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Aspects of stratigraphy and structure in relation to the Woolpunda Groundwater Interception Scheme, Murray Basin, South Australia

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Micropalaeontological and biostratigraphic studies have been used to assist understanding of the stratigraphic and structural context of groundwater flow systems in the vicinity of the Woolpunda Groundwater Interception Scheme (WGIS) — a major area of saline groundwater discharge to the River Murray in the western Murray Basin. Structure was defined by tracing several stratigraphic markers in the Late Oligocene to Middle Miocene succession, including the *Lepidocyclina* foraminiferal zone and three clay or marl units of low permeability. A cross-section through the upper part of the Cainozoic sequence illustrates east–west arching, gentle Middle to Late Miocene folding, and intermittent mild Cainozoic uplift. Arching and doming across the WGIS area is confirmed by a structure contour plot on top Renmark Group, and by limited drilling in the deeper Eocene and Cretaceous sediments. The arched structure apparently relates to draping of the Tertiary succession over a high of pre-Tertiary rocks related to the Hamley Fault. This high acts as a permeability barrier to the Renmark Group confined aquifer which thins significantly over it, promoting upward leakage into the water table aquifer, with resultant high saline discharge to the River Murray.

Introduction

The Woolpunda Groundwater Interception Scheme (WGIS) is a scheme designed to minimise saline groundwater inflows to the Murray River in the critical stretch between Overland Corner and Waikerie (Figs 1, 2), where about 200 tonnes of salt per day enter the river. This has a major impact on the domestic, industrial and agricultural users downstream. The Scheme, which is planned to cost $25 million over 5 years during the present stages of investigation and construction, will involve drilling about 50 extraction wells distributed both north and south of the river, to pump the Murray Group (water table aquifer) and stop the saline groundwater (20 000 mg/L) from entering the river system. The Scheme is designed to reduce river salinity by 40–50 electrical conductivity units (ECUs), which will save downstream users well over $1 million per year in costs related to salinity, such as corrosion, water treatment, and loss in agricultural yields.

The WGIS area is also one of long-standing geological and biostratigraphic interest. To illustrate the stratigraphy and structure, we have constructed an east–west cross-section through the upper part of the Cainozoic sequence (Fig. 3) and a structure contour diagram for the top of the Renmark Group (Fig. 4). For practical hydrogeological purposes in this area, upper Renmark Group (i.e. Olney Formation) is taken to include fossiliferous sediments of marine incursions which preceded Ettrick Formation and which correlate in part with the Late Eocene Buccleuch Group or the Oligocene Compton Conglomerate.

Telfer (1987, 1988) has recently outlined aspects of the WGIS. Groundwater flow lines of the Renmark Group confined aquifer converge on the Waikerie–Overland Corner area from the east and north (Telfer, 1988, fig. 2). Marls of the overlying Ettrick Formation act as an aquitard. Asymmetric, low-angle anticlinal folding and draping of the sequence over resurgent structures in pre-Tertiary strata, together with the observed head difference between the aquifers, appear to encourage convergent groundwater flow to the area, and upward leakage of saline groundwater from the deep confined aquifer into the unconfined Murray Group aquifer, and hence into the Murray River.

Stratigraphy and structure

Regional Cainozoic stratigraphy has been outlined recently by Brown (1983, 1985), and a major synthesis is due to be published soon (Brown & Stephenson, in press). Table 1 lists Tertiary units relevant to the area under discussion.

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Table 1. Stratigraphic table of Paleocene to Middle Miocene rock units of the western Murray Basin, S.A

Age	*Formation*	*Group*
Middle Miocene	Pata Limestone	Murray Group
Early Middle Miocene	Morgan Limestone (including Cadell Marl Member)	(water table aquifer, with marl and clay aquitards)
Early Miocene	Finniss Clay and equivalents	
Early Miocene	Mannum Formation	
Earliest Miocene to	(Gambier Limestone)	Glenelg Group
Late Oligocene	Ettrick Formation.	(Ettrick Fmn marl unit is aquitard)
Oligocene	Compton Conglomerate and correlatives	
Late Eocene	Informal units	Buccleuch Group correlative (part of confined aquifer)
Oligocene–Eocene–Paleocene	Olney Formation and Warina Sand	Renmark Group (confined aquifer)

