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# The Ivanhoe Block—its structure, hydrogeology and effect on groundwaters of the Riverine Plain of New South Wales.

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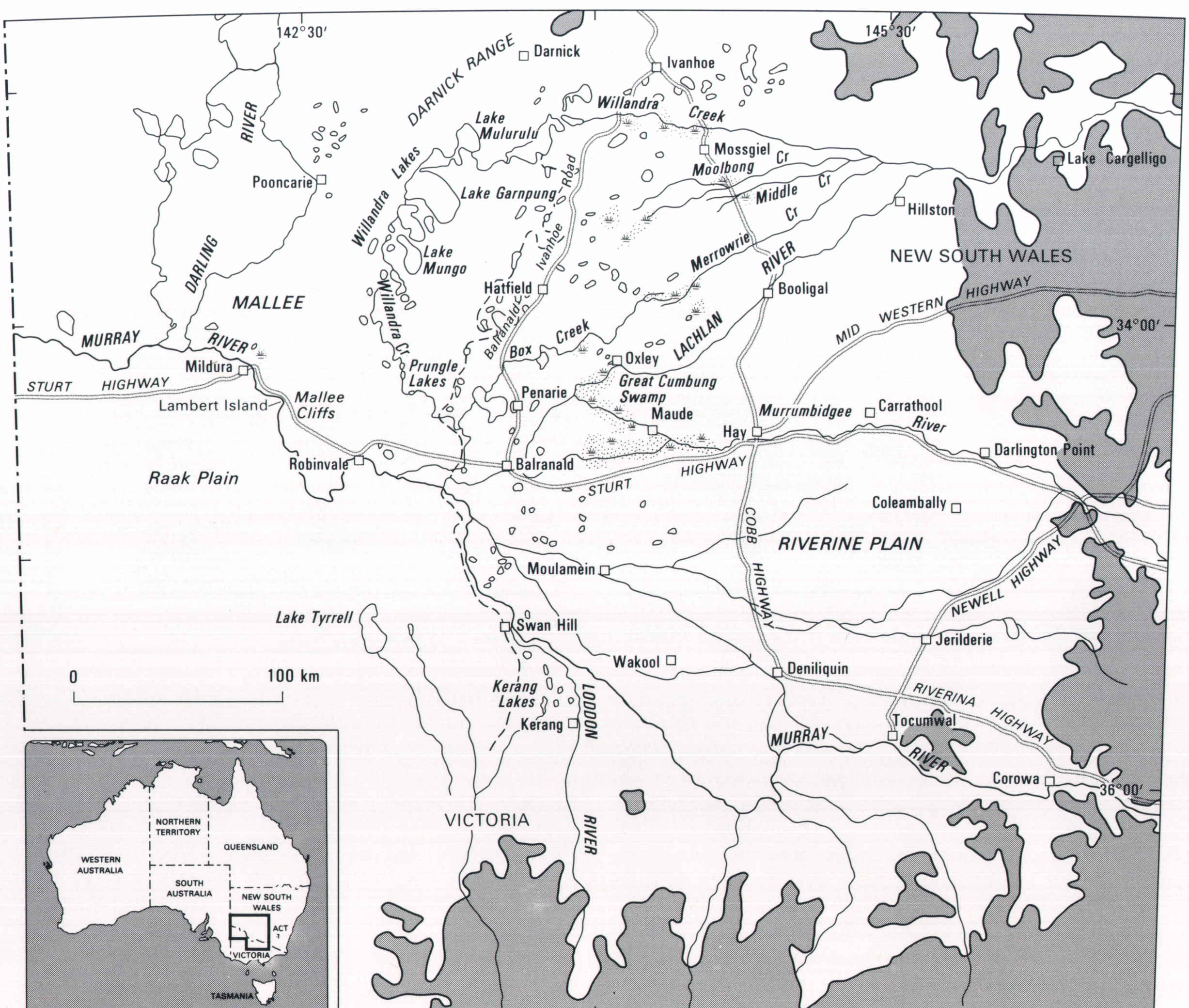
The Ivanhoe Block is a faulted and uplifted concealed basement ridge complex underlying the mallee sand dunes adjacent to the New South Wales part of the Western Riverine Plain in the central Murray Basin. The western ridge of the Ivanhoe Block forms the regional divide between the Darling and Lachlan–Murrumbidgee groundwater systems. The parallel basement ridges of the Ivanhoe Block deflect flow south in the deeper aquifers, and thinner beds on top of the ridges result in convergence of flow in the shallower aquifers. The Geera Clay aquitard is enveloped by the Renmark Group on the Ivanhoe Block—this produces an additional barrier to lateral groundwater throughflow.

Groundwater salinity is strata-bound in the aquifers of the Ivanhoe Block and Western Riverine Plain, and this enhances the value of electric logs in accomplishing a 3-fold subdivision of the Renmark Group—a basal fluvial succession, overlain by a paralic grading to marginal marine sequence which in turn is overlain by a prograding shoreline succession. The Western Riverine Plain is the regional groundwater discharge zone for the eastern Murray Basin in New South Wales, and it has been created by the impeding action of the bounding Ivanhoe Block. On the basis of rates of change of chloride concentration along regional flow lines in the Tertiary aquifers, the Western Riverine Plain is partitioned into the Balranald–Hatfield discharge zone in its western half and the Moulamein–Mossgiel buffer zone in its eastern half; the former defines the zone of salt production and accumulation in the shallower Tertiary aquifers and the latter defines the maximum historical extent of up-basin propagation of refluxed salts.

In recent years the Ivanhoe Block and western Riverine Plain of New South Wales have been the focus of growing community concern about clearing in the mallee lands and the susceptibility of these areas to land salinisation. This paper addresses the second issue. The Balranald–Hatfield discharge zone and the lower Willandra Lakes are most at risk from land salinisation if water tables continue to rise. The Moulamein–Mossgiel buffer zone is in the second-highest risk category, and the eastern Riverine Plain has a low risk of salinisation in its non-irrigated lands.

## Introduction

John Oxley is reputed to have been the first white man to gaze out over the Riverine Plain of New South Wales. In a letter to Governor Macquarie, dated 30 August, 1817, Oxley (1820) wrote 'The country south of the parallel of 34 and west of the meridian of 146 30 was uninhabitable and useless for all the purposes of civilised man'. History




---- *Mallee–Riverine Plain boundary*

**Figure 1. Locality map.**

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has not supported the Surveyor-General's opinion—the first settlers moved into the area in 1825, and by 1840 pioneer pastoralists had occupied all grazing land by free selection (Gibbons & others, 1972). Today, the eastern Riverine Plain of New South Wales is some of the most highly productive agricultural land in Australia. No doubt soured by his abortive attempts to negotiate the Lachlan River, Oxley in the same letter described the topography of the eastern Riverine Plain thus: 'There was neither hill nor rising ground of any kind within the compass of our view, which was only bounded by the horizon in every quarter, entirely devoid of timber except a few diminutive gums on the very edge of the streams'. Had he persevered westwards for another 200 km, Oxley would have seen the open undulating grasslands of the eastern Riverine Plain merge into the vast saltbush plains of the western Riverine Plain, with a more varied landscape pockmarked by an extensive network of fossil gypsum playas and associated lunettes, increasing in abundance westwards. The western Riverine Plain is about 100 km wide, and gives way abruptly to the elevated east-west longitudinal sand dunes of the Ivanhoe Block (Fig. 1). Not only is this boundary a sharp physiographic one, as shown in the LANDSAT mosiac (Fig. 2), but it also defines a distinct vegetation break from saltbush and bluebush of the western Riverine Plain to mallee of the Ivanhoe Block.

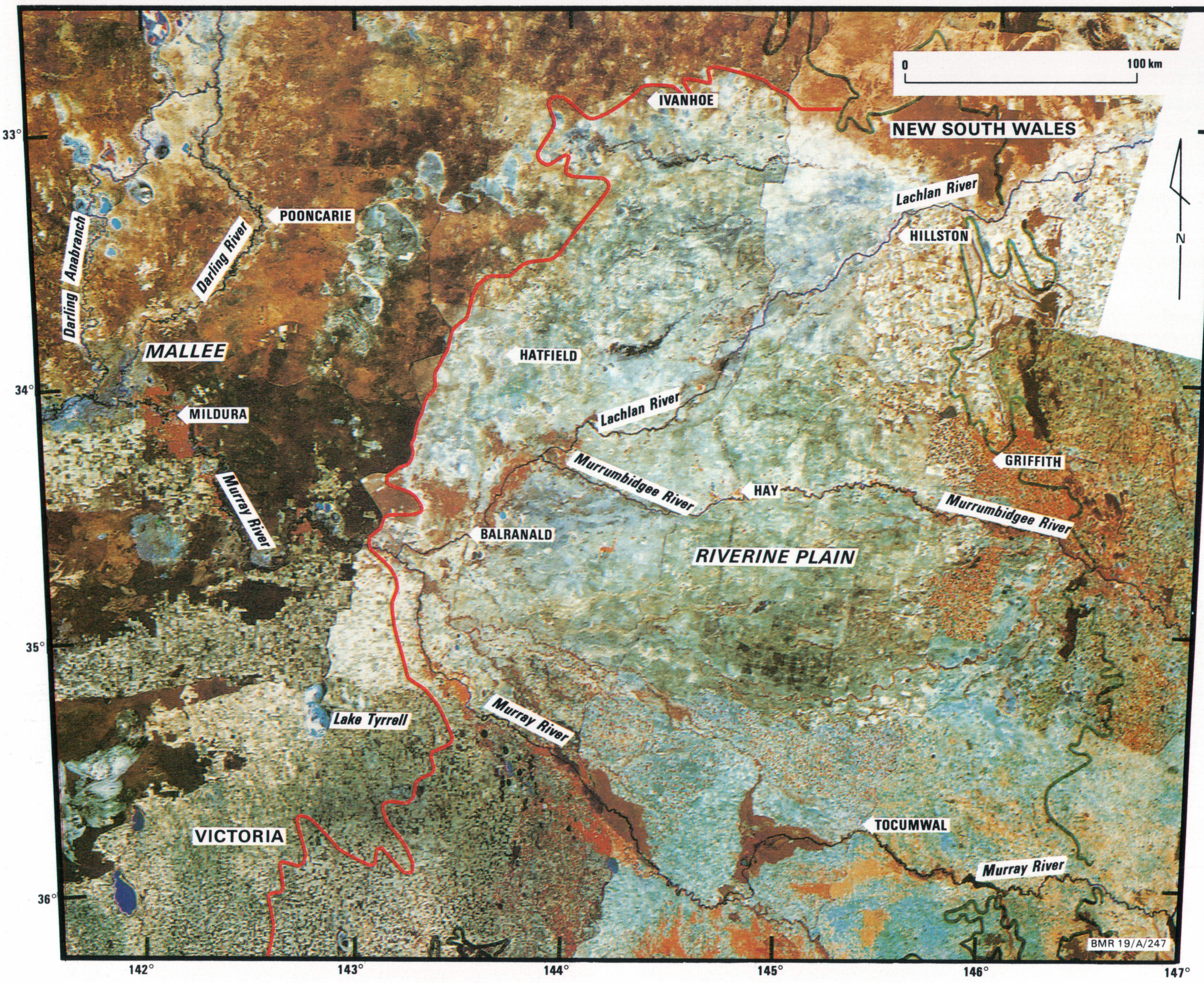



**Figure 2. LANDSAT mosaic of the central and eastern Murray Basin, New South Wales.**

There are two major depocentres of Tertiary sedimentation in the Murray Basin. The easterly depocentre contains more than 400 m of Cainozoic continental sediments below the western Riverine Plain, and is separated from the western depocentre by a north-northeast-trending concealed basement ridge complex (Fig. 3). Gibbons & others (1972) described the basement ridge as an elliptical body running between Robinvale and Darnick, and named it the 'Arumpo High'. They depicted the ridge extending along the same axis for 50 km or so south of the Murray River into Victoria. In this paper the basement ridge complex is referred to as the *Ivanhoe Block*. Williams (1983) investigated the structure and local hydrogeological influence of the southwestern part of the Ivanhoe Block around Mallee Cliffs/Lambert Island, and showed that the lower Renmark Group sediments are truncated by the basement ridge. Odins (1985, 1987) defined the broadscale structure of the southern half of the Ivanhoe Block by extensive seismic refraction traversing, and observed that there is a one-to-one correspondence between pre-Tertiary basement ridges and topographic highs. During 1986 and 1987, the Ivanhoe Block and western Riverine Plain were investigated in a joint deep drilling project between the Bureau of Mineral Resources and the New South Wales Department of Water Resources (New South Wales Department of Water Resources, 1987).

