1 well corresponds to a similar structure inferred from the travel-time structure map (Figure 3) at the base the Winduck Interval. Further detail of the structural high (H-3) around the Snake Flat-1 Well, representing the Snake Flat Anticline (cf. Mullard 1995, Khalifa 2005), is shown in Figure 9. This is the most deformed part of the anticline, and is marked by a high angle reverse fault and an asymmetrical fold.

Comparison of Structure Contour and Isochore Maps

Isochore maps have been constructed for the Devonian sequence in the Blantyre Sub-basin, based on the seismic data. The units evaluated were of the Snake Cave and Winduck Intervals.

(A) Thickness of the Ravendale Interval

The thickness of the Ravendale Interval in many parts of the Blantyre Sub-basin is incomplete, due to removal of strata by erosion following uplift associated with the faults and folds that have deformed the strata since deposition (e.g. seismic section F5-F6, Figure 10). This and other sections have been used to identify those parts of the region where the Ravendale Interval, and in some cases other units, are partly or completely removed by post-structure erosion, and to separate those areas from areas with the full (un-eroded) interval thickness.

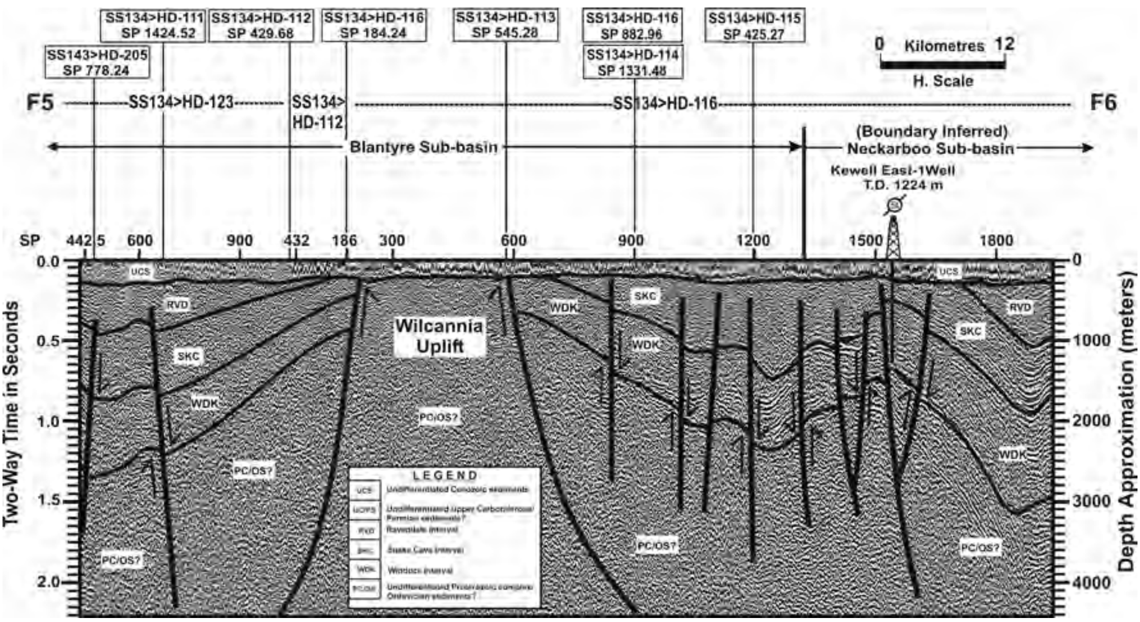

Figure 10. Interpreted seismic section F5-F6, showing the geometry of the tectonic and stratigraphic units within the Blantyre Sub-basin across the Wilcannia Uplift. Cross-section is based on well data, gravity data and seismic profiles SS134>HD-123, 112 and 116. See Figures 6 and 7 for location of seismic section F5-F6.

(B) Thickness of the Snake Cave and Winduck Intervals

The isochore maps for the Winduck and Snake Cave Intervals (Figures 6 and 7) show a broad similarity to the structure contour maps of their boundary horizons (Figures 3 and 4), with some degree of thickening and thinning in areas where the travel-time structure contours show low and high elevations respectively.

The structure contour map on the base of the Winduck Interval (Figure 3) indicates structural lows, or synclinal areas, along the sub-basin axis (a NE-SW oriented feature identified as L-1 and a NW-SE oriented feature identified as L-2), and the corresponding thickness variations (Figure 6) indicate that these areas subsided more rapidly during Winduck Interval deposition. Similar structural lows or synclinal areas are observed by thickening in the isochore map of the Snake Cave Interval (Figure 7), although the extent is more limited due to erosion of the unit within the sub-basin (Figure 6). Nevertheless, there are clear increases in thickness of the Winduck and Snake Cave Intervals from near the western and eastern edges of the Blantyre Sub-basin towards its centre.