Figure 3 presents a cross-section of the area, vertically exaggerated by a factor of 250. This large expansion is needed to distinguish the various units, especially in the Murray Group, but it results in distortion, particularly in relation to the steepest dip on the cross-section (immediately east of Overland Corner), which is only 1°18′ at natural scale. The next steepest dip (between Lowbank

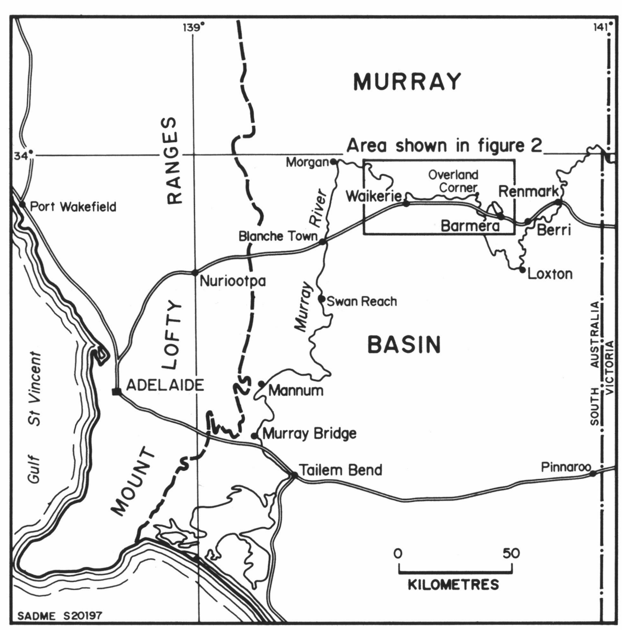

Figure 1. Locality map, western Murray Basin, South Australia.

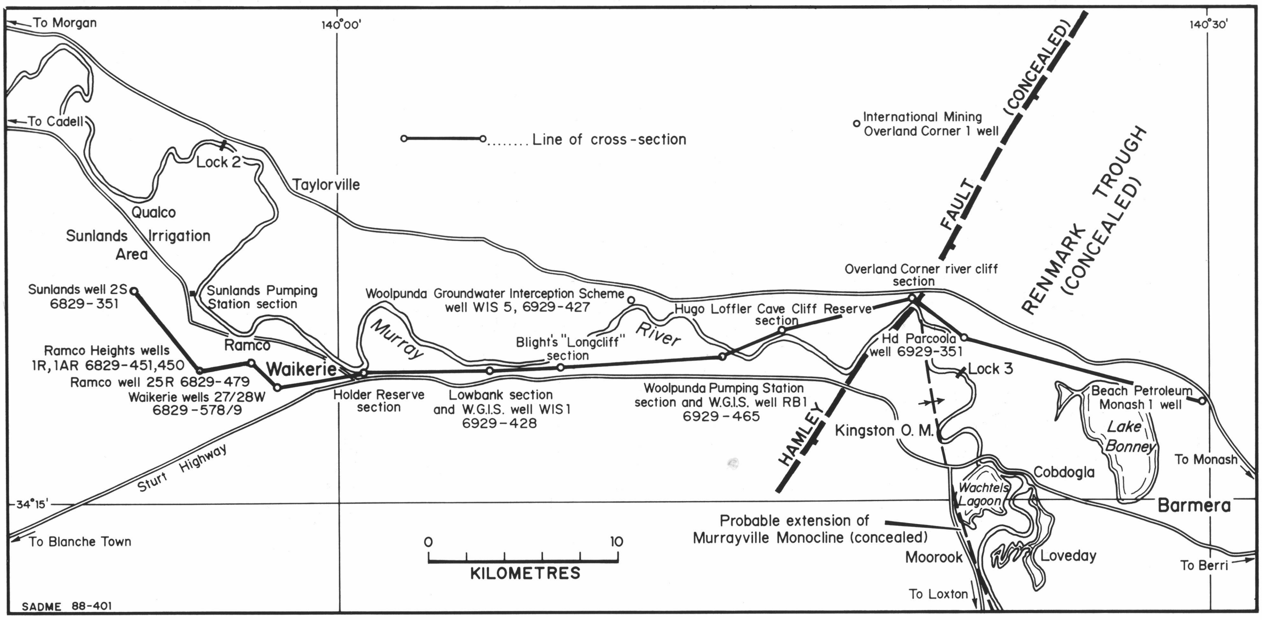

Figure 2. Locality map for east–west cross-section, Monash–Sunlands, Woolpunda Groundwater Interception Scheme, western Murray Basin, S.A.

and Waikerie) is only 13'. At natural scale, the total vertical dimension of the cross-section would be only about one millimetre. Although the units shown would appear extremely thin at this natural scale, most of them display considerable continuity across the area, and the correlations that are made relate to a consistent succession of lithostratigraphy and biostratigraphy.