This paper highlights the results of the drilling investigation work, and attempts to give some insight into hydrogeological processes in the Ivanhoe Block and adjoining western Riverine Plain. In particular, the paper seeks to assess the influence of the Ivanhoe Block on the regional groundwater flow system in the Riverine Plain of New South Wales. In recent years, the Ivanhoe Block/western Riverine Plain

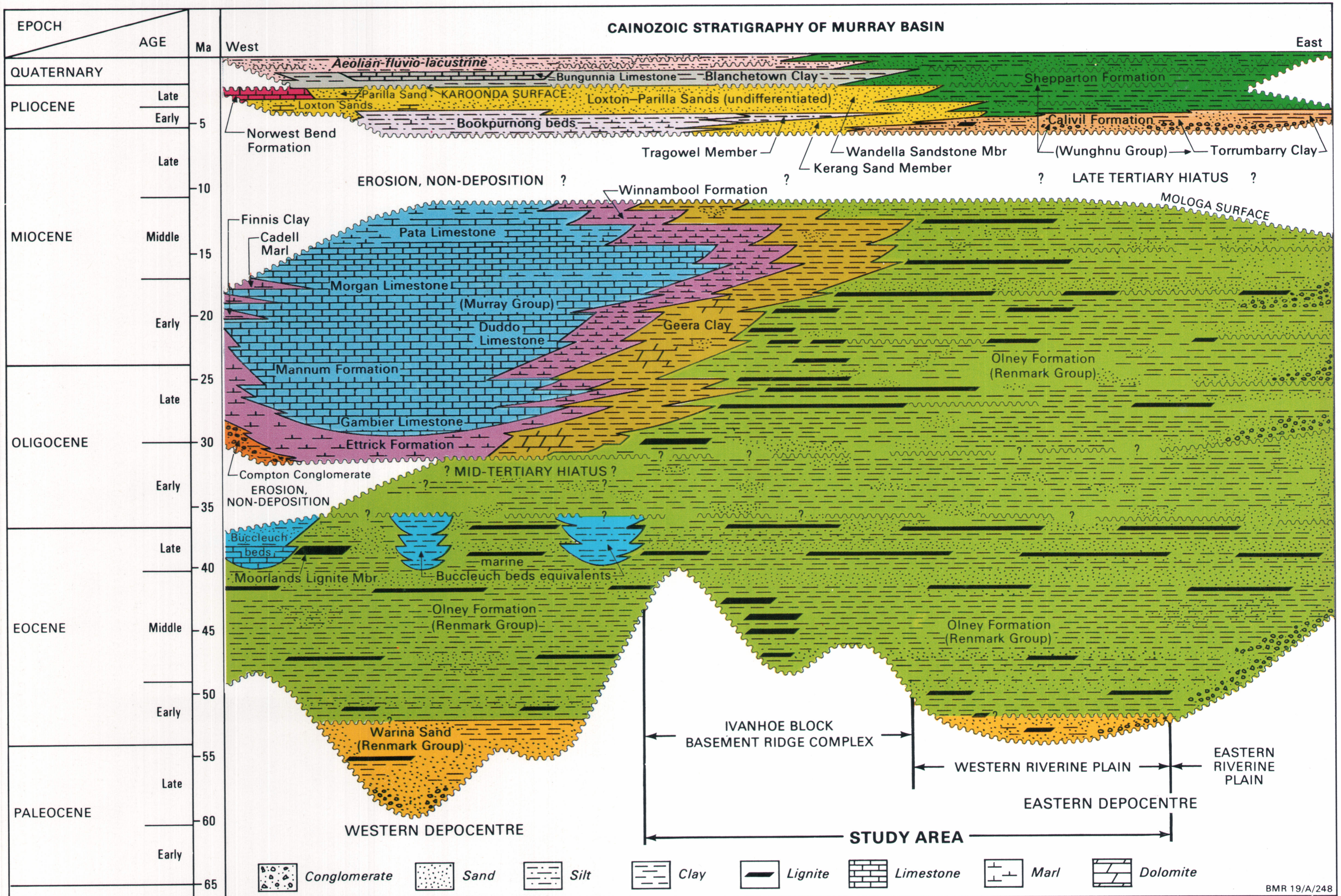



**Figure 3.** Cainozoic stratigraphy of the Murray Basin, showing regional setting of the Ivanhoe Block and western Riverine Plain.

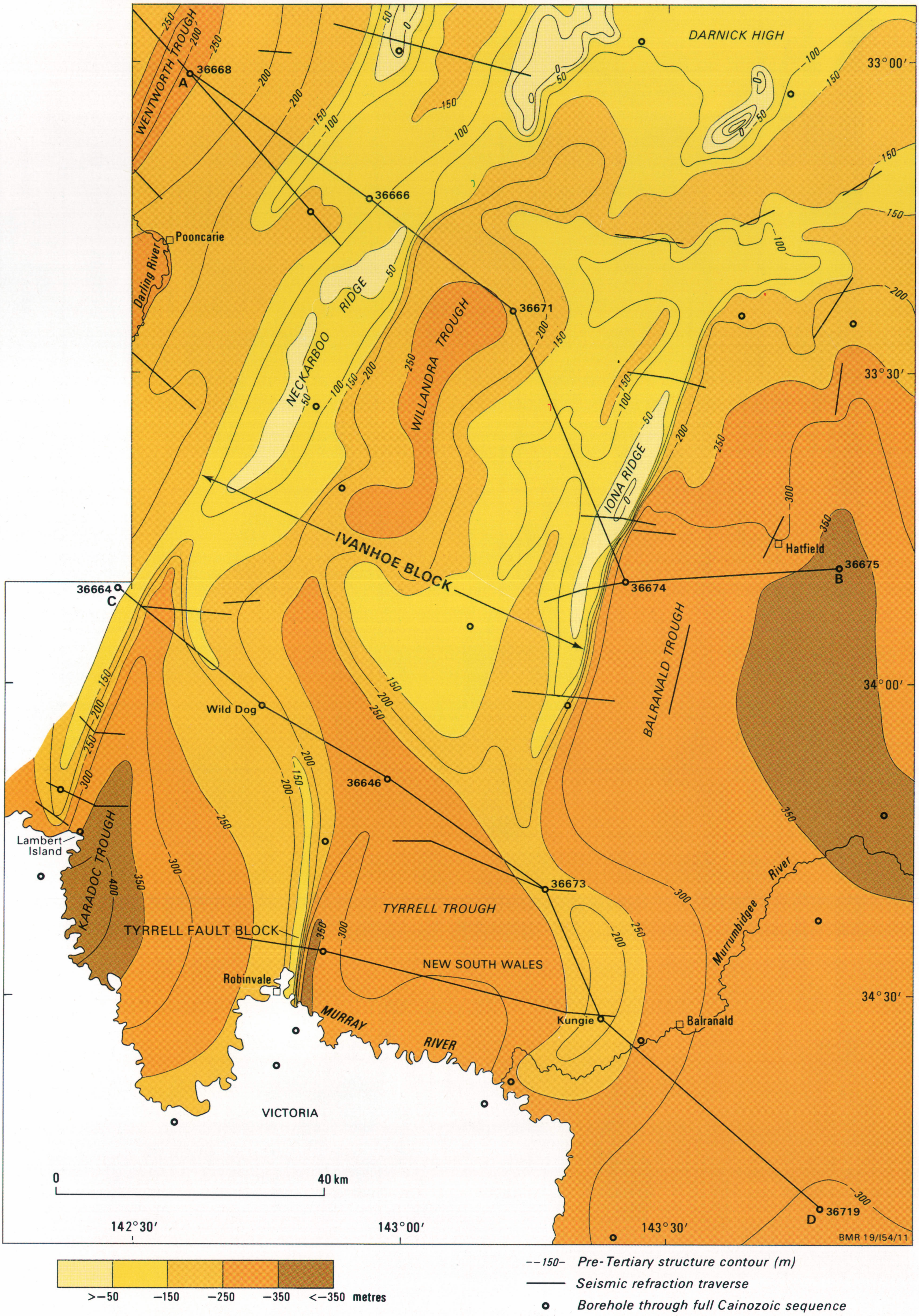



**Figure 4.** Structure contours of pre-Tertiary basement on the Ivanhoe Block and under part of the western Riverine Plain.

area has been the focus of growing community concern on the key issues of clearing in the mallee lands and the susceptibility of the area to land salinisation. Neither of these problems can be addressed without an understanding of regional hydrogeological processes.

## Basement structure of the Ivanhoe Block and western Riverine Plain

Figure 4 shows the pre-Tertiary structure contours on the Pooncarie 1:250 000 sheet and parts of the Balranald and Mildura 1:250 000 sheets, compiled from both drilling and seismic investigations carried out over the past few years. The Ivanhoe Block is a composite structure, consisting of two south–southwest-trending basement ridges separated by a saddle. The western limb of the Ivanhoe Block, the *Neckarboo Ridge* (Fig. 4), extends south–southwest towards the Murray River at Lambert Island, and separates the coarse-grained Tertiary sediments of the Darling River provenance in the west from the much finer-grained sediments of the Lachlan-Willandra provenance in the east; it forms the regional divide between the Riverine and Scotia Groundwater Provinces (Evans & Kellett, this issue). About 60 km along strike above Lambert Island, the Neckarboo Ridge bifurcates into two major basement ridges; one ridge continues along the regional south–southwest trend and the other ridge strikes initially southeast and then trends south to become the northerly extension of the *Tyrrell Fault Block* (Fig. 4).

The eastern limb of the Ivanhoe Block, the *Iona Ridge* (Fig. 4), becomes subdued about 60 km north of the confluence of the Murrumbidgee and Murray Rivers, where it is linked to a buried granite pluton to the south, thereby propagating the elevated basement topography down to the Murray River, along a similar arc as the Tyrrell Fault Block extension. Both the Neckarboo and Iona Ridges are fault-bounded with throws in excess of 100 m. Devonian sandstone outcrops of the Manfred and Darnick Ranges, and the prominent ridges northwest of Lake Mulurulu define the *Darnick High* (Fig. 4), an uplifted and tilted block forming the massive northern tongue of the Ivanhoe Block.

The *Willandra Trough* is the basement depression between the Neckarboo and Iona Ridges, and its aquifers are hydraulically connected to those of the *Tyrrell Trough* to the south (Fig. 4) and to those of the basement depression, cut by the ancestral Willandra Creek, to the northeast. The *Karadoc Trough* (Fig. 4) is sandwiched between the Neckarboo Ridge and the Tyrrell Fault Block; it extends southwest into Victoria, and its deep aquifers are hydraulically connected to those beneath the Raak Plain boinka.

The *Balranald Trough* (Fig. 4) represents the Cainozoic depocentre for the Western Riverine Plain. It is essentially a closed sub-basin, completely encompassed by rising basement. Its deepest point is −361 m ASL beneath the Great Cumbung Swamp at the terminus of the Lachlan River.

## Hydrostratigraphy of the Ivanhoe Block and western Riverine Plain

Total thickness of the Cainozoic sediments in the study area ranges from less than 150 m on the ridges of the Ivanhoe Block to more than 400 m in the Balranald Trough. The area has been the focus of two major Tertiary marine transgressions (Fig. 3)—the Oligo-Miocene and Late Miocene-Pliocene shorelines, represented by the Geera Clay and Loxton-Parilla Sands boundaries respectively, run approximately north–south through the study area (Figs 7b,d). Cross-sections running perpendicular and oblique to the regional grain of the Ivanhoe Block are shown in Figures 5a and 5b.

The basal confined aquifer is the Renmark Group (Ter) (Fig. 3), which in this paper is subdivided into the lower Renmark Group aquifer ($Ter_1$—Middle Eocene to Early Oligocene), the middle Renmark Group aquifer ($Ter_2$—Oligocene to Early Miocene) and the upper Renmark Group aquifer ($Ter_3$—Middle Miocene).

### Lower Renmark Group aquifer

The lower Renmark Group aquifer is absent on the Neckarboo and Iona Ridges, Darnick High and Tyrrell Fault Block extension (Figs 5a,b). In the Balranald Trough, the average thickness of the unit is 130 m. The basal sequence consists of about 30 m of coarse lithic sand and fine gravel, restricted to the central axis of the trough. The coarse facies is overlain by a blanket of blueish grey to very dark brown silty and sandy clay with lignite bands and rhythmically bedded lignitic silt and fine to medium quartzose sands, coarsening upward into medium to coarse sand, with ubiquitous lignitic silt interbeds. The weighted mean hydraulic conductivity of the lower Renmark Group ranges from 4 m/day down the central axis of the Balranald Trough to 1 m/day along the eastern flanks of the Iona Ridge. In the northern Willandra Trough, the lower Renmark Group averages 80 m in thickness. It consists of dark brown lignitic clayey silt and fine sand, coarsening upwards into lignitic coarse sand with claybands, generally with a blueish or greenish pigmentation; in the southern Willandra Trough/Tyrrell Trough, the unit thins to around 30 m and is finer-grained than its northerly counterpart—the weighted mean k-values also gradually decrease from 5 m/day in the north to 1 m/day in the south. About 60 m of lower Renmark Group sediment overlies the raised bedrock platform between the Tyrrell Trough and the southern Balranald Trough. The sequence there consists of interbedded dark grey silt and fine sand with thin coarse sand bands towards the top; the weighted mean hydraulic conductivity is 2 m/day.

### Middle Renmark Group aquifer

During the Oligo-Miocene marine transgression, the middle Renmark Group sediments were laid down in coastal swamps and deltas throughout the study area, except for some elevated parts of the Darnick High. Because of its low-energy depositional environment, the middle Renmark Group is the finest-grained unit of the Renmark Group aquifers. It forms a continuous 100 m thick blanket on the up-basin side of the Geera Clay boundary (Fig. 7b), except on the Neckarboo and Iona Ridges, where it thins to 50 m. The middle Renmark Group initially wraps around and interfingers with the Geera Clay, but grades laterally into the latter immediately south and west of the study area. The sequence consists of dark grey or blue to black silty medium sand grading upwards into laminated clay and silt which in turn grade upwards into fine sand. The upper and lower parts of the unit contain some thin coarse sand bands; however, these are not as abundant as in the underlying aquifer. The middle Renmark Group is characteristically pyritic and lignitic, sometimes with brown coal bands. Its weighted mean hydraulic conductivity ranges from 1 m/day in the northern Willandra and Balranald Troughs to 0.5 m/day around the Geera Clay boundary.