Figure 10 shows thinning of the Winduck and Snake Cave Intervals on to the Wilcannia High in the west in seismic section F5-F6, and a remarkable thickening of the late Early Devonian to early Middle Devonian Snake Cave Interval in the Blantyre Sub-basin to the east of this structure, towards the Kewell East-1 well. It also indicates that the base of the Ravendale is present farther to the east, around shot point 1800 on seismic profile SS134>HD-116, where the Snake Cave Interval is again of more 'normal' thickness.

Figure 9 illustrates the stratigraphic and present-day structural configuration of the Blantyre Sub-basin. Lithostratigraphic unit relationships within the east-central Blantyre Sub-basin are similar to those in the west-central portion of the study area.

Although the nature of the sequence is poorly documented due to limited well penetration, the Winduck Interval and the Mulga Downs Group (Snake Cave and Ravendale Intervals) show little variation in thickness, suggesting tectonic quiescence within the region during the period of sediment accumulation. The most prominent feature is the alternate thickening and thinning of the area adjacent to the faults identified by this study in regional seismic sections, F3-F4 and F5-F6 (Figures 8 and 10). However, the characteristics of the Winduck, Snake Cave and Ravendale Intervals are particularly evident where sequences are thicker, in the central part of the section (between SP 400 and 800, Figure 9). They gradually disappear where the Winduck and Snake Cave Intervals become thinner, near the Wilcannia High, close to the northern margin of the sub-basin, for example between shot points 186 to 432 in seismic profile SS134>HD-112 (Figure 10).

Tectonstratigraphic Evolution of the Blantyre Sub-basin

Figures 11 and 12 provide a simplified reconstruction of the deformation history for the Winduck, Snake Cave and Ravendale tectonostratigraphic packages within the Blantyre Sub-basin. Four stages of tectonic evolution are suggested for the study area: (a) rapid subsidence, (b) compression associated with continued subsidence (Tabberabberan Event) (c) compression associated with uplift and erosion (Alice Springs/Kanimblan Event) and (d) extension associated with slow subsidence.

Cross-section through the Mount Emu High

Cross-section T1-T2 (Figure 11) represents a section across the Mount Emu-1 well, extending from seismic profile DMR03-05 near structural low L-2 (Figure 3) through the Mount Emu anticline, and north-east to seismic profile SS134>HD-125 and the end of seismic profile SS143>HD-204 (for location see Figure 2). High subsidence rates are interpreted during deposition of the Winduck, Snake Cave and Ravendale Intervals over the two low areas (i.e. the two ends of cross-section T1-T2), and lesser subsidence rates (smaller thicknesses) across the structural high (i.e. the Mount Emu anticline).