Gentle east–west arching of the Murray Group, the Ettrick Formation, and the Renmark Group is evident between Sunlands and Overland Corner. This was indicated by tracing the foraminiferal marker zone of *Lepidocyclina howchini* Chapman and Crespin, developed a few metres above the base of Morgan Limestone (Lindsay & Giles, 1973). This relatively large, extinct, benthonic foraminifer with 'tropical' affinities characterises a thin, local total-range zone which can now be dated accurately as early Middle Miocene by association with the First Appearance Datum of the planktonic foraminifer *Praeorbulina glomerosa curva* (Blow) (see, for example, Berggren & others, 1985, p. 227; Haq & others, 1987, fig. 2). The *Lepidocyclina* zone is developed a few metres above the Finniss Clay equivalent, and is usually several metres below the Cadell Marl Member of Morgan Limestone (Cadell Marl Lens of Ludbrook, 1957, 1961). However, in Ramco Heights well 6829-450 (Fig. 3) *Lepidocyclina* has not been found, despite careful searching, probably because of unsuitable marly facies in a locality where the Cadell Marl is abnormally thick. The *Lepidocyclina* zone represents a regional episode of warm watermass and climate; the Cadell Marl also bears evidence of warm water influence in a rich and distinctive molluscan fauna with tropical affinities (Ludbrook, S.A. Dept. Mines & Energy, oral communication, 1989). The zone is only a few metres thick, occurs in a consistent stratigraphic position, and has been of great value in correlating sections of the Murray Group in outcrop and subsurface. The synclinal structure which is evident in the vicinity of Sunlands, near Waikerie (Fig. 3), depresses the top of the zone at least 13 m below normal pool level, while in contrast the zone is elevated to nearly 33 m above the same datum at the Woolpunda Pumping Station valley section. The horizon provides an accurate indication of the 50 m displacement of the Murray Group east of Overland Corner.

This broadly arched structure has been confirmed by subsequent drilling (Barnett, 1984, 1988), for example WGIS wells 6929-427 (WIS 5) and 6929-465 (RB 1). East of Overland Corner, rock units and the *Lepidocyclina* zone dip more steeply down to the east. This feature is no doubt related to the deep-seated Hamley Fault and adjacent Renmark Trough, which trend northeast–southwest, and is also probably due to an extension of the Murrayville Monocline trending northwest–southeast (Fig. 2; see O'Driscoll, 1960, pp. 22–23; Lindsay & Bonnett, 1973; Firman, 1973, fig. 4; Thornton, 1974, fig. 5). No faults are shown on Figure 3: the very low natural dips do not seem to require fault displacements between correlation points, and gentle flexure appears sufficient. Thornton (1974, fig. 10) indicated that fault displacement on the Hamley Fault did not extend up above Cretaceous units. Other lineaments, as portrayed for example by Firman (1970) and Lindsay & Giles (1973), have not yet been observed to produce faulting in the outcrop areas traversed by the cross-section.

In accord with structure in the Murray Group, contours of top Renmark Group for this area show a central elongated zone of elevated structure above -100 m Australian Height Datum (AHD), aligned slightly east of north (Fig. 4). Contours fall away particularly east of this rise, affected apparently by the Hamley Fault/Monocline, the Renmark Trough, and an extension of the Murrayville Monocline.

Control for thickness and base of the Renmark Group is sparse for the line traversed by this cross-section, but available data agree with the structure outlined above. Only Beach Petroleum Monash 1 well, at the eastern end over the Renmark Trough, penetrated Renmark Group — with a thickness of at least 290 m — entering Cretaceous strata at a depth of 536 m (about -500 m AHD) (Ludbrook, 1965). Waikerie 28W well (6829-579), towards the western end of the cross-section, bottomed at 332 m (about -300 m AHD) in palynologically dated Middle Paleocene Renmark Group (Harris, in Lindsay & Bonnett, 1973, p. 22) which was considered to be probably near the bottom of the local Cainozoic sequence. Renmark Group in this well was at least 180 m thick. International Mining Overland Corner-1 well, 10 km north of the section line and west of the Hamley Fault (Fig. 2), is reported to have encountered