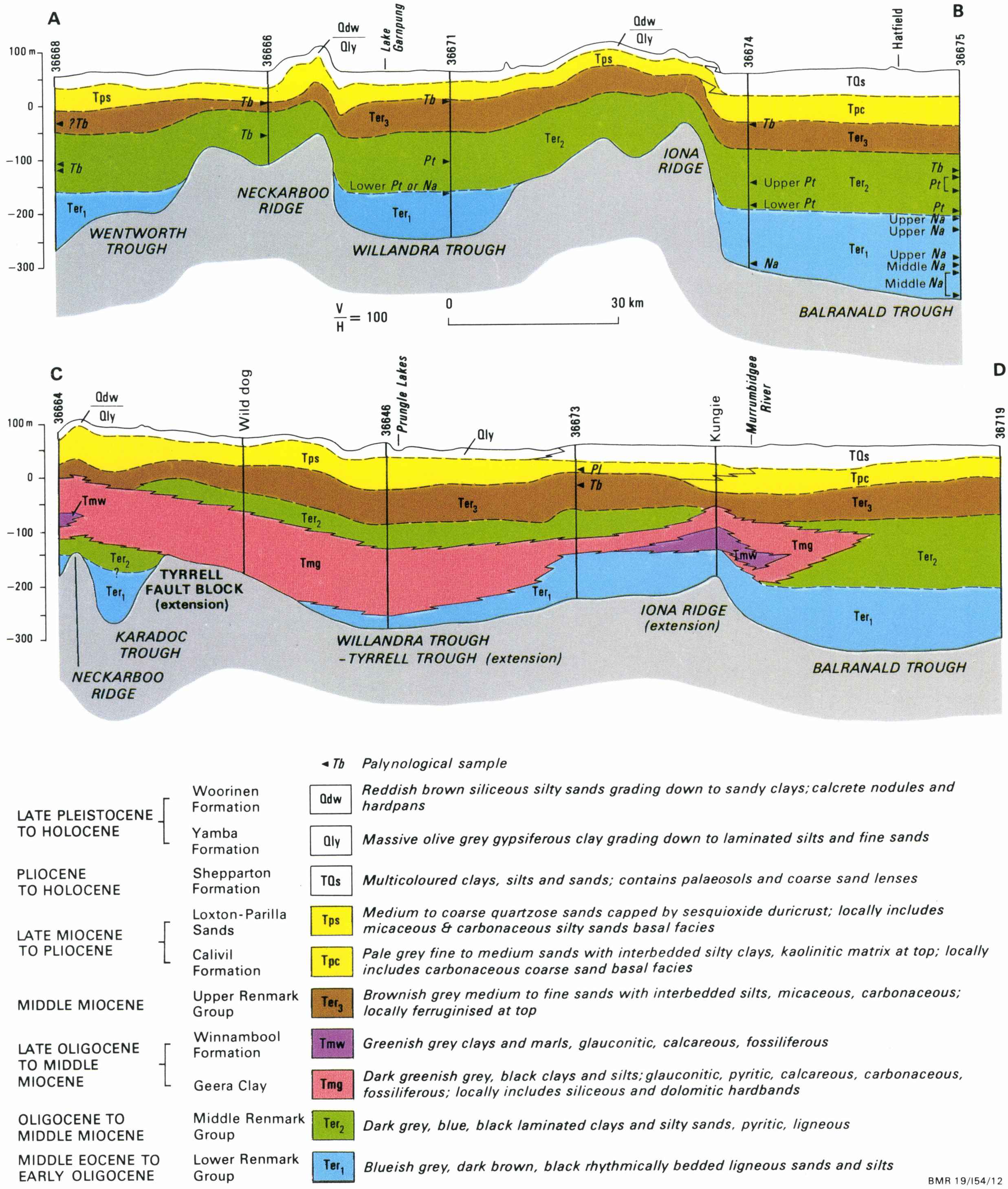



**Figure 5. Stratigraphic sections through the Ivanhoe Block and western Riverine Plain.**

(a) Section AB through northern and central continental Tertiary sequence. (b) Section CD through southern marginal marine Tertiary sequence. Refer to Figure 4 for borehole locations. Arrowed palynological zones: Pl, Pliocene daisies (*Asteraceae*), grasses and saltbush (*Graminidites*, *Chenopodipollis*); Tb, *Triporopollenites bellus*; Pt, *Proteacidites tuberculatus*; Na, *Nothofagidites asperus*.

## Upper Renmark Group aquifer

The upper Renmark Group is about 60 m thick in the troughs but thins to around 40 m on top of the basement ridges. It also does not persist much farther into the Murray Basin beyond the study area, pinching out against the Geera Clay. The unit is mostly medium to fine sand with minor silt interbeds; a basal coarse sand facies is present in the western Riverine Plain, but not through the Ivanhoe Block. The sand is micaceous and carbonaceous, but the upper Renmark Group is not as rich in lignitic material as the underlying Renmark Group units. Its colour varies from brownish grey to greenish grey, and in many places there is a purple ferruginised zone at the top with pedogenic features marking the Mologa Weathering Surface. Hydraulic conductivity is a reasonably constant 2 m/day throughout the troughs, and 1 m/day on the Neckarboo and Iona Ridges, where the weathering surface is best preserved.

## Geera Clay

Massive, tough dark greenish grey to black clay and silt make up the Geera Clay (Tmg) aquitard, part of the mid-Tertiary low-permeability barrier (Brown, this issue; Evans & Kellett, this issue). In the study area, the Geera Clay is a maximum thickness of 130 m in the Tyrrell Trough, but elsewhere it averages 100 m in thickness, except over the southern part of the Iona Ridge where it decreases to 30 m. The Geera Clay is glauconitic and rich in sulphide minerals, in some places carbonaceous and always highly fossiliferous. In the Tyrrell Trough the Geera Clay exhibits abundant siliceous and dolomitic hardbands throughout, and basal glauconitic sand interbeds. Elsewhere the unit is tight, but may possess high primary and secondary porosity in association with pyritised sand burrow infills and shell casts. Thin pods of greenish grey glauconitic and calcareous clay and marl (Winnambool Formation — Tmw) are enveloped by the basal Geera Clay across the Neckarboo and Iona Ridges.

## Pliocene Sands

The Pliocene Sands aquifer is a composite of the Calivil Formation (Tpc) in the Western Riverine Plain and Darnick High, and the Loxton-Parilla Sands (Tps) farther west.

The Calivil Formation reaches 50 m thickness in the northern half of the Balranald Trough, but southwards thins to 40 m and reaches only 30 m on the Darnick High. The basal sediments of the Calivil Formation consist of 25 m of coarse quartzose sand with pale grey carbonaceous silty clay interbeds. This basal coarse-grained facies is present only as channel fills next to the eastern flanks of the Iona and Neckarboo Ridges. The upper fine-grained facies consists of pale grey fine to medium sand with silty clay interbeds. The top of the unit is generally weakly cemented by kaolinitic clay and sesquioxides. This imparts a characteristic mauve/purple and white pigmentation to the sediments.

The Loxton-Parilla Sands vary from about 30 m thick next to the Calivil Formation boundary (Fig. 7d) to over 50 m average thickness in the western part of the study area — the unit does not thin out over the Neckarboo Ridge. In the southern Willandra Trough and Tyrrell Trough, the Loxton-Parilla Sands are dark brown to grey, micaceous and carbonaceous, silty fine to medium sands which coarsen upward to yellowish brown coarse sands with abundant fine sand interbeds. Elsewhere the unit is more homogeneous, consisting of medium to coarse sand with varying degrees of iron oxide grain coatings and, in some places, opaque mineral grains. The top of the Loxton-Parilla Sands is generally conspicuous by its sesquioxide hardpans and white mottles of kaolinitic clay. The unit is unconfined on the elevated basement of the Ivanhoe Block, and becomes unsaturated on some parts of the Neckarboo Ridge.

The stratigraphic boundary between the Calivil Formation and the Loxton-Parilla Sands also delineates a permeability boundary in the Pliocene Sands aquifer (Fig. 7d). The weighted mean hydraulic conductivity of the Calivil Formation in the western Riverine Plain is 2.5 m/day. The k-value of the adjoining Loxton-Parilla Sands is 4 m/day, and averages 10 m/day west of the Tyrrell Fault Block. The hydraulic conductivity of the Loxton-Parilla Sands is greatest under the Murray Trench where it exceeds 15 m/day.

## Quaternary units

The Shepparton Formation (TQs) is the unconfined aquifer in the western Riverine Plain. It reaches an average thickness of 50 m in the northern and central Balranald Trough, but decreases to half this value in the southern part of the trough. The formation terminates about 20 km west of the Tpc/Tps boundary (Fig. 7d) in the southern half of the study area, is absent on the Iona Ridge, and forms a thin (<15 m) veneer on the eastern half of the Darnick High. The unit is far more heterogeneous than the underlying Tertiary sequence, therefore its hydrogeology is almost impossible to characterise on a regional scale. In the northern Balranald Trough, it consists of a drab-coloured succession of blueish and greenish grey mottled clays overlying thinly bedded clayey and silty sand; this in turn overlies multicoloured clay and silt with abundant fine sand interbeds. The coarse sands in the intermediate facies are lenticular bodies and, as such, cannot be correlated over distance, but there is probably scope to correlate the palaeosols within the Shepparton Formation through the study area.

In the central Balranald Trough, the intermediate sandy facies has not been detected in boreholes through the Shepparton Formation. Instead, the sequence consists of mottled brown and grey sandy clays overlying a steel-blue clay, which in turn overlies thinly laminated fine sand and silt—the blue clay horizon is a reasonably consistent marker bed. In the southern Balranald Trough, the Shepparton Formation consists of mottled reddish and yellowish brown sandy clays overlying blueish grey silty and clayey fine to medium sand containing stringers of pale grey coarse sand. Since there is a high degree of pedogenesis in the Shepparton Formation, its weighted mean hydraulic conductivity is low, from an average 1 m/day in the northern and central Balranald Trough to 2 m/day in the south.

The fossil gypsum playas in the western Riverine Plain and Willandra Trough/Tyrrell Trough are capped by an olive grey gypsiferous clay with a substratum of variegated, finely laminated silt and fine sand — the sequence is probably equivalent to the Yamba Formation (Qly). In the western Riverine Plain the Yamba Formation overlies the Shepparton Formation, and in the Willandra Trough it directly overlies the Pliocene Sands, for which it forms the confining bed. The unit is generally <10 m thick. Its clays are blocky or prismatic, highly plastic and gypsiferous, with characteristic manganese staining on the ped faces and sesquioxide nodules concentrated towards the base of the clay facies. The clay grades down into finely laminated silt and fine to medium sand, often very brightly coloured because of the high degree of iron mobilisation, especially along bedding planes.

The longitudinal east–west dunes overlying the basement ridges of the Ivanhoe Block consist of reddish brown siliceous silty sand of the Woorinen Formation (Qdw). The sand is only a few metres thick, and contains ubiquitous calcrete nodules and hardpans. The Woorinen Formation is unsaturated throughout the study area.

## Tectonic influences on aquifer geometry and surface drainage

The Ivanhoe Block has undergone small-scale episodic tectonism since the Early Oligocene. By measuring displacements between time-lines on the sections in Figure 5, it is possible to reconstruct the tectonic history, using formations in the Balranald Trough as baseline reference levels.

Following deposition of lower Renmark Group sediments, there was 40 m uplift uniformly along the Iona Ridge. Tilting on the Neckarboo Ridge produced a comparable uplift of 40 m in the north of the study area, but virtually none at the southern end of the ridge. This period also saw the initiation of subsidence in the Tyrrell Trough, which has resulted in a cumulative downwards displacement of 55 m relative to the Balranald Trough and 95 m relative to the Iona Ridge.

The Ivanhoe Block appears to have been stable during the Miocene marine transgression. However, following deposition of the upper Renmark Group sediments, there was a further uplift of 30 m on the southern Iona Ridge, with virtually none in the north or on the Neckarboo Ridge. Both basement ridges have been tilted since deposition of the Pliocene Sands. The displacement was greatest on the southern Neckarboo Ridge and Tyrrell Fault Block, which were uplifted a further 65 m; uplift on the northern part of the Neckarboo Ridge was 30 m. Tilting on the Iona Ridge produced 45 m uplift in the north, but only about 5 m in the south.

Whilst these periods of tectonism can only be described as subtle, they did have a profound effect on the regional hydrogeology and surface drainage system. Hydraulic and topographic gradients are very gentle in the central Murray Basin, so changes of tens of metres in one part of the system induce far-ranging adjustments elsewhere. In the study area, the adjustment of the surface drainage pattern is shown by the defeat of the ancestral Willandra Lakes outflow. The outflow was originally in a south-southwest direction parallel to the axis of the Willandra Trough; it was deflected to a southeast direction (by post-Pliocene uplift on the southern Neckarboo Ridge and Tyrrell Fault Block) and captured by Box Creek (Fig. 1).

## Subdivision of the Renmark Group by palynology and geophysical logs

The Renmark Group exhibits significant salinity stratification throughout the central Murray Basin. This necessitates subdivision of the Renmark Group into discrete aquifers, each of which has negligible or small internal vertical salinity gradients. In the western Riverine Plain and Ivanhoe Block, a satisfactory partitioning of the Renmark Group is attained with a threefold subdivision. For example, at Lake Garnpung (36671), groundwater salinity ranges from 20 000 mg/L TDS in the upper Renmark Group aquifer to 4500 mg/L TDS in the lower Renmark Group aquifer; the intermediate middle Renmark Group aquifer contains water which has 9000 mg/L TDS salinity. Although there are often large differences in groundwater salinity between the overlying Renmark Group aquifers, vertical concentration gradients within each aquifer are small. For example, at Hatfield (36675), groundwater salinity is 6000 mg/L TDS at the top of the lower Renmark Group aquifer and 4700 mg/L TDS at the bottom of the unit.

The cross-sections in Figure 5 are constructed from 11 exploratory drillholes from the joint BMR–NSW Department of Water Resources regional hydrogeological study of the Murray Basin. The Neckarboo Ridge (36664) and Hatfield (36675) sites were continuously cored, but the remainder were sampled from drill cuttings. It is exceedingly difficult to subdivide the thick accumulation of Renmark Group sediments through the northern section (Fig. 5, section A–B) on the basis of examination of drill cuttings alone, because the sequence contains no marine sediments and is lithologically uniform. Subdivision through the southern section (Fig. 5, section C–D) is more straightforward because of the presence of the Geera Clay, but the Geera Clay surface does not constitute a time-line since it is enveloped by the middle Renmark Group.