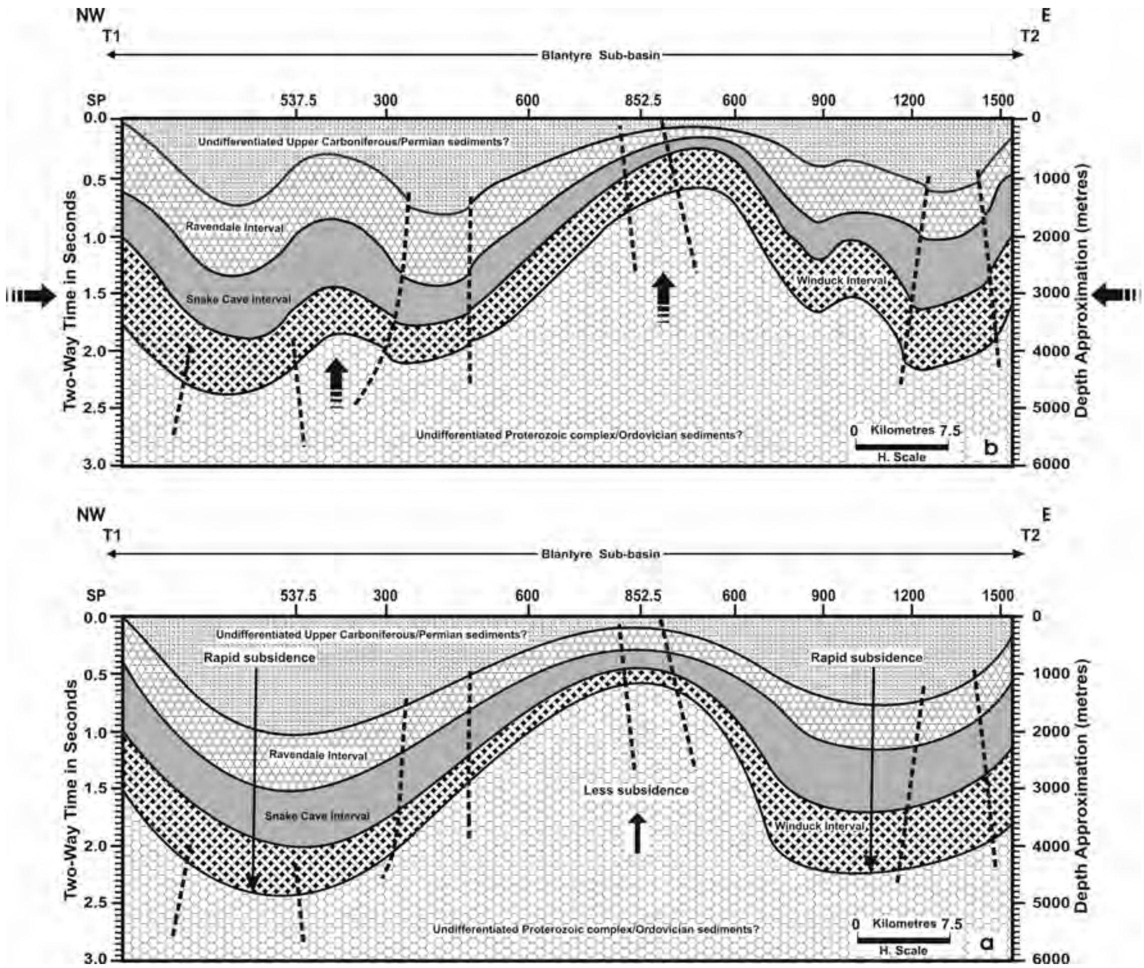

Figure 11 a & b. Cross-section T1-T2, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (a) High subsidence rates in the trough areas (b) Compression and localized deformation associated with subsidence. (Figure 11c & d on next page.)

Figure 11a represents a schematic reconstruction of the section during the rapid subsidence phase of basin development. The Winduck and the Snake Cave Intervals are of similar thickness in the two synclinal areas. However, the Ravendale Interval appears from seismic data, where a complete section is preserved, to be thinner in the synclinal area east of the Mount Emu High.

Compressive deformation then gave rise to folding in the synclinal areas (Figure 11b, c), and reverse faulting developed at several locations associated with both the synclinal and anticlinal areas. Additional downwarping occurred in the synclinal areas, and additional uplift on the intervening basement highs.

Regional uplift and erosion possibly associated with relaxation of the compressive stresses and development of the extensional regime, gave rise to the present-day structure of the sub-basin (Figure 11d). Cenozoic sediments were late deposited on the deformed Darling Basin units during the slower subsidence associated with this extensional phase.