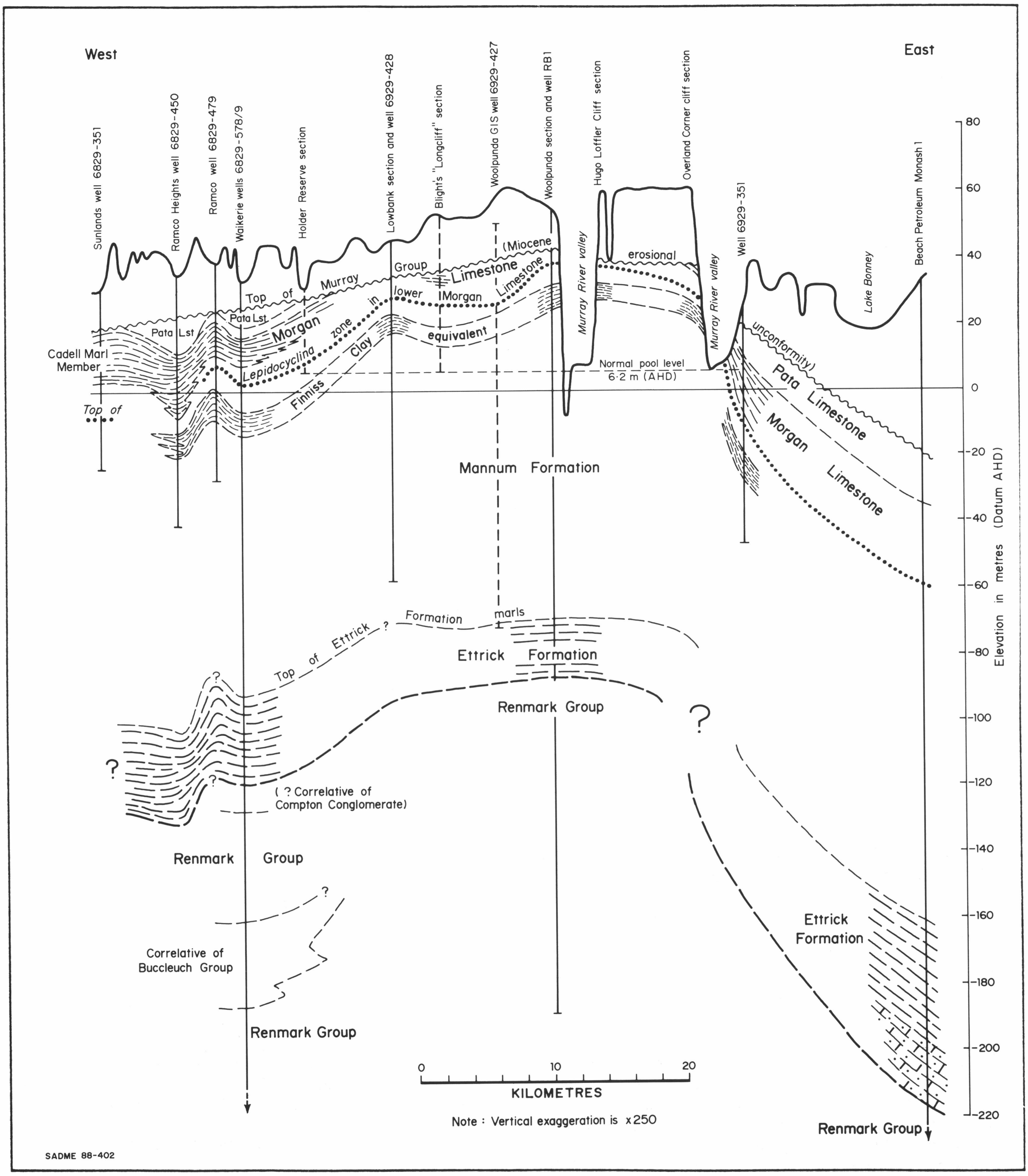

Figure 3. East–west cross-section, Monash–Sunlands, showing correlations and structure in mid-Tertiary succession (prepared by JML). Location of section is shown on Figure 2.