Palynological zonations after Truswell (1987) are shown in Figure 5. The mid to late Miocene *Triporopollenites bellus* Zone occurs in the upper Renmark Group and extends down into the top of the middle Renmark Group aquifer in the western Riverine Plain, and throughout the middle Renmark Group aquifer to the west of the Neckarboo Ridge. East of the Neckarboo Ridge, the middle Renmark Group aquifer is characterised by the occurrence of the early Oligocene to early Miocene *Proteacidites tuberculatus* Zone. However, east of the study area, the A Subdivision of the *P. tuberculatus* Zone (Martin, 1984a,b) extends down into the top of the lower Renmark Group aquifer. The middle Eocene to early Oligocene *Nothofagidites asperus* Zone occurs throughout the lower Renmark Group aquifer east of the Neckarboo Ridge.

Geophysical logs have proved useful in delimiting the facies boundaries within the Renmark Group. Natural gamma and spontaneous potential (SP) logs for ten of the exploratory drillholes are shown in Figure 6; the Nambucurra (36666) logs were corrupted by hardware malfunctions. Where available, long and short normal resistivity logs are shown in Figure 6.

In places where the Mologa Weathering Surface is preserved, the top of the Renmark Group is defined by a sharp peak in the gamma log, reflecting preferential enrichment at the palaeosurface of elements which emit high gamma activity. In the elevated basement areas, the Mologa Surface is clearly shown by the sharp gamma peak in the Neckarboo Ridge borehole, and to a lesser extent by the more diffuse peaks in the Kungie and Wild Dog holes. In the troughs, the palaeosurface is sometimes recognised in drill cuttings by a purple pigmentation at the top of $Ter_3$, but in this environment it seems that the high gamma-emitters have not been preserved.

The $Ter_2/Ter_3$ boundary is identified by a combination of the gamma and electric logs. The break in the gamma log occurs where the uniform, or locally fining-upward, trend in upper $Ter_2$ changes to a coarsening-upward sequence in the basal $Ter_3$ aquifer, best shown in the Iona, Prungle and Bramah drillholes. In drillholes which intersect Geera Clay (Fig. 6b), the $Ter_2/Ter_3$ and $Tmg/Ter_3$ boundaries are marked in the SP log by a basic change in shape, and an abrupt positive shift; through $Ter_3$ the SP log is serrated and bell-shaped, but it changes abruptly to smooth or serrated cylinder-shaped in $Ter_2$ and Tmg. The magnitude of the positive shift in the SP log is slightly less through $Ter_2$ than Tmg. The best examples for using the SP log to pick the $Ter_2/Ter_3$ boundary are shown by the Prungle and Bramah logs. The long and short normal electric logs can also be useful boundary indicators. For example, the Kungie normal electric logs show an abrupt down-hole increase in resistivity at the $Tmg/Ter_3$ boundary, and the SP log displays a similar positive shift towards shale (Fig. 6b).

The SP logs of the drillholes with no marine intercalations (Fig. 6a and Perekerton) are basically serrated cylinder-shaped through the entire Renmark Group sequence. There is an abrupt positive shift in the SP log at the $Ter_2/Ter_3$ boundary at Iona, a gradational positive shift at Perekerton, a steady positive drift towards shale (Mitfords Corner and Lake Garnpung) and an abrupt negative shift towards sand (Hatfield). The corresponding deflection in the normal resistivity logs at Hatfield indicates an abrupt and sustained change in formation water salinity (lower TDS) in $Ter_2$.

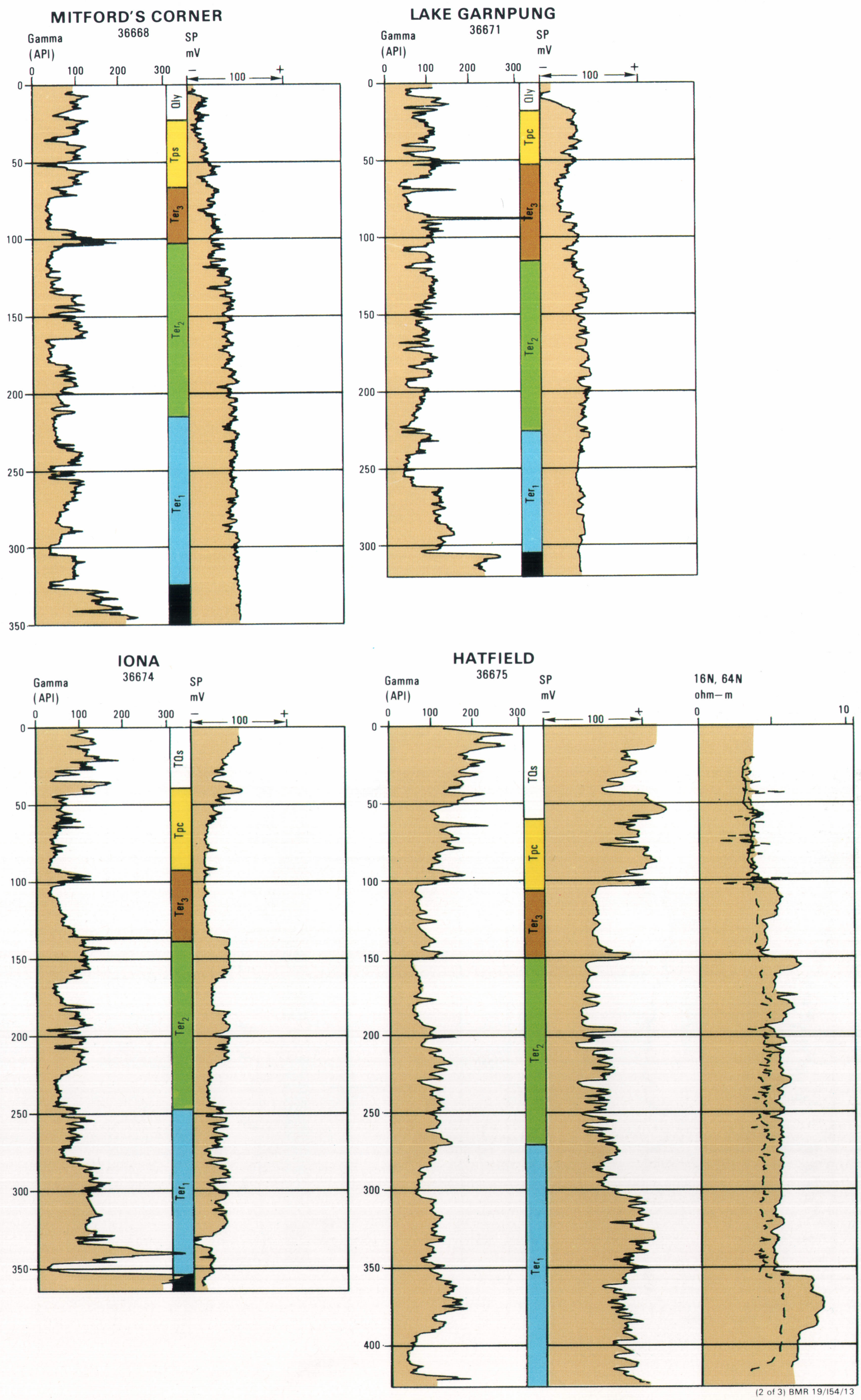



**Figure 6a. Gamma and electric logs with subdivision of Renmark Group shown.**
See Figure 5 for location of bores on section A–B.

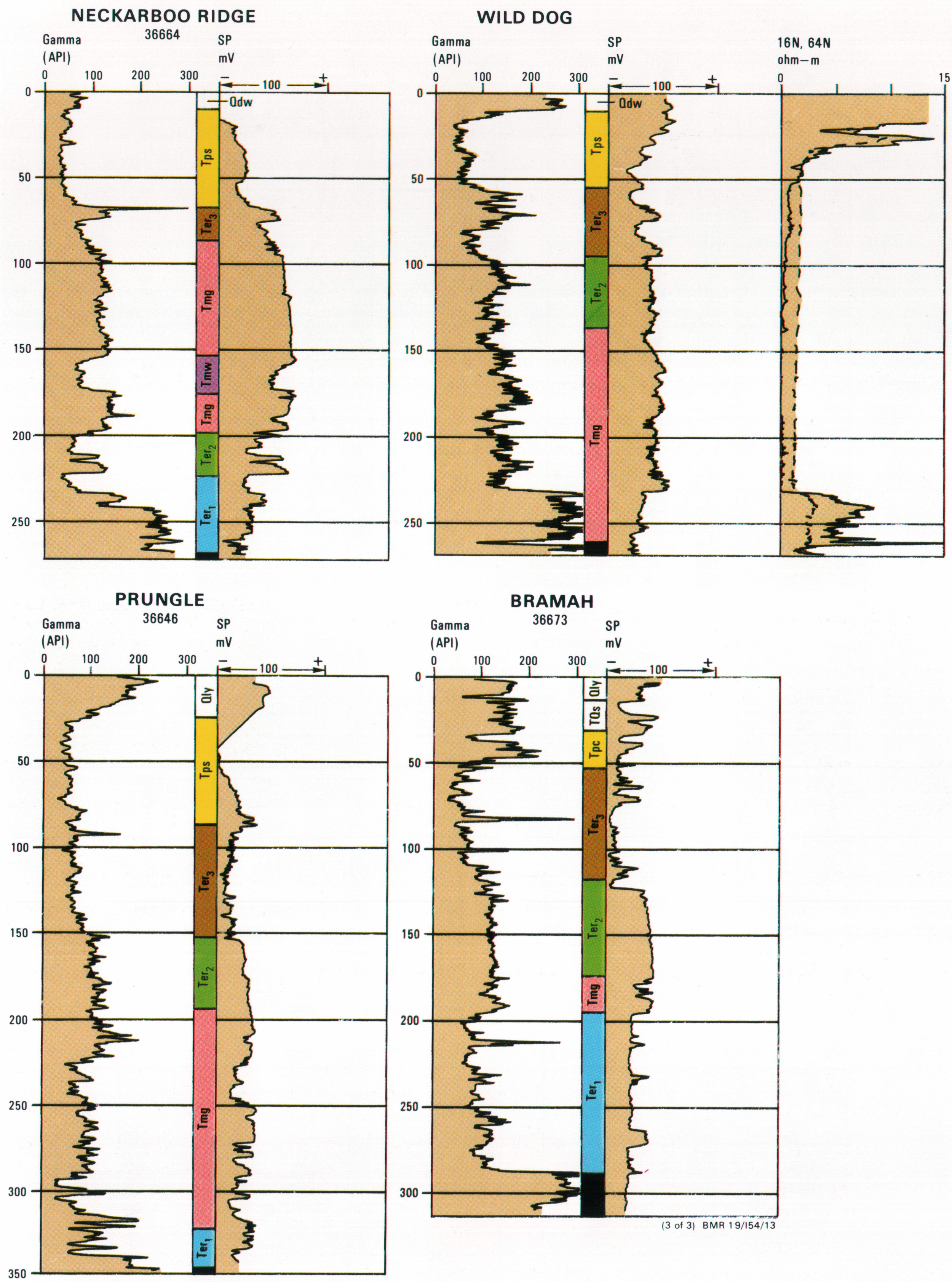
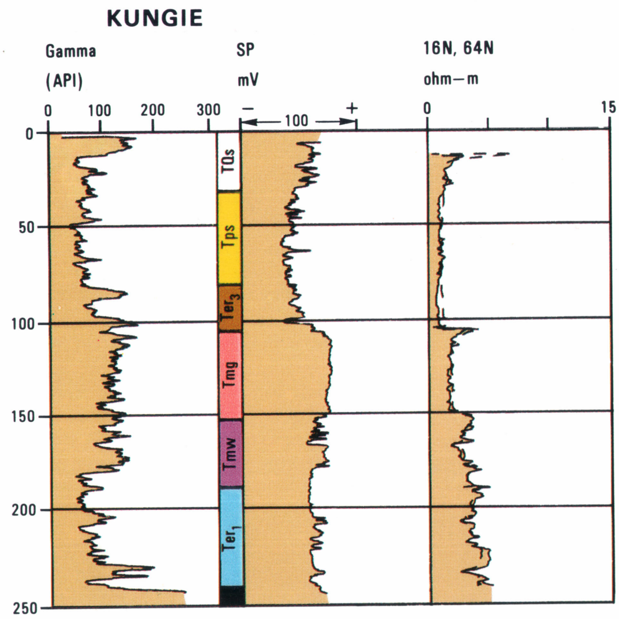



**Figure 6b. Gamma and electric logs with subdivision of Renmark Group shown.**
See Figure 5 for location of bores on section C–D.