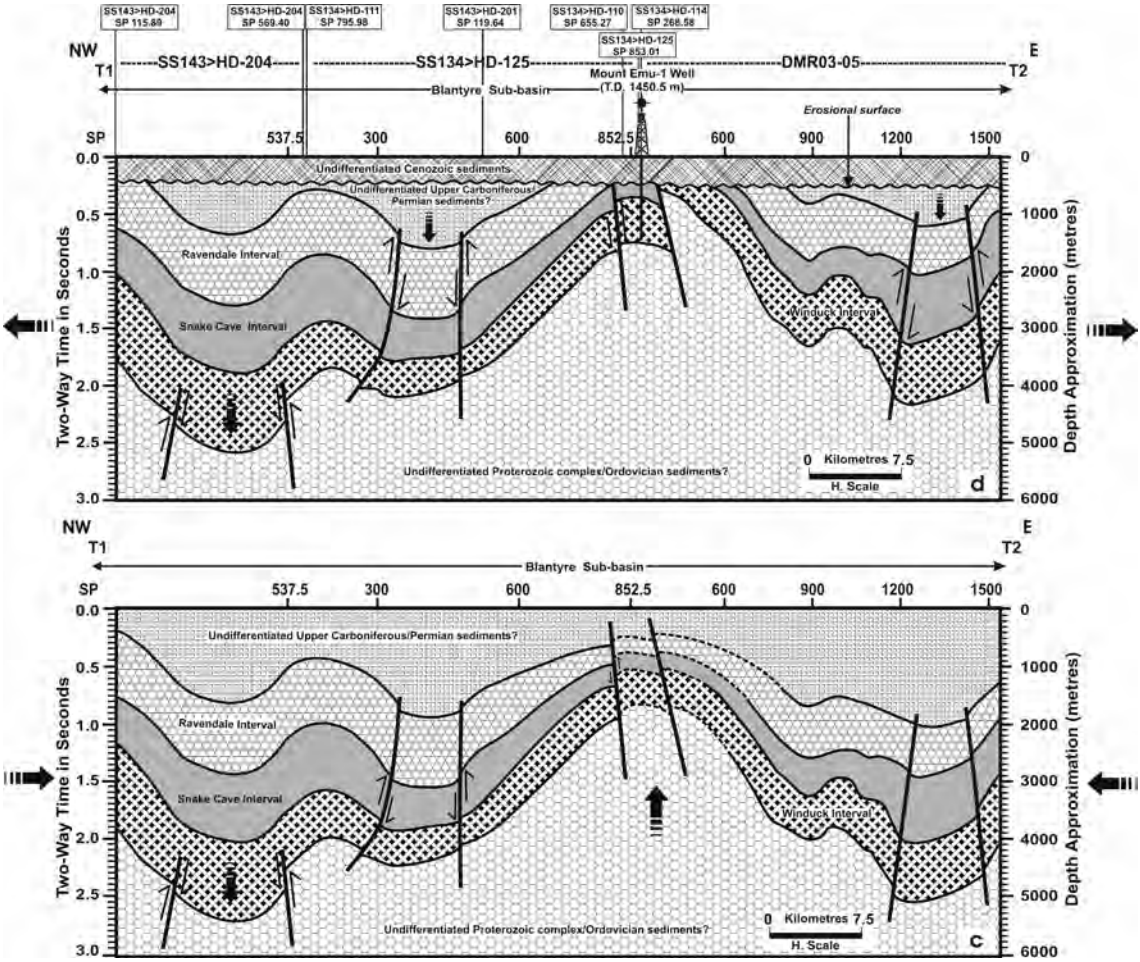

Figure 11 c & d. Cross-section T1-T2, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (c) More compression, showing further anticlinal folding associated with the Mount Emu structure to create complex reverse faults (d) Further development of the Mount Emu thrust fault, followed by extension, erosion and deposition of the Cenozoic sediments.

Cross-section through the Wilcannia High

Cross-section T3-T4 (Figure 12) is a dip section across the Wilcannia High, extending from the Kewell East-1 well in the east (part of the Neckarboo Sub-basin) through seismic profile SS134>HD-116 and part of seismic profile SS134>HD-114 (between shot points 937.66 to 1331.48), as shown in Figure 2, to the end of seismic profile SS134>HD-124.

Figure 12a represents a schematic reconstruction of the section during the rapid subsidence phase of sub-basin development. Lower subsidence rates are interpreted across the high area in the central part of cross-section T3-T4 during deposition of the Winduck, Snake Cave and Ravendale Intervals (Figure 12a). Higher subsidence rates during Winduck, Snake Cave and Ravendale deposition are interpreted in the trough area farther to the west on the same cross-section.