Cretaceous strata at a depth of only 257 m (-188 m AHD): Renmark Group was only 111 m thick (in Furr, 1984: data released with the permission of International Mining N.L.). This relatively shallow and thin intersection, supported by recent seismic data, suggests that Renmark Group is thinned and anticlinally draped over a high of pre-Tertiary rocks centred west of the Hamley Fault. Dips are steeper to the east, over the Hamley Fault: available information indicates that the vertical difference between the Cretaceous intersections in Overland Corner and Monash wells is 312 m. This is essentially the configuration shown by Telfer (1987, fig. 12, after Barnett).

The upwarping and thinning of Tertiary units over a ridge of pre-Tertiary 'basement' rocks associated with the Hamley Fault has apparently contributed to significant upward leakage from the Renmark Group confined aquifer to the overlying water table aquifer in the Murray Group, which

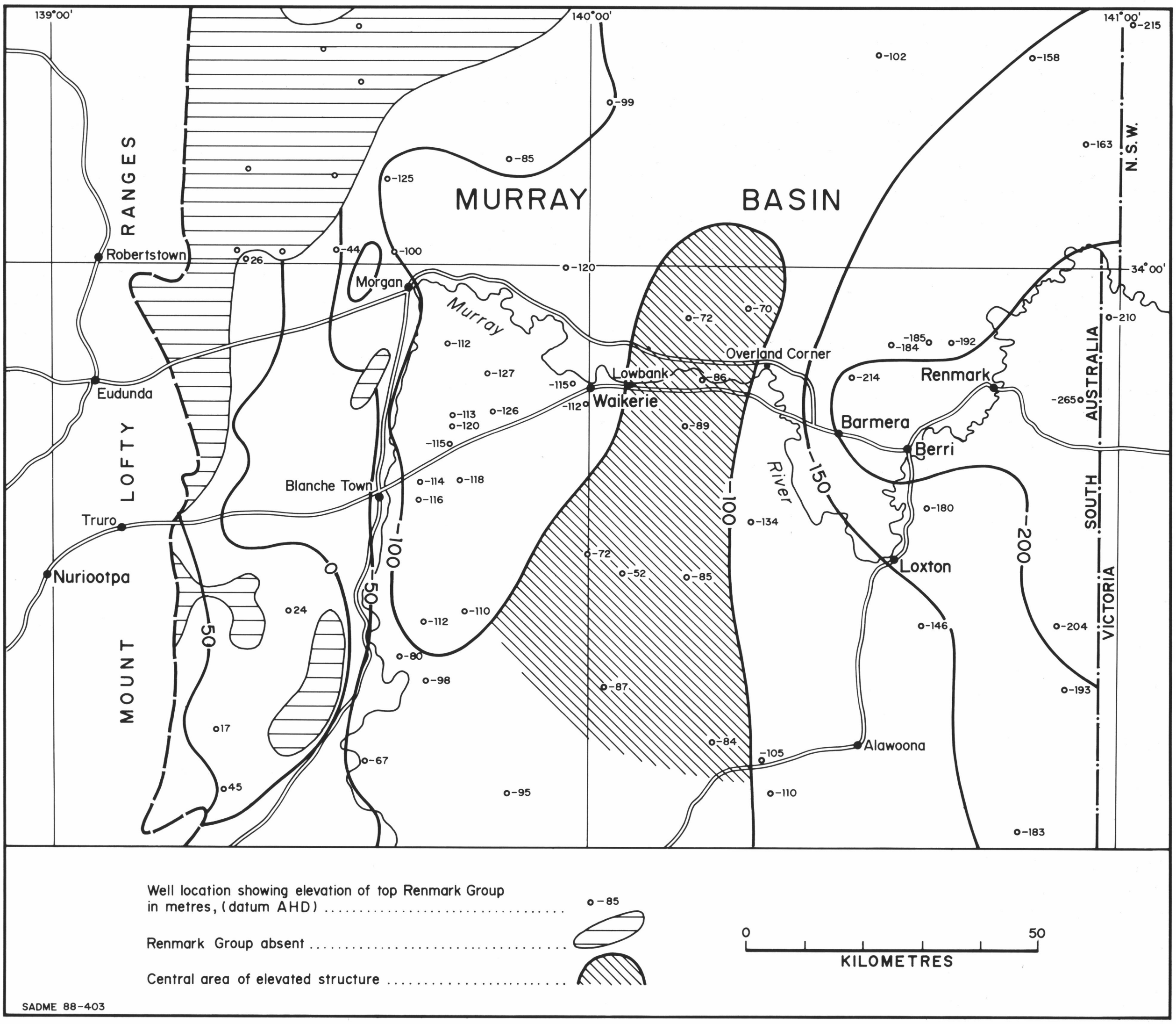

Figure 4. Contours of top of Renmark Group, central western Murray Basin, S.A. (prepared by SRB).