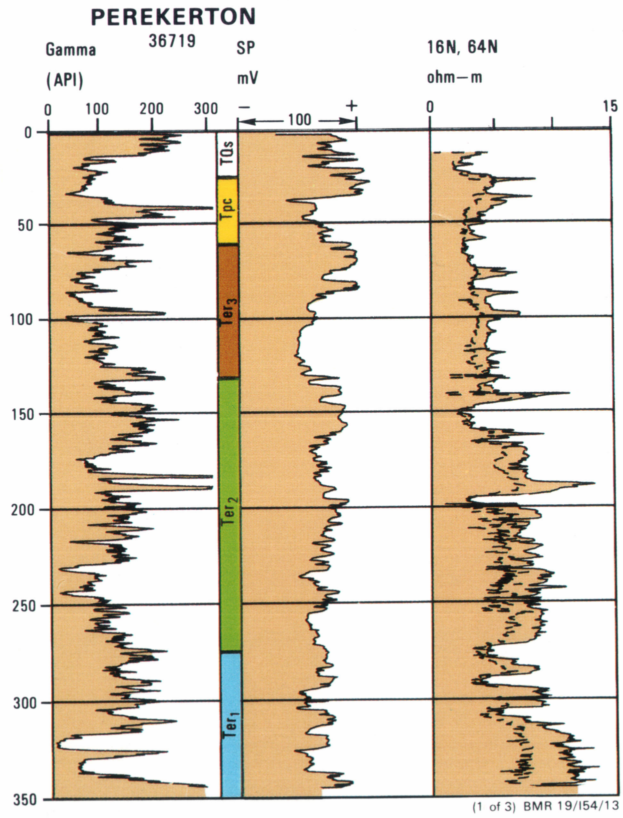




**Figure 6b** (**continued**)

The generally higher levels of background gamma activity through $Ter_2$ and Tmg reflect the clayey nature of the deltaic, lacustrine and marginal marine sediments of $Ter_2$, Tmg and Tmw, which were deposited in the central Murray Basin at the height of the Oligo-Miocene marine transgression. Discrete, sharp gamma peaks within $Ter_2$ correspond to lignite bands, as they do in $Ter_1$ and $Ter_3$.

The gamma logs through $Ter_1$ display a general trend of coarsening upward, within which there are a number of fining-upward cycles. The $Ter_1/Ter_2$ boundary occurs at the top of the general coarsening upwards trend. At the boundary, there is a corresponding abrupt negative shift in the SP baseline (Neckarboo Ridge and Bramah), a gradational positive shift (Iona and Hatfield), or virtually constant baseline. In the last case, the $Ter_1/Ter_2$ boundary is delineated by deflections in the normal resistivity logs (Kungie and Perekerton). In the Hatfield bore, the normal logs do not deflect at the $Ter_1/Ter_2$ boundary, but do so where the groundwater becomes marginally fresher at 350 m below ground surface.

In all drillholes the gamma logs and electric logs show the Renmark Group (including intercalated Tmg and Tmw) as a complete sedimentary package which initially fines upwards above $Ter_1$, and then coarsens upwards, indicative of a marine transgression with associated paralic sediments over a fluvial environment followed by a prograding shoreline. The electric logs are most useful for hydrostratigraphic purposes where there are large contrasts between salinities of the formation waters. Their utility for picking formation boundaries by baseline shifts and step-wise deflections comes about because *groundwater salinity is strata-bound in the aquifers of the central Murray Basin.* The electric logs for the Perekerton and Mitfords Corner drillholes have low discriminatory power because at these sites there is very little contrast between groundwater salinities in the Renmark Group aquifers. At Mitfords Corner all water in the Renmark Group aquifers exceeds 30 000 mg/L TDS. At Perekerton the $Ter_2/Ter_3$ boundary is delineated by a moderate baseline shift in the SP log (5500 mg/L in $Ter_3$, 2400 mg/L in $Ter_2$) but there is no comparable baseline shift at the gradational $Ter_1/Ter_2$ boundary because there is negligible difference in groundwater salinity across the boundary (2200 mg/L in $Ter_1$).

## Hydrogeology of the Ivanhoe Block and western Riverine Plain

Figure 7a shows the potentiometry and salinity characteristics of the lower Renmark Group in the Ivanhoe Block and part of the western Riverine Plain. The boundary conditions imposed on the regional flow system by the basement ridges are clearly evident; the groundwater flux from the Willandra Creek/Ivanhoe area to the northeast is constrained to flow parallel to the axis of the Willandra Trough and flow lines from the Lachlan Alluvial Fan to the east are deflected southwards by the blocking action of the Iona Ridge. The 'Hatfield groundwater discharge lake complex' (Brown, this issue) overlies the 55 m ASL closed potentiometric contour and zone of steepening hydraulic gradients in the northern Balranald Trough (Fig. 7a). A 'stagnation zone' exists between the 45 m contour through Lake Garnpung, where the regional flow direction is south-southwest, and the 45 m contour around the northern edge of the Prungle Lakes where the flow direction is north-west—i.e. *the system is filling up from both north and south.* This appears to be a comparatively recent phenomenon generated by increased pressures from the south, and if they continue to rise, the southern 45 m potentiometric contour will be pushed farther up into the southern Willandra Trough. The groundwater discharge zones at Hatfield and in the southern Willandra Trough are sites of upwards leakage from the lower Renmark Group aquifer to the overlying aquifers, and they also represent zones of increased groundwater salinity from refluxing. Groundwater salinity in the lower Renmark Group aquifer increases very rapidly (Fig. 7a) through the study area—south of the Iona

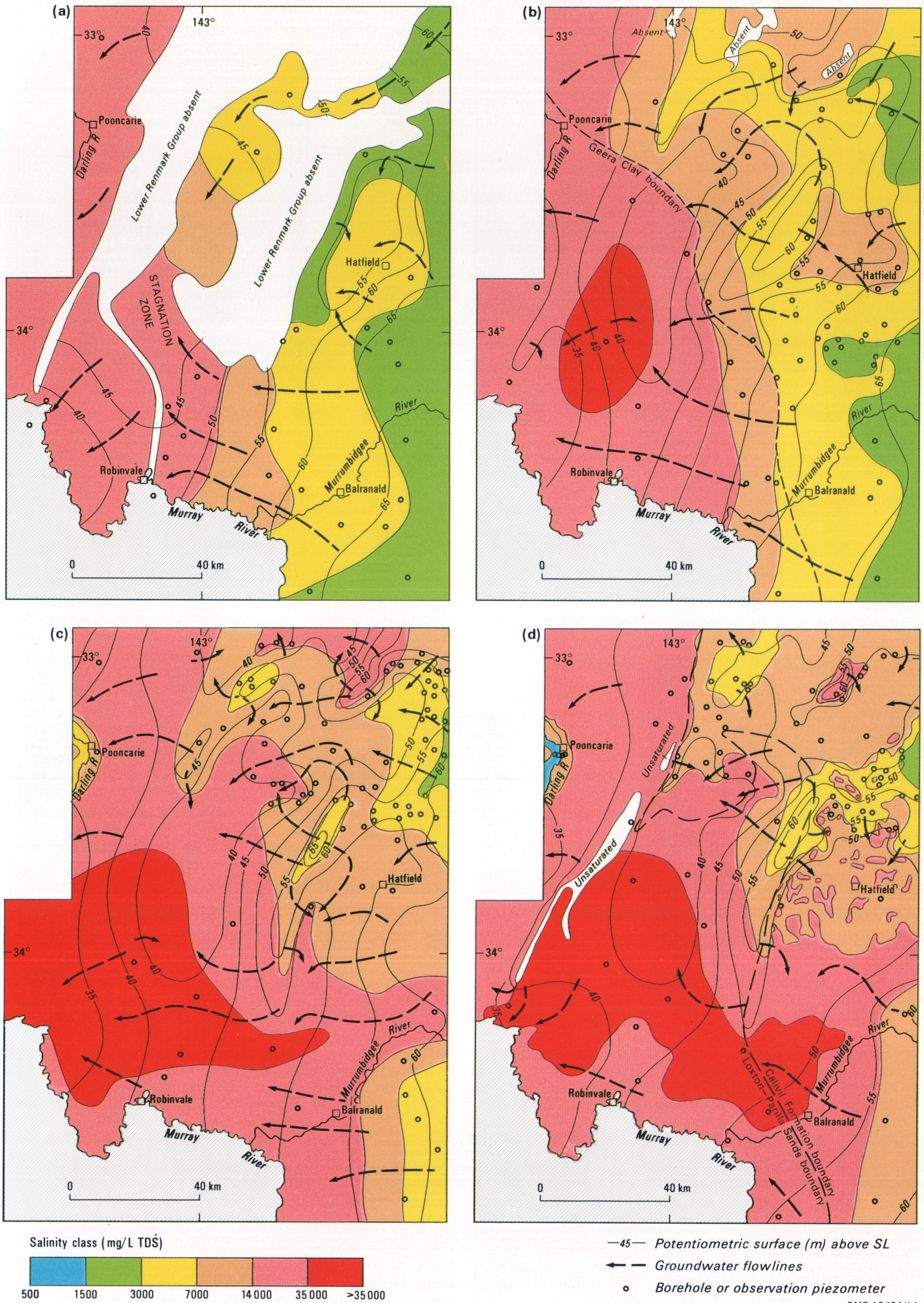



**Figure 7. Contours of potentiometric surface (1989) and salinity classes.**
(a) Lower Renmark Group. (b) Middle Renmark Group. (c) Upper Renmark Group. (d) Pliocene Sands.

Ridge salinity increases from 3000 mg/L TDS to 20 000 mg/L within 50 km. This is in direct contrast to the gradual increase along regional flow lines through the Riverine Plain farther east.

The flow patterns and chemistry in the middle Renmark Group (Fig. 7b) are controlled largely by those in the underlying aquifer and by the distribution of the Geera Clay. The middle Renmark Group aquifer/Geera Clay boundary shown in Fig. 7b is a transition zone between continental sediments on the eastern side and marginal marine sediments to the west because of the interfingering of the units over several tens of kilometres. In the Hatfield area, groundwater from the lower Renmark Group is discharged upward into a conspicuous zone of higher salinity water in the middle Renmark Group aquifer (Fig. 7b). The middle Renmark Group is draped over the Iona Ridge, and it forms a local recharge zone there, but the unit is absent over some parts of the Darnick High. The major discharge zone is the closed 40 m potentiometric contour in the Willandra Trough, and groundwater salinity in the middle Renmark Group exceed 35 000 mg/L TDS where it overlies the lower Renmark Group stagnation zone. The effect of the Geera Clay is to generate steeper hydraulic gradients in response to the marked decrease in permeability and to create a buffer zone about 20 km wide in the middle Renmark Group. This buffer zone defines the westerly limit of water suitable for stock. Comparison between Figs 7a & 7b shows that water quality is always better in the underlying aquifer.

The major discharge zone in the upper Renmark Group aquifer (Fig. 7c) and Pliocene Sands (Fig. 7d) is defined by the closed 40 m potentiometric contour in the Willandra Trough. The upper Renmark Group becomes unconfined along the crest of the Neckarboo Ridge where the Pliocene Sands are unsaturated; the other basement ridges in the study area define localised recharge zones. These two aquifers contain substantial volumes of highly saline water (TDS >35 000 mg/L) through the southern part of the Ivanhoe Block, and the area where the >35 000 mg/L salinity class boundary intercepts the Murray River (Mallee Cliffs) coincides with the upstream limit of aquifer discharge to the river. The upper Renmark Group and Pliocene Sands appear to be in equilibrium with the Murray and Murrumbidgee Rivers over the rest of the study area because their belts of highly saline groundwater run subparallel to the rivers, indicating dilution and mixing with surface waters. The Darling River, too, dilutes the regional groundwater of these two aquifers, but only to the extent of its 10 km wide flooodplain (Figs 7c & 7d). The northern part of the Balranald Trough contains saline groundwater in the Pliocene Sands beneath the mosaic of fossil gypsum playas (Fig. 7d). The Calivil Formation/Loxton-Parilla Sands boundary runs north-south through the study area, and there is no apparent relationship between its location and salinity trends in the Pliocene Sands, except perhaps along the northern part of the Neckarboo Ridge (Fig. 7d).

## Regional chloride trends in groundwater through the Riverine Plain and Ivanhoe Block

Figure 8 shows chloride concentrations in mg/L in vertical slices of the Pliocene and Renmark Group aquifers along four flow lines which transect the New South Wales Riverine Plain (for locations see Fig. 9). Shepparton Formation chlorinities are not included in the sections because their variance depends just as much on local influences as on regional processes. The central northern flow line has been terminated in the centroid of the Balranald–Hatfield discharge zone (Fig. 9) because of data deficiencies. The location of water bores, most of which are slightly offset from the regional flow lines, is shown in Figure 9. Plots of chloride concentration versus distance along the flow lines are presented in Figure 10 (note that distances are measured from the flow line's projections to the basin boundary for standardisation).

### Eastern Riverine Plain

On all four flow lines the boundary between the eastern and western Riverine Plain generally occurs where vertical salinity gradients start to develop — salinity in this case is reflected by chloride concentration, chloride being the most frequently measured conservative ion. The general trend (Fig. 10) consists of chloride concentrations in all aquifers under the eastern Riverine Plain increasing linearly from east to west. An exception to this is the initial 20 km of the far southern flow system (Fig. 8), an area which is strongly influenced by vertical leakage from the overlying Shepparton Formation. Another minor deviation is the bulge of fresher groundwater (chloride concentration <200 mg/L) in the upper Renmark Group aquifer of the far northern system (Fig. 8), which is a consequence of the rapid decrease in hydraulic conductivity of the overlying Calivil Formation sediments relative to the upper Renmark Group sediments along the northern edge of the Lachlan alluvial fan.

The mean rate of chloride accumulation is remarkably constant for all aquifers under the eastern Riverine Plain. In the Pliocene Sands and upper Renmark Group aquifers the rate is 7 mg/L/km, for the middle Renmark Group it is 6 mg/L/km, and for the lower Renmark Group aquifer 4 mg/L/km (Table 1). There is no significant difference in chloride enrichment rates by aquifer group between flow lines. The trend of salinity being proportional to distance along a flow line shown in all aquifers indicates simple mixing between groundwater and evaporated surface water inputs, by stream leakage and rainfall infiltration, *at a constant rate along the flow line*. It also shows that the aquifers are essentially hydraulically interconnected beneath the eastern Riverine Plain.