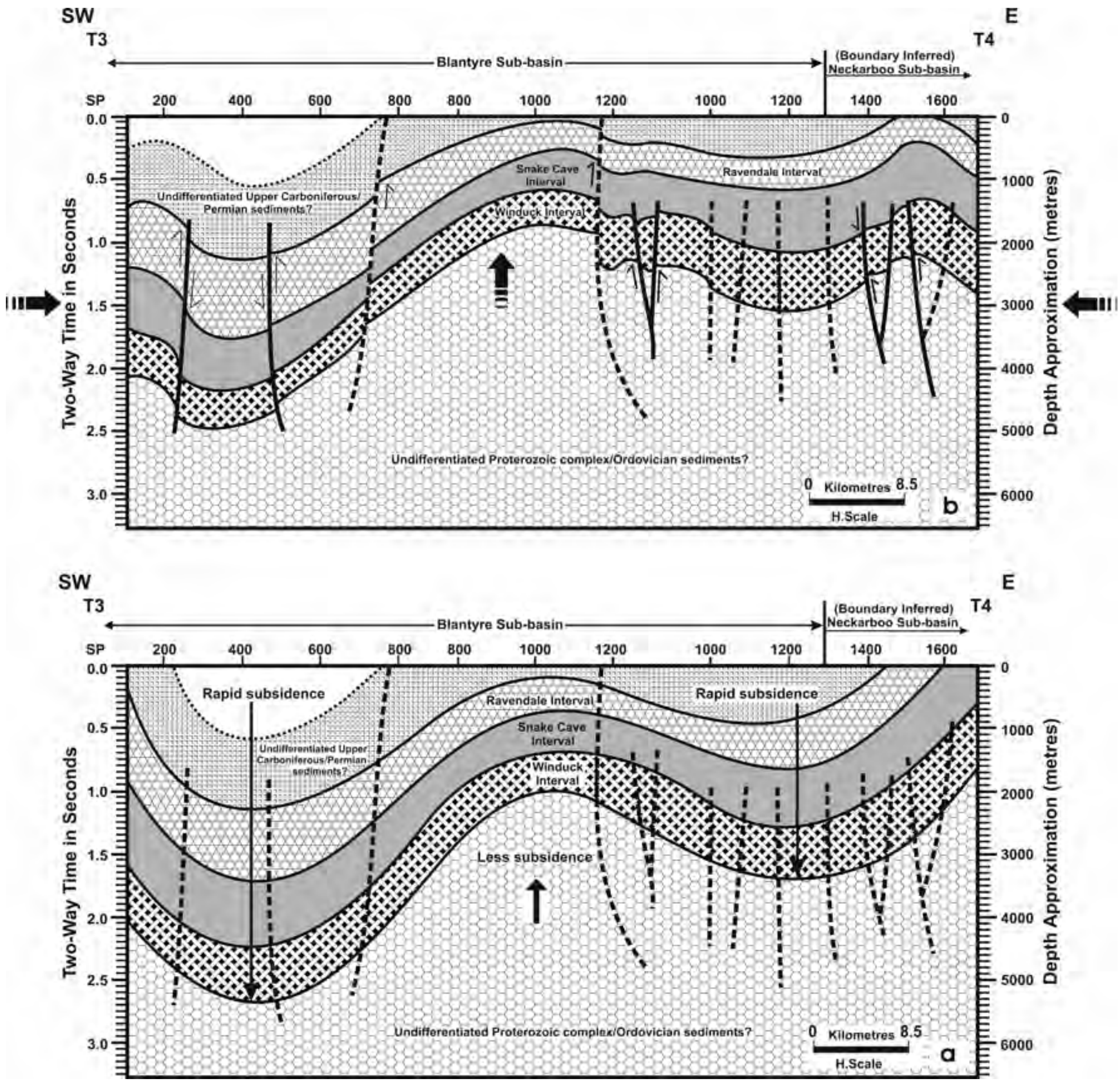

Figure 12 a & b. Cross-section T3-T4, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (a) High subsidence rates in the trough areas (b) Compression and localized deformation associated with further subsidence, especially in the southwest. (Figure 12 c & d on next page.)

The lithostratigraphic units representing the Winduck, Snake Cave and Ravendale Intervals are of similar thickness in the two synclinal areas, but the three tectonostratigraphic packages appear from the seismic data, where a complete section is preserved, to be thinner on the Wilcannia High itself, for example around shot points 1000 to 1200 on cross-section T3-T4 (Figure 12a).