then discharges to the Murray River. Elsewhere in the Murray Basin, the driving force for groundwater discharge can also be related to high pressures and upward leakage created at permeability barriers formed where the aquifers are truncated by facies changes or significantly thinned by concealed basement barriers (Evans & Kellett, 1988).

East of Overland Corner, Pata Limestone occurs at the top of the Murray Group as described by Ludbrook (1961) and as in Parcoola well 6929-351 (Fig. 3). However, west of Overland Corner the formation has mostly been removed during a time of uplift, regional warping and erosion in the Middle to Late Miocene. A remnant of Pata Limestone, with a characteristic foraminiferal microfauna of Bairnsdalian (Middle Miocene) age, is preserved subsurface in a synclinal keel in the vicinity of Waikerie well 28W 6829-579 (Lindsay & Bonnett, 1973). A more complete section of the formation, 13.4 m thick, is preserved in a similar synclinal setting at the top of the Murray Group and over a thick development of the Cadell Marl in Ramco Heights 1R well 6829-451 (Figs 2, 3; Lindsay, 1965). The same structure is probably responsible for the only known outcrop of Pata Limestone, at Sunlands Pumping Station (Fig. 2; Lindsay, 1965; Pledge, 1985).

It is evident that the Murray Group was gently folded before the formation of the erosional unconformity, of latest Miocene or earliest Pliocene age, which truncates it. The unconformity itself, at the base of Bookpurnong Formation (Bookpurnong Beds of Ludbrook, 1957, 1961; see Carter, 1985), or the base of the Loxton Sands where the Bookpurnong Formation is absent, is also slightly arched, suggesting possible subsequent deformation. Even the broadly domed land surface, discernible despite the exaggerated topography, suggests that such intermittent movement might have continued into relatively recent times. Resurgent tectonics, the effects on overlying sedimentary sequences of the intermittent activity of deep-seated faults and flexures, have been noted previously in connection with the Murray Basin (Twidale & others, 1978, p. 30). Since the time of Plio-Pleistocene Lake Bungunnia (Firman, 1965, 1973; An Zhisheng & others, 1986; Stephenson, 1986), incision of the Murray River gorge, particularly at times of cyclical low sea level, has in general kept pace with any uplift. As a result the river is deeply but unevenly entrenched into the Murray Group.

Clay and marl units

The Cadell Marl occurs above the *Lepidocyclina* zone and is also of early Middle Miocene age, preceding the *Orbulina* First Appearance Datum. The member is recognised widely in the Riverlands region, both subsurface and in outcrop, with a major development between Sunlands and Waikerie (Fig. 3). This is the 'blue clay' unit distinguished by Barnes (1951, p. 17) and still to be seen as figured by him in the river cliffs near Waikerie Pumping Station. It weathers to a soft, sloping surface in contrast to the vertical cliffs of limestone or sandstone. The sloping shelf of damp marl is a prominent feature along the river cliffs near Waikerie, where it is associated with seepages, slumps, and hydrophytic vegetation. The Cadell Marl Member is at the eroded, local top of Morgan Limestone in Sunlands well 6829-351, and at the cliff sections at 'Longcliff' and Overland Corner. The lenticular habit of the member is evident, but the lensoid developments can be much larger than the type section: the Sunlands–Waikerie–Holder body, which extends at least 17 km east–west and is up to 22 m thick, comprises a substantial proportion of the Morgan Limestone in this area compared with the type section 5 km south of Morgan, where the lens of Cadell Marl is only 91 m long (north–south) and up to 6.7 m thick (Ludbrook, 1961). Southeast of Overland Corner, in Parcoola well 6929-351, the Cadell Marl Member—logged as 'grey fossiliferous sticky clay'—is prominent between 18 and 36 m depth in the Morgan Limestone section. Where the member is well developed it may act as an aquitard and have a significant influence on the hydrogeological properties of the upper Murray Group. This appears to be the case in the Waikerie–Ramco–Sunlands area, where the member is substantial, structurally depressed, and is intersected by the water table (compare Fig. 3 with Telfer, 1988, fig. 1). However, in the WGIS area, any developments of Cadell Marl are above the water table and do not affect the section being pumped.