**Table 1. Average rates of chloride concentration in mg/L/km along flow lines through the Riverine Plain and Ivanhoe Block.**

| *Flow line* | *Pliocene Sands* | *Upper Renmark* | *Middle Renmark* | *Lower Renmark* |
|---|---|---|---|---|
| Eastern Riverine Plain | | | | |
| a | 7 | 6 | 6 | 4 |
| b | 6 | 7 | 7 | 5 |
| c | 7 | 8 | 6 | 4 |
| d | 7 | 7 | 5 | 4 |
| average | 7 | 7 | 6 | 4 |
| Western Riverine Plain: Moulamein—Mossgiel buffer zone | | | | |
| a | 24 | 35 | 17 | 10 |
| b | 49 | 36 | 21 | 12 |
| c | 78 | 167 | 15 | 7 |
| d | 55 | 55 | 16 | 13 |
| average | n/a | n/a | 17 | 11 |
| Western Riverine Plain: Balranald—Hatfield discharge zone | | | | |
| a | 46 | 50 | 26 | 12 |
| b | 78 | 86 | 30 | 35 |
| c | 296 | 211 | 45 | 37 |
| d | 289 | 290 | 42 | 37 |
| average | 272(c,d) | | 36 | 36(b-d) |
| Ivanhoe Block | | | | |
| a | 50 | 97 | 42 | 15 |
| c | — | — | — | 300 |
| d | — | — | — | 139 |

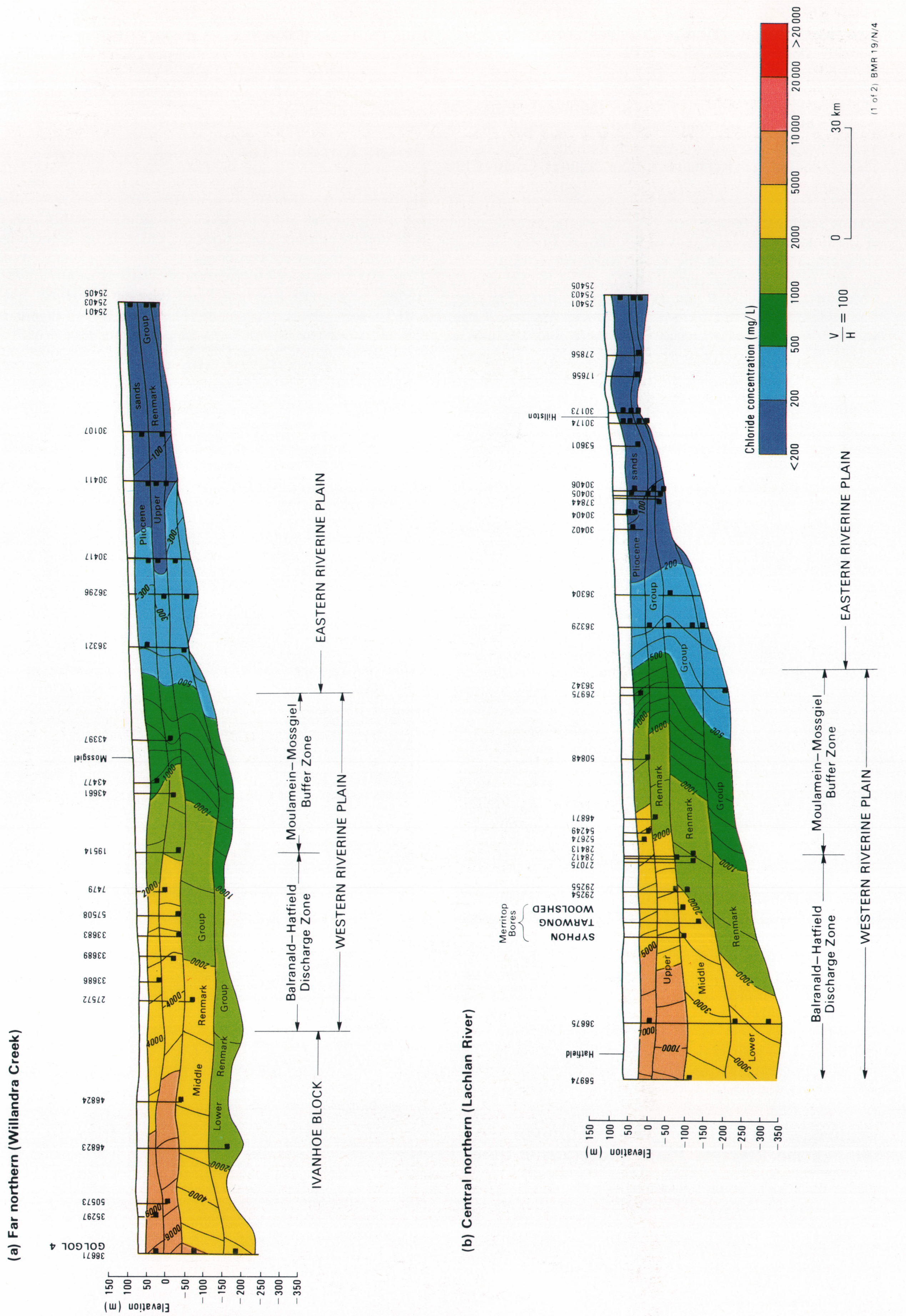
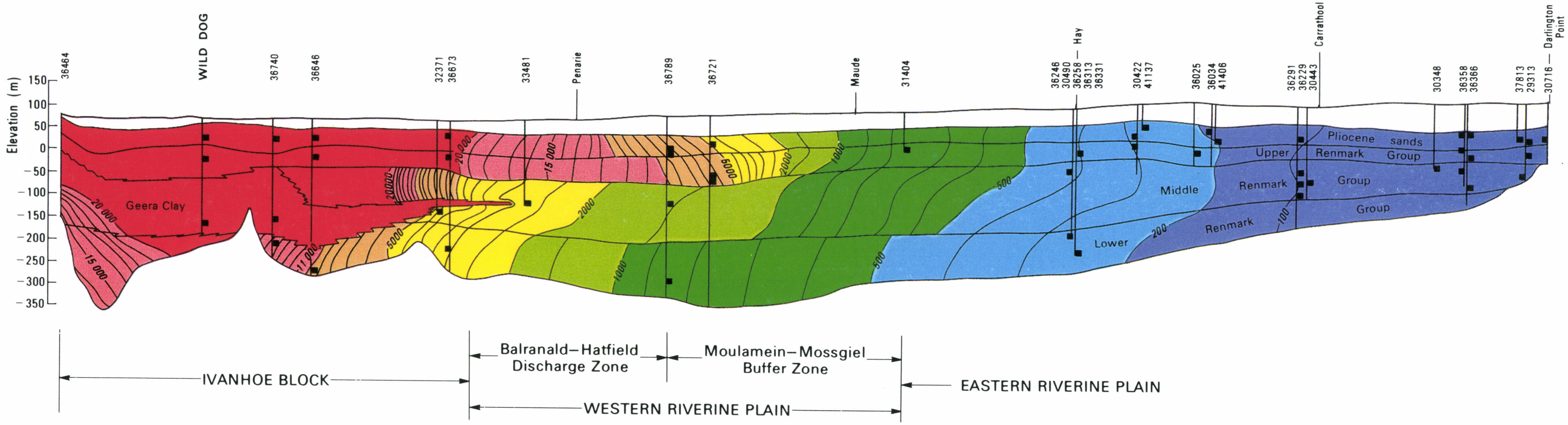


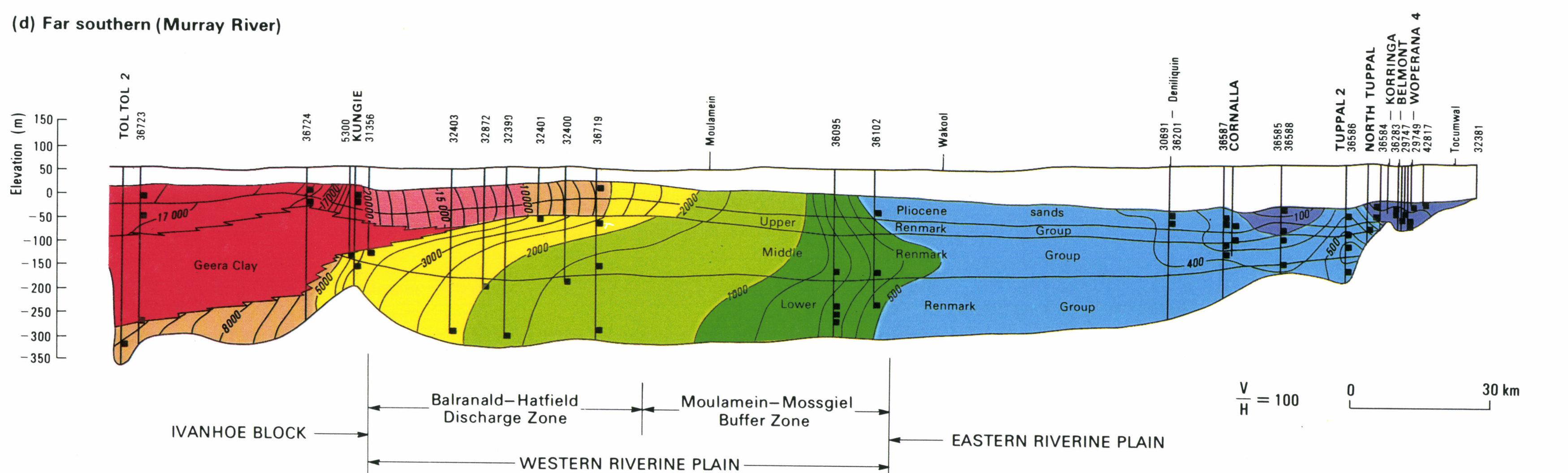

**Figure 8. Chloride profiles in Tertiary aquifers along regional flow lines.**

(a) Far northern (Willandra Creek). (b) Central northern (Lachlan River). (c) Central southern (Murrumbidgee River). (d) Far southern (Murray River). Borehole locations shown in Figure 9.

(c) Central southern (Murrumbidgee River)




(d) Far southern (Murray River)

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The chloride concentration versus distance plots (Fig. 10) permit a rigorous definition of the hydrogeological boundary between the eastern and western Riverine Plains: *the boundary occurs at the first change in gradient of the salinity vs distance curve, consistently across all the aquifers.*

## Western Riverine Plain

Upon entering the western Riverine Plain, chloride concentrations in the lower and middle Renmark Group aquifers initially increase almost linearly, but at a higher rate than in the eastern Riverine Plain—an average increase of 11 mg/L/km in the lower Renmark Group and 17 mg/L/km in the middle Renmark Group. After about 50 km there is another change in gradient, leading to a steepening non-linear rate of chloride accumulation in the two lower aquifers. This second inflexion point suggests subdivision of the western Riverine Plain into two hydrogeological zones, the Moulamein–Mossgiel buffer zone and Balranald–Hatfield discharge zone. The latter zone includes the Hatfield groundwater discharge lake complex (Brown, this issue), so named because this area contains the greatest frequency of gypsum playas and lunettes in the Riverine Plain. The formal definition for the hydrogeological boundary between the two sub-zones of the western Riverine Plain is that *the boundary occurs at the second major change of slope of the salinity vs distance curve in the lower aquifers.*

Salinity layering in the aquifers is well established by the time the Moulamein–Mossgiel buffer zone is traversed, with the freshest water in the lower Renmark Group and the saltiest water in the upper Renmark Group or Pliocene Sands aquifers. On the two northern flow lines, chloride concentrations in the upper aquifers are around double those of the lower Renmark Group, but on the Murrumbidgee flow line, chlorinities in the Pliocene Sands aquifer are at least five times those of the lower Renmark Group, whilst the ratio exceeds 10:1 in the upper Renmark Group. On the Murray flow line the ratio is almost 3:1 in both of the upper aquifers.

The shape of the chloride enrichment curve for the upper two aquifers in the Moulamein–Mossgiel buffer zone is quite different between the northern and southern flow lines. On the two northern systems the curves are very close to linear and show an average increase of 36 mg/L/km for the Pliocene Sands and upper Renmark Group aquifers (Fig. 10; Table 1). However, the chlorinities increase exponentially for these two aquifers on the southern flow lines. There is an 'average' rise of 55 mg/L/km for both aquifers in the Murray system, and a rate of 78 mg/L/km is recorded for the Pliocene Sands on the Murrumbidgee flow line—the corresponding rate for the upper Renmark Group is 167 mg/L/km. The unique boundaries in the lower two aquifers defined by inflexion points on essentially straight lines are no longer operative here, the boundaries having been fixed by the behaviour of the lower aquifers in an endeavour to describe the regional system. There are extraneous processes which increase salinity in the Pliocene Sands and upper Renmark Group aquifers, and these processes are stronger in the south of the western Riverine Plain than in the north. Furthermore, the source of salts must be close to the upper two aquifers since they are the ones most affected, and the exponential increases suggest mixing (or refluxing) with a continuously replenishing salt store.

The Balranald–Hatfield discharge zone represents the highest rate of chloride accumulation for all aquifers under the western Riverine Plain. The boundary between it and the Ivanhoe Block is an unequivocal structural feature: *the commencement of rising basement on the eastern flanks of the Iona Ridge and its southerly extension.* In some cases it also coincides with an inflexion point on the chloride versus distance curves. Chloride concentration increases linearly at a rate of 12 mg/L/km in the lower Renmark Group aquifer along the Willandra flow line, but a sharp curvilinear rise is recorded on the two southern flow lines with a somewhat more subdued (but nevertheless non-linear) increase along the Lachlan flow line, the average rate of chloride accumulation being 36 mg/L/km in the latter three systems. This is the same average rate for the middle Renmark Group aquifer across all four flow lines, all of which exhibit curvilinear chloride enrichment throughout the Balranald–Hatfield discharge zone. In contrast, the chloride increases in the Pliocene Sands and upper Renmark Group aquifers are close to linear in all four flow systems, but their rates are significantly different; for both aquifers the Willandra flow line rate is 48 mg/L/km and 82 mg/L/km in the Lachlan system. There is an average value of 272 mg/L/km in the two upper aquifers along the southern flow lines.