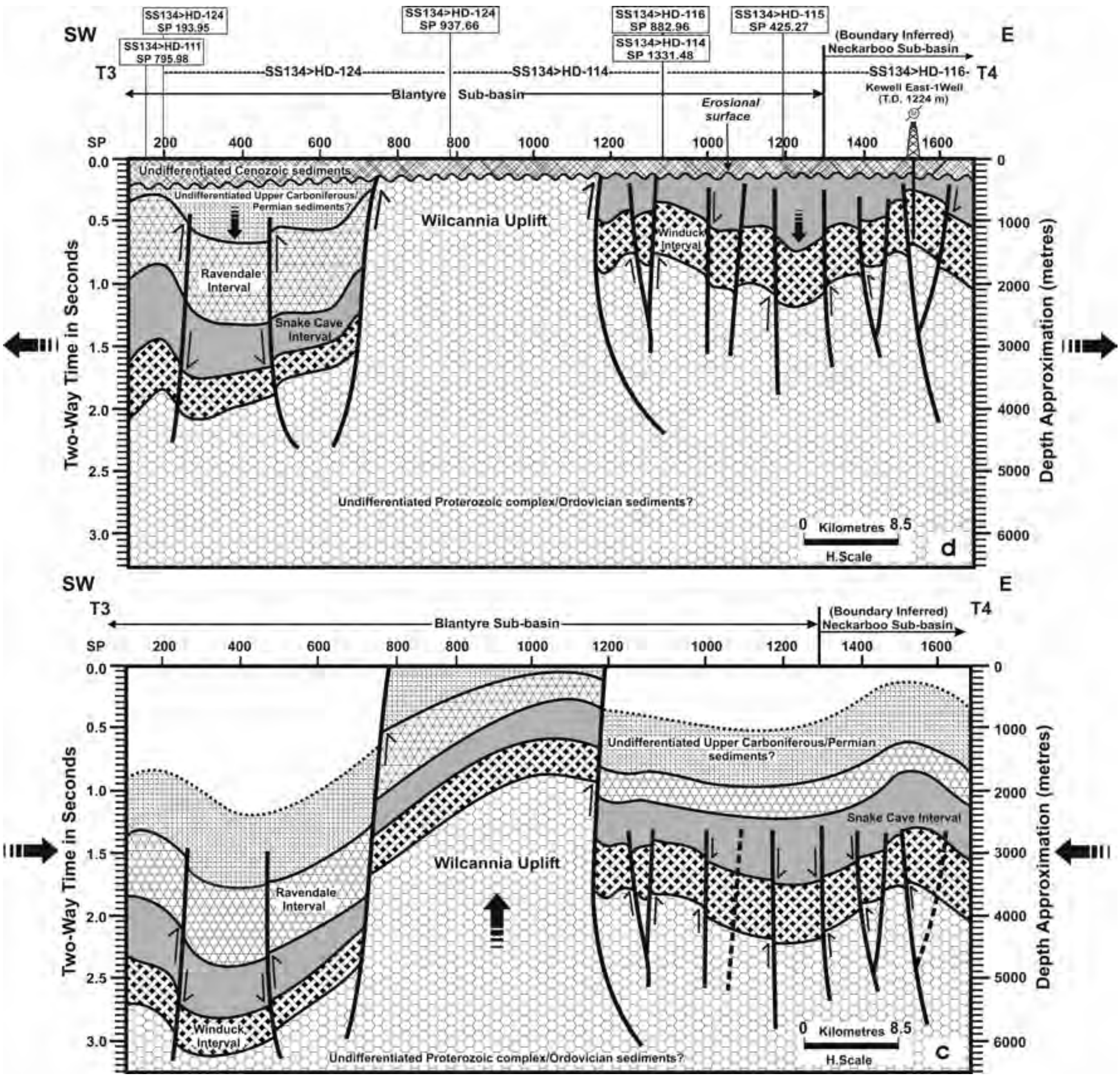

Figure 12 c & d. Cross-section T3-T4, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (c) More compression with maximum movement of the Wilcannia Uplift contrast in complex thrust and normal-faults in the east (d) Extension, enhancement of horst-graben structures, erosion and deposition of the Cenozoic sediments.

Figure 12b shows a reconstruction of the highly faulted area on the eastern end of section T3-T4, suggesting that major subsidence occurred around the eastern margin of the Blantyre and the western margin of the Neckarboo Sub-basins. The more structurally complex zone of normal and reverse faults in between the sub-basins is associated with later compression forming a relatively symmetrical synclinal fold. Figure 12c suggests that, by the end of the second tectonic stage, the Wilcannia Uplift had begun to develop in the area, with the Winduck, Snake Cave and Ravendale Intervals being partly or completely removed by post-structure erosion. The extent of erosion of the Ravendale Interval is further indicated in Figure 5.

The last stage of tectonic development represents extension, enhancement of the fault structures, regional uplift, erosion and deposition of the Cenozoic sediments over the whole of the Blantyre Sub-basin. However, Figure 12d shows extension with faults after the Devonian, and then deposition of the overlying Upper Carboniferous/Permian sediments during a tectonically quiet period with broad slower subsidence. Cenozoic sediments were deposited over the whole section following erosion.

The high on the eastern side of cross-section T3-T4 is part of the Kewell East Anticline, bounded on the west side by fault zones (complex of normal and reverse faults) and a near symmetric synclinal fold (Figure 12d). This high was drilled by the Kewell East-1 well (Clark et al. 2001).

Basement Surface

A change in basement dip is evident on regional seismic sections across kilometer-scale wavelength fold structures (e.g. Mount Emu and Snake Flat anticlines) and a basement 'pop-up' feature that was formed in post-Devonian time. Also shown on the regional sections that integrate the gravity data and the seismic profiles (Figures 11 and 12) is a strong onlap and thinning of the Winduck and Snake Cave Interval on to palaeo-basement highs, indicating that many of the present sub-surface highs were highs during sediment deposition. However, the faults bounding these paleo-highs had northwest-southeast, east-west and north-south strike orientations, supporting a suggestion that all of these fault systems were co-active during the extensional part of the sub-basin history and controlled differential subsidence. Similarly, 'palaeo-basement' character is inferred for the Mount Jack High and the Lake Wintlow Highs by Glen et al. (1996), Alder et al. (1998), Willcox et al. (2003) and Cooney and Mantaring (2007).