Finniss Clay equivalent comprises a fine-grained, clayey and silty intercalation within the limestones of the Murray Group, stratigraphically distinct from the Cadell Marl Member and generally found in this area a few metres below the *Lepidocyclina* zone at about the (bio)stratigraphic level of the Finniss Clay at its type section. The type section, at Mannum Pumping Station (Ludbrook, 1961, p. 46), disconformably overlies echinoid-rich sandstone and limestone of stratotype Mannum Formation. Above the main, basal bed which is 1.8 m thick, the clay passes upwards conformably, by interbedding, into an erosional remnant of basal Morgan Limestone at the top of which the lowest part of the *Lepidocyclina* zone has been preserved (Lindsay & Giles, 1973).

In the Hugo Loffler Cave Cliff Reserve section (location shown on Fig. 2) Finniss Clay equivalent, which was recognised by these authors in the same biostratigraphic succession, is a soft silty marl with minor limestone, eroding more readily than the limestones above and below: the 4 m high cave, after which 'Cave Cliff' is named, is weathered out of the unit. The underlying sandy limestone, which is echinoid-rich in parts and extends down more than 20 m to normal river level, is Mannum Formation. At the Lowbank, 'Longcliff', Woolpunda valley, and Overland Corner sections (Lindsay & Giles, 1973), similar softer and fine-grained intercalations at the same (bio)stratigraphic level weather to more gentle slopes than the surrounding limestones (compare Ludbrook, 1961, fig. 16) and are also underlain by Mannum Formation down to normal river level. Both Cadell Marl and Finniss Clay equivalents can be recognised as slope-forming units at separate stratigraphic levels at 'Longcliff' and Overland Corner. Lindsay & Bonnett (1973, p. 14) noted that in wells drilled at Waikerie, Finniss Clay equivalent comprised brownish-grey, soft, quartzose, fossiliferous silty marl with subordinate bryozoal limestone. Similar lithologies are encountered in wells at other localities. The unit does not develop to as great a thickness as the Cadell Marl Member, but seems to be more persistent. However, it appears to wedge out between the Ramco Heights and Sunlands wells shown in Figure 3. Hydrogeologically, the Finniss Clay equivalent might also be an aquitard, interrupting the succession of Murray Group limestones, and it would need to be taken account of in the Holder, Waikerie, and Ramco areas, where it occurs beneath the water table. However, in the WGIS area it is in most places elevated above the water table and does not affect the section to be pumped.

Within the succession, there is a distinctive unit of fossiliferous glauconitic marl, mudstone, or clay of the Ettrick Formation, forming a significant aquitard between the unconfined Murray Group limestone aquifer and the confined Renmark Group aquifer. Marl lithology was the original distinguishing feature of the formation (Ludbrook, 1957), and the top of this lithology is a useful marker horizon although transitional at some localities. A generally concordant relationship to marker units in the Murray Group is apparent in Figure 3. Limestone at the top of Ettrick Formation forms part of the upper aquifer, and although microfaunally characteristic, may be difficult to distinguish lithologically from Mannum Formation limestone or a widespread tongue of Gambier Limestone (Ludbrook, 1969; Lindsay & Williams, 1977). In Monash 1 well (Figs 2, 3), the interval 226–247 m, comprising brown glauconitic sandy limestone with pyrite-quartz aggregates, and carbonised wood fragments at the base, and about which there was some doubt as to correlation (Ludbrook, 1965), has been re-examined by one of us (JML). The interval is confirmed as containing no recognisable microfauna, and continues to be accommodated tentatively in Ettrick Formation beneath the marl unit. At 247 m, taken to be top Renmark Group, the well passed into carbonaceous pyritic quartz sand, and at 253 m into earthy lignite. In contrast, the recently drilled WGIS well RB 1 (6929-465) at Woolpunda (Figs 2, 3) passed directly from Ettrick Formation marl into brittle lignite, comprising the top of Renmark Group, at the relatively shallow depth of 146 m.