The Balranald–Hatfield discharge zone of the western Riverine Plain represents a key area of accelerated chloride uptake in all aquifers. Chloride concentration in the lower aquifers increases sharply with proximity of the Geera Clay aquitard, and it is apparent that the sudden permeability decrease caused by the combination of the presence of the aquitard itself and aquifer thinning by rising basement of the adjacent Ivanhoe Block create the potential for vertical upwards discharge. This in itself is not sufficient to explain the salinity profiles in the deeper aquifers — there must be a deep source of salt, and diffusion from the Geera Clay seems to be the most likely explanation. Also, the process which generates the high chlorinities in the upper aquifers at the edge of the western Riverine Plain is sustained throughout the Balranald–Hatfield discharge zone. The vertical salinity gradients developed at the edge of the western Riverine Plain are accentuated by the time the regional flow lines traverse the Balranald–Hatfield discharge zone. On the two northern flow lines the upper aquifers are 2–3 times saltier than the lower ones, whilst the chloride concentrations of 20 000 mg/L in the Pliocene Sands and upper Renmark Group on the southern flow lines are 5–6 times those in the middle and lower Renmark Group aquifers.

## Ivanhoe Block

It is difficult to adequately describe regional hydrogeochemical trends within the Ivanhoe Block for several reasons; the lower Renmark Group aquifer is not continuous there, the middle Renmark Group is largely replaced by the Geera Clay, the upper Renmark Group is considerably thinned, and the Pliocene Sands become unconfined on the basement ridges, even unsaturated on some parts of the Neckarboo Ridge (Fig. 7d). The Willandra flow line, however, retains its linearity in chlorinities for the lower Renmark Group (15 mg/L/km increase) and for the Pliocene Sands (50 mg/L/km) down the central axis of the block, but this trend would not persist beyond another 20 km or so, as the Geera Clay lies 25 km down hydraulic gradient. For the same reason, the curvilinear trend shown by the middle Renmark Group ('average' chloride increase of 42 mg/L/km) would be short-lived. On the other hand, the curve for the upper Renmark Group aquifer is asymptotic to the far southern flow line (Fig. 10), and therefore a sympathetic linear increase would probably persist until

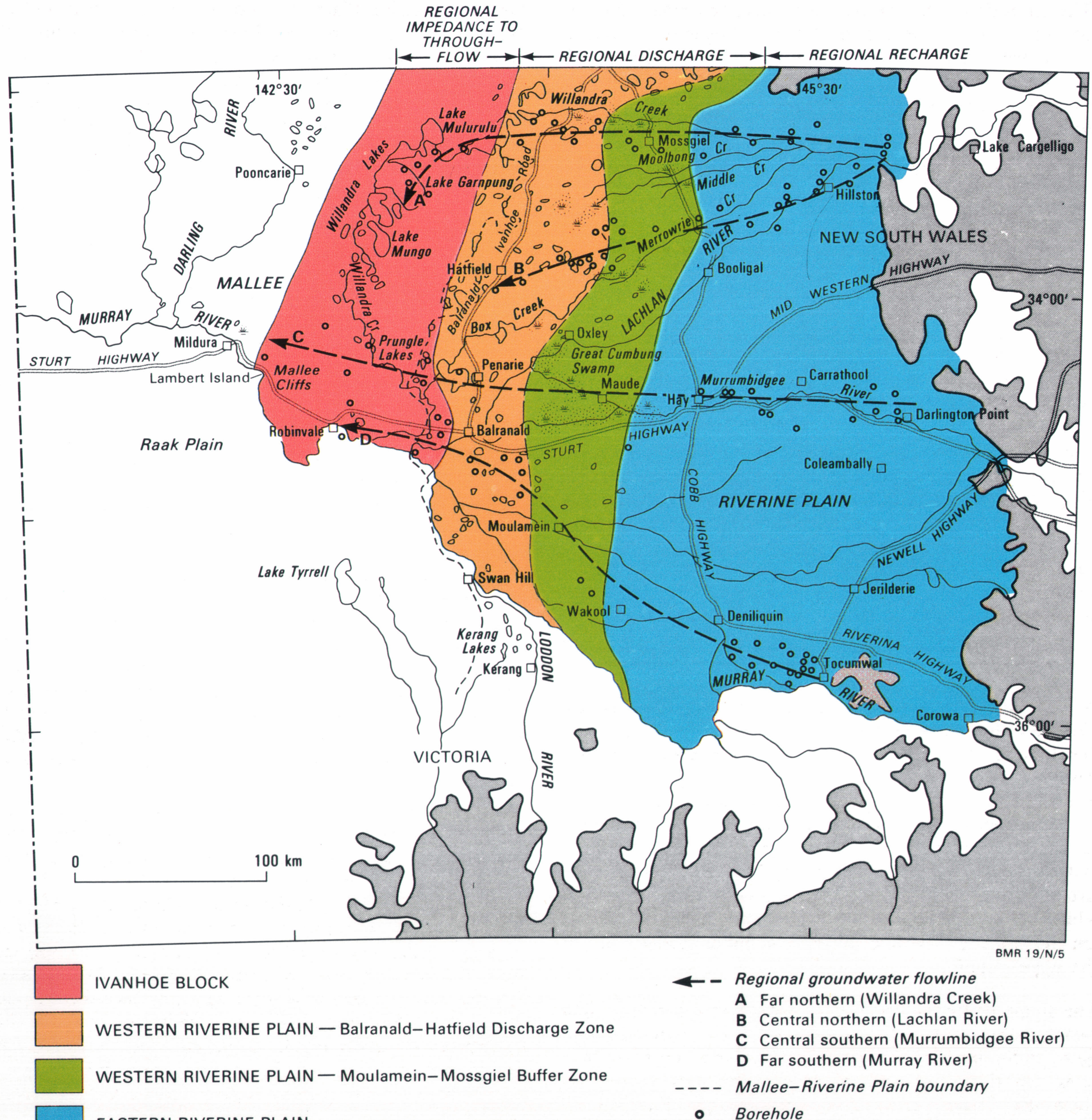


**Figure 9. Hydrogeological zones in the eastern and central Murray Basin, New South Wales.**
Zone boundaries are based on rates of change of chloride concentration along regional flow lines shown.

its chloride concentration reached 20 000 mg/L; this is the upper value for chloride in all the aquifers across the Ivanhoe Block.

Highest regional chloride concentrations in the lower Renmark Group aquifer occur within very short distances along the flow lines through the Ivanhoe Block. The 'average' rate along the Murrumbidgee system is 300 mg/L/km and along the Murray flow line 139 mg/L/km. It is likely that the latter value is a consequence of mixing and dilution in the Murray Trench by lower salinity deep groundwater from Victoria. Piezometers installed at various depths in the lower Renmark Group aquifer in the northern Tyrrell and southern Willandra Troughs show a distinct vertical concentration gradient diminishing away from the Geera Clay/lower Renmark Group interface; there seems little doubt that the Geera Clay is diffusing salts into the lower Renmark Group aquifer here.

## Influence of the Ivanhoe Block on the Riverine Plain aquifers

It has been demonstrated that chloride concentrations increase linearly in all aquifers along flow lines through the eastern Riverine Plain, but increase non-linearly through the western Riverine Plain. The inflexion points on the curvilinear chloride profiles in the upper two aquifers are out of phase with those of the lower two aquifers, implying there are two different sources of salts for the shallow and deep systems. Diffusion of salts from the Geera Clay is the most feasible explanation for the lower source, and perhaps the vital clue to the upper source is given at the land surface, by the presence of the fossil playas, which are abundant to the west but sparse to the east of the first internal Riverine Plain boundary (Fig. 9). The playas testify to former periods of widespread groundwater discharge to the land surface over the western Riverine Plain, in response to recharge and transmission rates from the east which were much greater than contemporary ones. The easterly limit of the playas defines the maximum up-basin migration of the boundary between regional palaeorecharge and palaeodischarge.

## Loddon Valley analogue

The trends shown in the chlorinity plots for the New South Wales flow lines may be put into perspective by comparison with Macumber's (1983) plot of distance down the Loddon Valley flow line vs TDS in the Calivil Formation (Pliocene Sands) aquifer (Fig. 11). The relatively high scatter of data points about the curve drawn by Macumber is probably attributable to his use of TDS as the dependent variable, rather than a tracer such as chloride which does not participate in chemical equilibrium reactions down the flow line; it may also reflect a higher degree of interaction between Calivil and Shepparton Formation groundwaters

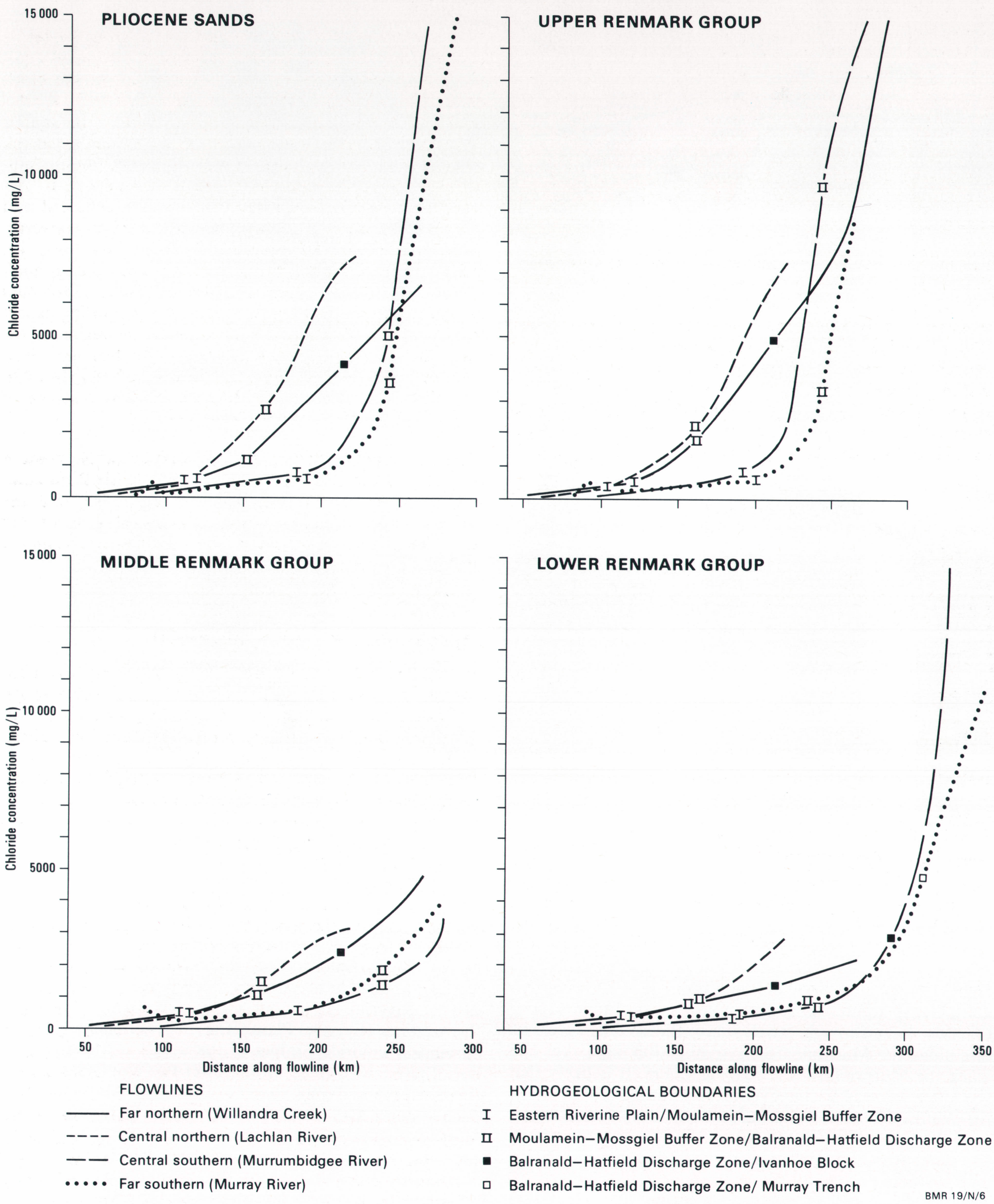


**Figure 10. Chloride variations in Tertiary aquifers along regional flow lines.**
Inflexion points define the boundaries of hydrogeological zones shown in Figure 9.

in the Loddon system. Of the chloride profiles for the Pliocene Sands aquifers on the New South Wales flow lines, the Murray system most closely resembles the shape and form of the Loddon salinity profile. The curve of best fit for the Loddon data is essentially linear until the first inflexion point at 70 km, corresponding to a TDS value of 1200 mg/L — approximately 500 mg/L chloride, the same concentration as that corresponding to the first change of gradient in the chloride profile on the Murray flow line. Between 70 km and 100 km down the Loddon Valley, Macumber's curve is curvilinear before rising steeply but almost linearly; the start of the third segment occurs at 3000 mg/L TDS (approximately 1450 mg/L chloride), which is substantially lower than the value of 3500 mg/L chloride at the second inflexion point on the Murray flow line. The most significant factor to emerge from the Loddon Valley study was that Macumber used potentiometry to show that *the 'hinge line' between the regional recharge and discharge zones for the Pliocene Sands aquifer lies between the first and second inflexion points of the salinity curve*.