The basement structure may have influenced thickness variations in the Winduck and Snake Cave Interval. There are hints of this on the seismic data, where the basal Winduck Interval is interpreted to be faulted or gently warped (Figures 11 and 12). In turn, the shape and thickness of the Winduck Interval may have influenced fold development, such as across the Mount Emu anticlinal fold. In contrast, for areas to the northwest and southeast, gravity lows do correspond to basement depth estimated from seismic profiles SS134>HD-123, 124, SS143>HD-204, 218B and DMR03-05 (Figure 2).

Structural Aspects and Implications for Hydrocarbon Potential

The hydrocarbon potential of the Darling Basin has been discussed by Evans (1977), Brown et al. (1982), Byrnes (1985), Bembrick (1997a, b) and Wilcox et al. (2003), and described in more detail by Alder et al. (1998), Pearson (2003), Cooney and Mantaring (2007), Khalifa (2005), and Khalifa and Ward (2009). Herein, I summarize the specific structural aspects of the hydrocarbon potential prospects in the Blantyre Sub-basin related to the folding and associated complex faulting that have affected the latest Silurian-Devonian stratigraphic geometry.

The anticlinal crests of Snake Flat, Mount Emu and Kewell East folds are the primary targets for any future exploration (Figures 8 and 9), with additional potential for stratigraphic pitch-out plays on the flanks of some structures. Individual structures have areal closure of up 100 square kilometres, with more than 2000 metres of section under closure. The different models of fold formation described in this paper would influence any prospects. A tectonostratigraphic model of anticlinal geometry is assumed to have developed, as the fold translated over a fault, bending would predict a repetition of the deep section within the core of the fold structure. The fracture patterns predicted by the tectonostratigraphic model (Figures 11 and 12) also would be quite different, an important point considering that fracture permeability may play a significant role in developing viable hydrocarbon targets across the folds. The extent of these major folds beneath the Upper Carboniferous/Permian sediment and their possible hydrocarbon potential are important unanswered questions in the Blantyre Sub-basin.

CONCLUSIONS

This paper has attempted to integrate the data from the seismic profiles, several maps and wells into a consistent geologic picture, in order to add some new insights into the structural styles and tectonostratigraphic framework of the Blantyre Sub-basin.

A geological model has been derived from interpretation of two-way travel time structure contour maps, in conjunction with the regional gravity contour map. Several major structures have been identified and named. These include a large structure situated at the junction of three major high complexes, referred to as the Wilcannia High (H-2), and two smaller high areas. One of these, the Mount Emu High (H-1), is an anticlinal fold with thrust fault; the other, the Snake Flat High (H-3), is an asymmetric anticlinal fold with a number of high angle reverse faults. Two structural lows have also been identified, aided by correlations between the structure contour data and the gravity map, especially the structure contours on the base of the Winduck Interval. In the central part of the Blantyre Sub-basin, around the Blantyre-1 exploration well, there is a structural low (L-1). This is an elongate, synclinal fold, and covers an area of approximately 400 square kilometres. There is a second generally smooth structural low (L-2) within the Blantyre Sub-basin. This is also shown on the gravity contour map and the structure contour map on the base of the Winduck Interval, and is seen on seismic profile DMR03-05.

Isochore maps for each stratigraphic interval (in two-way travel time) have been compared with the travel-time structure contour patterns, especially for the Winduck and Snake Cave Intervals, to identify any thickening and thinning associated with structural development. Improved isochore maps will provide control for structure mapped on seismic profiles, especially the Wilcannia, Mount Emu and Snake Flat structural highs. Key seismic cross-sections, T1-T2 and T3-T4, were also constructed to assist the analysis process, and further investigation of relationships between the tectonostratigraphic sequences, sub-basin geometry, and the development of complex structures within the study area.

The following broad history has been identified from these interpretations and a review of the basin's tectonic evolution: (a) high subsidence rates in the trough areas, (b) compression and localized deformation associated with further subsidence, (c) extension, enhancement of normal and reverse faults, including the Wilcannia Uplift and (d) erosion and deposition of the undifferentiated Permo-Carboniferous, Early Cretaceous and Cenozoic (Tertiary and Quaternary) sediments, identified at shallow depths within the main Blantyre Sub-basin.

A tectonostratigraphic model has been put forward to address the variation in compressional and extensional fault and fold-related stresses that created the observed differences in the deformation of the original normal and reverse faults, and the synclinal and anticlinal fold structures. The positive subsidence patterns are always fault-controlled, as shown in cross-sections T1-T2 and T3-T4 (Figures 11 and 12). Understanding the ongoing structural processes within interpreted seismic data should help to decrease the risk of hydrocarbon exploration by applying up-to-date concepts throughout the Blantyre Sub-basin.