Buccleuch Group

In the deep Waikerie wells 6829-578 and 579, an interval 66 m thick underlying Ettrick Formation, and comprising silty sand with subordinate clay or marl, was correlated broadly with the Buccleuch Beds (Buccleuch Group of Ludbrook, 1957, 1961) by Lindsay & Bonnett (1973). In particular, the lowest part, 10.7 m thick, was compared both lithologically and microfaunally with the lower part of the subsurface type section of Buccleuch bed 'A', 160 km to the south, described by Ludbrook (1961). The 24 m thick 'lower shelly unit' (Fig. 3) (including the 'lower Buccleuch A equivalent') continues to be recognised as a Late Eocene correlative of the Buccleuch Group, the 'intermediate (regressive) unit' is regarded as part of upper Renmark Group (Olney Formation), and the sandy 'upper shelly unit', of Oligocene age, is correlated tentatively with Compton Conglomerate. Further drilling and study are needed to determine the extent and appropriate nomenclature of the various recognisable Buccleuch lithologies and the Buccleuch marine transgression, including relationship to marginal-marine influence in Olney Formation. However, so far as is known, these facies changes in the upper part of the Renmark Group confined aquifer do not have a significant effect on the hydrology.

It may be noted that although constituent formations of the Buccleuch Group still await formal naming, group terminology which was formerly inappropriate under the earlier Australian Code of Stratigraphic Nomenclature (Lindsay & Bonnett, 1973, p. 21) is now allowable, according to the International Stratigraphic Guide now generally applicable to Australian usage. Although 'the term group is generally used for an assemblage of formations, . . . it may also be used for a stratigraphic sequence of any kind of rocks that will probably be divided in whole or in part into formations in the future' (Hedberg, 1976, p. 34).

Conclusions

1. Foraminiferal biostratigraphic analysis and, in particular, tracing of the *Lepidocyclina* zone in outcrop and subsurface, has proved a useful tool to correlate sections of the Murray Group across the western Murray Basin, including the recently prominent WGIS area.
2. Once the position of the *Lepidocyclina* zone is known within the various possible limestones and clayey intercalations of the Murray Group at a locality, it has generally not been difficult to identify the local succession, including the Cadell Marl Member of the Morgan Limestone above the zone, and the Finniss Clay equivalent below.
3. These clay and marl marker units in the Murray Group, and also the Ettrick Formation marl unit, have been traced across the area. To varying degrees they are of actual or potential hydrogeological significance as aquitards. In the Waikerie–Sunlands area, the Cadell Marl is relatively thick and, at least in part, structurally depressed below the water table, hence is likely to have a significant effect on the local hydrology. In contrast, both the Cadell Marl and the Finniss Clay equivalent are elevated above the water table through most of the WGIS area. The Ettrick Formation marl unit is important throughout as the aquitard separating the water table aquifer from the confined aquifer.
4. The cross-section demonstrates gentle arching of the Murray Group and Ettrick Formation across the WGIS area. Noteworthy features are elevation east of Waikerie to Woolpunda and Overland Corner, depression from Waikerie westwards to Ramco and Sunlands, and, east of Overland Corner, the previously known downwarping over the Murrayville Monocline and the Hamley Fault into the Renmark Trough.
5. This structure is confirmed in depth by available drill hole penetration, shown for example by structure contours drawn on the top of the Renmark Group confined aquifer. Relatively shallow and thin intersections of the Renmark Group, as in Overland Corner 1 well, indicate that it is anticlinally draped and thinned over a high of pre-Tertiary rocks centred west of the Hamley Fault. Other studies suggest that this high acts as a permeability barrier to the confined aquifer, promoting upward leakage of highly saline groundwater through the Ettrick aquitard into the Murray Group water table aquifer. This, in turn, results in high saline discharge to the River Murray where it has incised the Murray Group deeply across the Woolpunda structural arch.
6. Marine facies intercalated in upper Renmark Group (Olney Formation) near Waikerie, and correlated in part with the Late Eocene Buccleuch Group, apparently do not affect the hydrology of the Renmark Group but are discussed briefly as a stratigraphic feature.
7. In the structurally depressed Waikerie–Sunlands area, Middle Miocene Pata Limestone at the top of the Murray Group has been preserved as subsurface synclinal remnants after pre-Pliocene erosion, providing also the only known outcrop of Pata Limestone, at Sunlands Pumping Station. This episode of Middle to Late Miocene warping and minor folding is one expression of the intermittent and gentle Cainozoic resurgent tectonics suggested by the cross-section through the WGIS area.

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