By analogy, the inflexion points of chloride profiles along the New South Wales flow lines define limits of regional recharge and discharge. The western Riverine Plain represents the groundwater discharge zone of the New South Wales Riverine Plain system, and is composed of two major elements: a westerly discharge zone (Balranald–Hatfield discharge zone) where a vast salt store has been produced in the Pliocene Sands/upper Renmark Group aquifers by evaporative concentration and refluxing when water tables have been within the capillary fringe, and an easterly

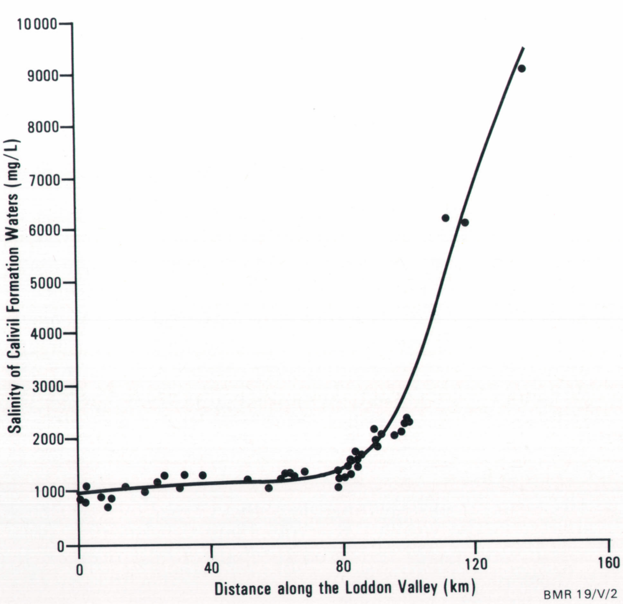


**Figure 11. Salinity variations in the Calivil Formation of the Loddon Valley (from Macumber, 1983).**

The rapid rise in salinity commences at the hinge line between regional groundwater recharge and discharge.

'expansion' zone (Moulamein–Mossgiel buffer zone) which represents the up-basin limit for the propagation back into the system of refluxed salts in these aquifers. Macumber (1983) gives the definitive account of evaporative salt concentration and the reflux mechanisms in playa lake systems in the Murray Basin, and their effect on the regional groundwaters of northern Victoria; his hinge line corresponds to the boundary between the Balranald–Hatfield discharge zone and the Moulamein–Mossgiel buffer zone. The eastern boundary of the latter zone is relatively constant, having been fixed by the periods of maximum playa activity during the initial drying-out phases following large-scale palaeorecharge events — the last major period was 18 000 years B.P. — but the western boundary oscillates in response to the prevailing balance between regional recharge and discharge.

### Role of the Ivanhoe Block in regional groundwater discharge

Westerly throughflow of Riverine Plain groundwater is impeded by the Ivanhoe Block, because the regional aquifers either thin out over the rising basement of the block or are truncated by it. As well as the reduction in aquifer thickness, there is an accompanying decrease in aquifer permeability at the western Riverine Plain/Ivanhoe Block boundary, particularly in the middle Renmark Group aquifer where it grades into the Geera Clay aquitard. In this way, flow lines in the deeper aquifers are deflected and flow lines in the shallow aquifers are forced to converge, thereby inducing the potential for upwards flow, i.e. groundwater discharge. If the block did not exist, groundwater of the Murrumbidgee and Lachlan alluvial fans would discharge into the Darling River, thereby permitting export from the basin of salts accumulated along the regional flow lines. Instead, the impeding action of the Ivanhoe Block has promoted retention of salts within the basin. In addition, the Geera Clay on the Ivanhoe Block is a source of salt for the lower Renmark Group aquifer.

Thus, the Ivanhoe Block fixes the location of the western boundary of the discharge zone of the Riverine Plain aquifers by structural and permeability constraints, and the regional effect of its impedance to lateral groundwater throughflow is felt up-basin as far as the western boundary of the eastern Riverine Plain.

## Implications for land salinisation

The history of land salinisation in the northern Victorian Riverine Plain may be used as a model to predict possible scenarios in New South Wales. The Kerang Lakes area lies in the groundwater discharge zone of the Loddon Valley, and before its lands were degraded by rising water tables, the area would have resembled many parts of the Balranald–Hatfield discharge zone. In any groundwater discharge zone, land salinisation is inevitable when water tables rise to within the capillary fringe and refluxing becomes an active process.

Based on the Victorian example, the Balranald–Hatfield discharge zone in the western Riverine Plain, and the area between Prungle Lakes and Lake Mungo (overlying the stagnation zone in the lower Renmark Group aquifer) on the Ivanhoe Block are identified as the areas most susceptible to land salinisation if water tables rise to within the capillary fringe (generally assumed to be within 2 m of ground surface). The salinity hazard is greater in the south of the Balranald–Hatfield discharge zone than in the north, because there is less available storage there to accomodate rising water tables. Currently the unsaturated zone in the Shepparton Formation in the south is 6–10 m, and under the gypsum playas in the north, about 12 m. There is about 5 m of unsaturated zone in the playas at Prungle Lakes (Gates, 1986). The Moulamein–Mossgiel buffer zone is considered to be in the second-highest risk category, and the eastern Riverine Plain has a low risk of salinisation in its non-irrigated lands.

Whether the lands of the high risk areas designated above become salinised or not depends on the behaviour of the regional water table. The worst possible scenario is a sustained rise in water levels at the same rate as that of the worst salt-affected lands in Victoria — 0.2 m/year. This would result in complete land salinisation of the entire western Riverine Plain and Willandra Trough within the next 50–60 years. The most likely scenario is a far more modest rate of rise in the water table since the input to the recharge zones of these systems is substantially lower (lower proportion of cleared land and less rainfall) than in the Loddon Valley analogue, and available storage is much larger in the New South Wales system because of a thicker unsaturated zone and longer flow paths. The true rate of rise will be determined only by careful monitoring of the water table in the high risk areas.

## Conclusions

- The Ivanhoe Block is a concealed basement ridge complex separating the two major depocentres of Tertiary sedimentation in the Murray Basin. Two parallel, fault-bounded basement ridges extend south-southwest towards the Murray River from the Darnick High, an uplifted and tilted block whose outcrop is exposed in the Manfred and Darnick Ranges.
- There is a one-to-one correspondence between the basement ridges of the Ivanhoe Block and the elevated topography of the mallee country. The western limb, the Neckarboo Ridge, forms the regional groundwater divide between the Darling and Lachlan–Murrumbidgee systems. The Neckarboo Ridge splits into two about 60 km above the Murray River. One limb continues along the south–southwest trend to intersect the Murray River at Lambert Island, and the other limb becomes the northern extension of the Tyrrell Fault Block, which runs beneath the Murray River at Robinvale. The eastern limb of the Ivanhoe Block, the Iona Ridge, sharply delineates the boundary between the western Riverine Plain and mallee country. The Iona Ridge becomes subdued above the junction of the Murrumbidgee and Murray Rivers, but the elevated basement topography is propagated southwards by an adjoining granite pluton.
- The Willandra Trough is the saddle between the Neckarboo and Iona Ridges and its aquifers are hydraulically connected with those of the Tyrrell Sub-basin to the south. The Balranald Trough lies east of the Iona Ridge and was the depocentre for Cainozoic sedimentation in the western Riverine Plain.
- The combination of episodic, small-scale uplift on the Iona and Neckarboo Ridges, and subsidence in the Tyrrell Trough, have resulted in a cumulative displacement of 100 m between aquifers in the troughs and ridges. Post-Pliocene uplift of 65 m on the southern Neckarboo Ridge and Tyrrell Fault Block changed the course of the ancestral lower Willandra Creek to its present southeast direction.
- Thickness of the Cainozoic sequence varies from less than 150 m on the Ivanhoe Block to over 400 m in the Balranald Trough, and more than 80% of it consists of the Renmark Group and its intercalated marginal marine aquitards. A threefold subdivision of the Renmark Group is facilitated by changes in shape and baseline shifts in gamma and electric logs in 10 key boreholes through the study area. The gamma logs discriminate on the basis of depositional environment, and indicate paralic grading to marginal marine sediments (middle Renmark Group, Geera Clay, Winnambool Formation) over a fluvial sequence (lower Renmark Group) followed by a prograding shoreline (upper Renmark Group). The SP and normal resistivity logs are additionally influenced by groundwater salinity, which is strata-bound throughout the study area.
- The basal regional confined aquifer consists of lignitic silt and sand of the lower Renmark Group. It is 130 m thick in the Balranald Trough and 80 m thick in the northern Willandra Trough, thinning to 30 m in the Tyrrell Trough and 60 m on the adjoining basement platform to the east. The hydraulic conductivity of the lower Renmark Group decreases from 4–5 m/day in the north and east, to 1–2 m/day in the south and west.
- Since the lower Renmark Group is absent on the basement ridges, the groundwater inflow from the northeast is constrained to flow parallel to the axis of the Willandra Trough, and flow lines from the east are deflected southwards by the blocking action of the Iona Ridge.
- Major discharge zones are developed in the lower Renmark Group aquifer beneath the playa lake complex at Hatfield and between Lake Mungo and Prungle Lakes. The western Riverine Plain and Ivanhoe Block are zones of steepening hydraulic and salinity gradients in the lower Renmark Group aquifer — TDS increases by up to 20 000 mg/L along the final 100 km of the regional flow lines.
- Lignite, silt, clay and fine sand of the middle Renmark Group are about 100 m thick in the western Riverine Plain and 50 m thick on the northern parts of the basement ridges. The hydraulic conductivity of the aquifer is 1 m/day but this drops to 0.5 m/day about halfway across the study area at the Geera Clay contact. Thereafter the middle Renmark Group laterally interfingers with the Geera Clay, which attains a maximum thickness of 130 m in the Tyrrell Trough.
- Discharge zones are developed in the middle Renmark Group aquifer at Hatfield and in the Willandra Trough. There is a 20 km wide buffer zone of brackish groundwaters up-gradient from the Geera Clay, and the marked permeability decrease caused by envelopment of the Geera Clay results in steepening hydraulic gradients down flow lines.
- Carbonaceous and micaceous fine to medium sands of the upper Renmark Group are 60 m thick in the troughs and thin to 40 m on the ridges. Regional hydraulic conductivity of the aquifer is 1–2 m/day, and within the study area 20% of its groundwater exceeds 35 000 mg/L TDS. The regional groundwater discharge zone for the upper Renmark Group aquifer occupies most of the Willandra Trough, but the aquifer also discharges to the Murray River at Mallee Cliffs (via the Loxton-Parilla Sands) — elsewhere the rivers dilute the upper Renmark Group waters.
- The Calivil Formation component of the Pliocene Sands aquifer in the western Riverine Plain consists of a basal coarse sand facies restricted to channel-fills, overlain by a sheet of pale grey fine to medium sand with silty clay interbeds. The Calivil Formation is 50 m thick in the Balranald Trough; its average hydraulic conductivity is 2.5 m/day. Most of its groundwater is brackish or saline and a major discharge zone is developed around the Hatfield playa lakes.
- On the Ivanhoe Block, the Pliocene Sands aquifer is predominantly the Loxton-Parilla Sands, a uniform sequence of medium to coarse sand which is characteristically ferruginised at the top. There is a carbonaceous, fine-grained basal facies in the Tyrrell Trough. The Loxton-Parilla Sands are 30 m thick on the Iona Ridge but thicken westwards to 50 m on the Neckarboo Ridge. Hydraulic conductivity increases from 4 m/day in the east to over 15 m/day in the Murray Trench at Lambert Island. The Loxton-Parilla Sands become unsaturated on

the crest of the Neckarboo Ridge. Apart from the Darling River floodplain, all of the groundwater in the Loxton-Parilla Sands is saline (>14 000 mg/L TDS), and one-third of it exceeds 35 000 mg/L. The unit is hydraulically continuous with the underlying aquifer, so its discharge zone in the Willandra Trough coincides with that of the upper Renmark Group. Significant volumes of highly saline water are discharged from the aquifer at Mallee Cliffs, where the Loxton-Parilla Sands are in hydraulic contact with the Murray River.

- A complex assemblage of clay, silt and shoestring sand make up the Shepparton Formation, the unconfined aquifer of the western Riverine Plain. Its thickness varies from 50 m in the northern Balranald Trough to 25 m in the south; its hydraulic conductivity is 1–2 m/day.
- Chloride concentration increases linearly in all the Tertiary aquifers along flow lines through the eastern Riverine Plain, indicating a constant rate of mixing with evaporated stream leakage and infiltrated rainfall.
- Chloride concentration increases in two steps along flow lines through the western Riverine Plain. The first sustained change in gradient of the chlorinity profiles occurs through the Moulamein–Mossgiel buffer zone, and represents the maximum historical extent of up-basin propagation of refluxed salts. The second stage defines the Balranald–Hatfield discharge zone, the centre of production of the salts in the two upper Tertiary aquifers by evaporative concentration and refluxing when water tables were high following prior wet phases.
- Comparison of the chloride trends with the Loddon Valley salinity profile indicates that the eastern Riverine Plain is the regional recharge zone in the New South Wales system, and the western Riverine Plain is the regional discharge zone. The latter has been created by the impedance to lateral groundwater throughflow exerted by the Ivanhoe Block's aquifer thinning and truncation. The presence of the Ivanhoe Block promotes the retention of salts within the central Murray Basin and its position fixes the western boundary of the Balranald–Hatfield discharge zone. The Geera Clay on the Ivanhoe Block is a prominent source of salts for the lower Renmark Group.
- The Balranald–Hatfield discharge zone and the lower Willandra Lakes are most at risk from land salinisation if water tables continue to rise. At present the thickness of the unsaturated zone in the Balranald–Hatfield discharge zone is from 6 m in the south to 12 m in the north, and 5 m in the playas of the lower Willandra Lakes. The Moulamein–Mossgiel buffer zone is in the second-highest risk category, and the eastern Riverine Plain has a low risk of salinisation in its non-irrigated lands.


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