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APPENDICES

Summary of seismic data acquisition and processing parameters in the study area.

Date: 1984 by Seiscom Delta United Inc. Example: SS134>HD-114, 116, 123, 124, 125

ACQUISITION

1. Energy Source

Type:	Vibroseis Mertz Y-12
Source interval	60 metres
Sweep length	6 seconds
Sweep frequency	16–96 Hz upsweep
Source array	16 sweeps per station
Number of vibrators	4

2. Recording Geometry

Fold of recording	1200%
Geophone group length	33 metres
Spread	1980-100-SP-100-1980 metres
Number of groups	96 at 40 metres intervals

3. Instrumentation

Geophones	GSC HS 20D (10Hz) 12 per group
Filters:	Low cut OUT Hz slope dB/octave
	High cut 128 Hz slope 72 dB/octave
Record format	SEGY
Record length:	5 seconds
Sample interval:	2 milliseconds

PROCESSING

1. Initial Process:	Resample	4 milliseconds
	Trace edit	
2. Trace Equalisation:	Gate length	800 milliseconds
3. Datum Statics:	Static corrections	source and receiver elevations
	Datum	100 metres
	Replacement velocity	3000 meter/seconds
4. Velocity Analyses:	Velocities	Seiscom's Dove Velocity Spectra
	Computed	before and after DEWL
5. DEWL:	Surface consistent statics adjustment	
6. Trace Equalisation:	Gate length	500 milliseconds
7. Stack:	Type	Standard CDP
8. Bulk Shift:	-70 milliseconds	
9. Display System:	Type	Trace equalized
	Vertical scale	10 cm/sec
	Horizontal scale	10 traces/cm
	Peaks represent	Increase impedance

Continued on next page.

Date: 1985 by Seiscom Delta United Inc. Examples: SS143>201, 204 & 218B

ACQUISITION

1. Energy Source	
Type	Vibroseis: Mertz Y - 12
Source interval	80 metres
Sweep length	6 seconds
Sweep frequency	16 – 75 Hz upsweep
Source array	16 sweeps per station
Number of vibrators	4
2. Recording Geometry	
Fold of recording	2400%
Geophone group length	33 metres
Spread	1980 – 100 – SP – 100 – 1980 metres
Number of groups	96 at 40 metres intervals
3. Instrumentation	
Geophones	GSC HS 20D (10Hz) 12 per group
Filters:	Low cut OUT Hz slope dB/octave
	High cut 128 Hz slope 72 dB/octave
Record format	SEGY
Record length:	5 seconds
Sample interval:	2 milliseconds

PROCESSING

1. Initial Process:	Resample	4 milliseconds
	Trace edit	
2. Trace Equalisation:	Gate length	800 milliseconds
3. Datum Statics:	Static corrections	source and receiver elevations
	Datum	100 metres
	Replacement velocity	3000 meter/seconds
4. Velocity Analyses:	Velocities	Seiscom's Dove Velocity Spectra
	Computed	before and after DEWL
5. DEWL:	Surface consistent statics adjustment	
6. Trace Equalisation:	Gate length	500 milliseconds
7. Stack:	Type	Standard CDP
8. Base Level Scaling:	9 window design	
9. Display System:	Type	Trace equalized
	Vertical scale	10 cm/sec
	Horizontal scale	10 traces/cm
	Peaks represent	Increase impedance

Continued on next page.

Date: 2003 by Trace Energy. Example: DMR03-05

ACQUISITION

Type	Vibroseis
Sweep frequency	5–90 Hz
Record length	6 seconds
Instruments	Sercel SN 388
Geophone group length	Sensor SM-4 LD SM-24
Sample rate	2 milliseconds
Record length	6 seconds
Filters:	Low cut OUT
	High cut 125 Hz
	Notch
Record format	SEGY
Spread	240 channel split spread
	Near offset - 12.5 metres
	Far offset - 2987.5 metres
Group spacing	25 metres
Shot spacing	25 metres

PROCESSING

Reformat	Input to promax internal format
Edit	Remove bad traces from shot record
Geometry	Set up shot and receiver co-ordinates
Filter	Zero to minimum phase filter
Deconvolution	Zero phase spectral whitening 5/7 - 90/110 Hz
	2 panels
Residual statics	Surface consistent residual statics calculated following structure.
	Window 1000 ms
	20 ms maxshift
Mute	First arrivals 30% stretch mute
Stack	CDP stack
	Data shifted to 122 metres datum
Filter	10 – 80 Hz filter
Scale	500 milliseconds AGC

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