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The Nulla Groundwater Discharge Complex, Murray Basin, SE Australia

by

J. Ferguson, B. M. Radke, G. Jacobson, W. R. Evans, L. A. Chambers, R. A. Wooding, I. A. White, D. Whitford, G. L. Allan, R. Grun

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Geological Controls on the Permeability and Hydrodynamics of Groundwater Discharge Complexes and Disposal Basins

The Nulla Groundwater Discharge Complex, Murray Basin, SE Australia

J.Ferguson, B.M. Radke, G. Jacobson and W R. Evans (AGSO)
L.A. Chambers
(CSIRO, Land and Water)
R. A. Wooding
(CSIRO, Land and Water)
I. A. White
(Centre for Resource and Environmental Studies, ANU, Canberra 200)
D. Whitford
(CSIRO, Division of Exploration Geoscience)
G. L. Allan
(ANU, Department of Nuclear Physics)
R. Grun
(ANU, Quaternary Dating Research Centre)

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CONTRIBUTORS

James Ferguson, Geohazards, Land and Water Resources Division, AGSO, P.O. Box 378, Canberra City, 2601.

Bruce M. Radke, Contract Sedimentologist, "Eungella" Farringdon-Bombay Rd., Braidwood, NSW 2622.

Lyn A. Chambers, CSIRO Land and Water, G.P.O. Box 1666, Canberra A.C.T. 2601.

Gerry Jacobson, Geohazards, Land and Water Resources Division, AGSO, P.O. Box 378, Canberra City, 2601.

Ian White, Centre for Resource and Environmental Studies, ANU Canberra 200.

Robin A. Wooding, CSIRO Land and Water, G.P.O. Box 821, Canberra A.C.T., 2601.

W. Ray Evans, Geohazards, Land and Water Resources Division, AGSO, P.O. Box 378, Canberra City, 2601.

David J. Whitford, CSIRO Division of Exploration Geoscience, P.O. Box 136, North Ryde, N.S.W. 2113.

Garry L.Allan, ANU Accelerator Mass Spectrometry Program, Dept. of Nuclear Physics, The Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601 (Present address: Dept. of Medical and Radiation Science, RMIT, 124 Latrobe St., Melbourne 310).

Rainer Grun, ANU, Quaternary Dating Research Centre, Canberra, ACT 0200, Australia.

SUMMARY

Nulla Groundwater Discharge Complex is located within the Mallee of the Murray Basin, approximately 50 km northeast of Lake Victoria, 30km southeast of New Bluff and Warwick Discharge Complexes, and 70km south of Scotia Discharge Complex. Nulla is a broad and shallow deflation depression that lies within a subtle but complex topography: dune and swale terrain of Tertiary Parilla Sand is subdued by overlying Pleistocene lacustrine clays (Blanchetown Clay) and seif dunes (Woorinen Sand). Nulla, Warwick, New Bluff, and additional discharge complexes align on a west-northwest Parilla strandline trend that indicates a transition from estuarine deposition (more permeable aquifer) to the northeast, to marginal marine (less permeable aquifer) to the southwest.

Nulla Discharge Complex began to develop with the final demise of Lake Bungunnia and subsequent outwatering of the Parilla Sand through both unconfined dune crests and structural permeability conduits in the overlying and confining Blanchetown Clay. With the evolution of the complex through at least 4 major deflation events, groundwater discharge presently occurs in two areas; northern shallow arcuate lakes that coincide with unconfined Parilla dunes, and a southern Nulla Spring Lake which is embedded in impermeable Blanchetown Clay ($k \leq 1 \times 10^{-4}$ m/day). Nulla Spring Lake is maintained predominantly by limited groundwater discharge from the underlying Parilla Sand aquifer (upwards gradients of <10 to 500m/km) upwards through structurally-controlled springs, and laterally from across a fault on the western margin. The artesian head is 1m above the surface of the lake. Surface runoff from the larger fossil playa and surrounding dune terrain into Nulla Spring Lake is both minimal and infrequent. Nulla Spring Lake is a closed system with generally constant input and seasonally-variable evaporative loss. It has winter salina and summer playa cycles. Evaporites are lost from the lake through deflation which has been volumetrically predominant over lacustrine accumulation in its Pleistocene to Holocene history. Concentric zonation of lunettes and relict playa surfaces on the eastern side of Nulla Spring Lake indicates a history from possibly 700ka with lunette deposits dated at 170±51, 115±35, 37±11, 23±7, and 6 to 2ka.

The lacustrine sediments of Nulla Spring Lake are mainly clays and it was therefore expected to be one end-member of a hydrodynamic spectrum ranging from almost complete isolation from the host aquifer to open connection. Theoretical models of fluid and salt movement predict that low-permeability substrates of the Nulla-type will constrain the vertical downwards movement of salt to diffusion, whereas higher-permeability substrates will allow density-driven advective reflux of brines into the underlying aquifer and, potentially, the formation of relatively stable brine-pools.

Linear salinity-depth profiles beneath Nulla Spring Lake imply salt is entering the Parilla aquifer by diffusion through the Blanchetown Clay. Brine in the Parilla Sand below Nulla Spring Lake is not a result of the present hydrodynamic regime and may have been a product of brine reflux elsewhere in the complex. There is an outwards lateral flow of brine along the base of the Parilla aquifer into the regional groundwater, even though there is evidence of a circulation pattern within the brine pool. This circulation facilitates entrainment of the brine in the shallow regional groundwater which discharges into the lake.

GENERAL OBJECTIVES AND METHODOLOGY

General Objectives

This investigation of the Nulla Discharge Complex was part of an NRMS - funded project " Groundwater dynamics of evaporative brines and their application to saline wastewater disposal". This project aimed to facilitate the siting and management of disposal basins by determining the geological controls on the permeability and hydrodynamics of natural and developed groundwater discharge sites.

Selection of Study Areas

Natural groundwater discharge complexes at Scotia and Nulla in the Murray Mallee of western NSW (Figure 1) were selected as likely end-members of a hydrodynamic spectrum ranging from open connection with the underlying host aquifer to almost complete isolation. The lacustrine sediments of the Nulla Discharge Complex were known to be mainly clays with potentially low permeability. In contrast, the Scotia Discharge Complex has a high sand content and a relatively high, though probably strongly anisotropic, permeability. The Mourquong Discharge Complex (Figure 1) was selected because it represents an intermediate situation in which the host sediments are a combination of lacustrine clays and fluvial sands.

General Methodology

For each site the present-day and historical features of the system have been considered because an historical context is necessary to explain a number of the existing hydrodynamic signatures.

The present-day lithostratigraphy and hydrodynamics provide information on the current processes by which water and salt are moving. This information is a basis for classifying the natural environments and disposal basins in terms of their potential for brine retention or reflux, and for assessing the limits and rates of future groundwater movement.

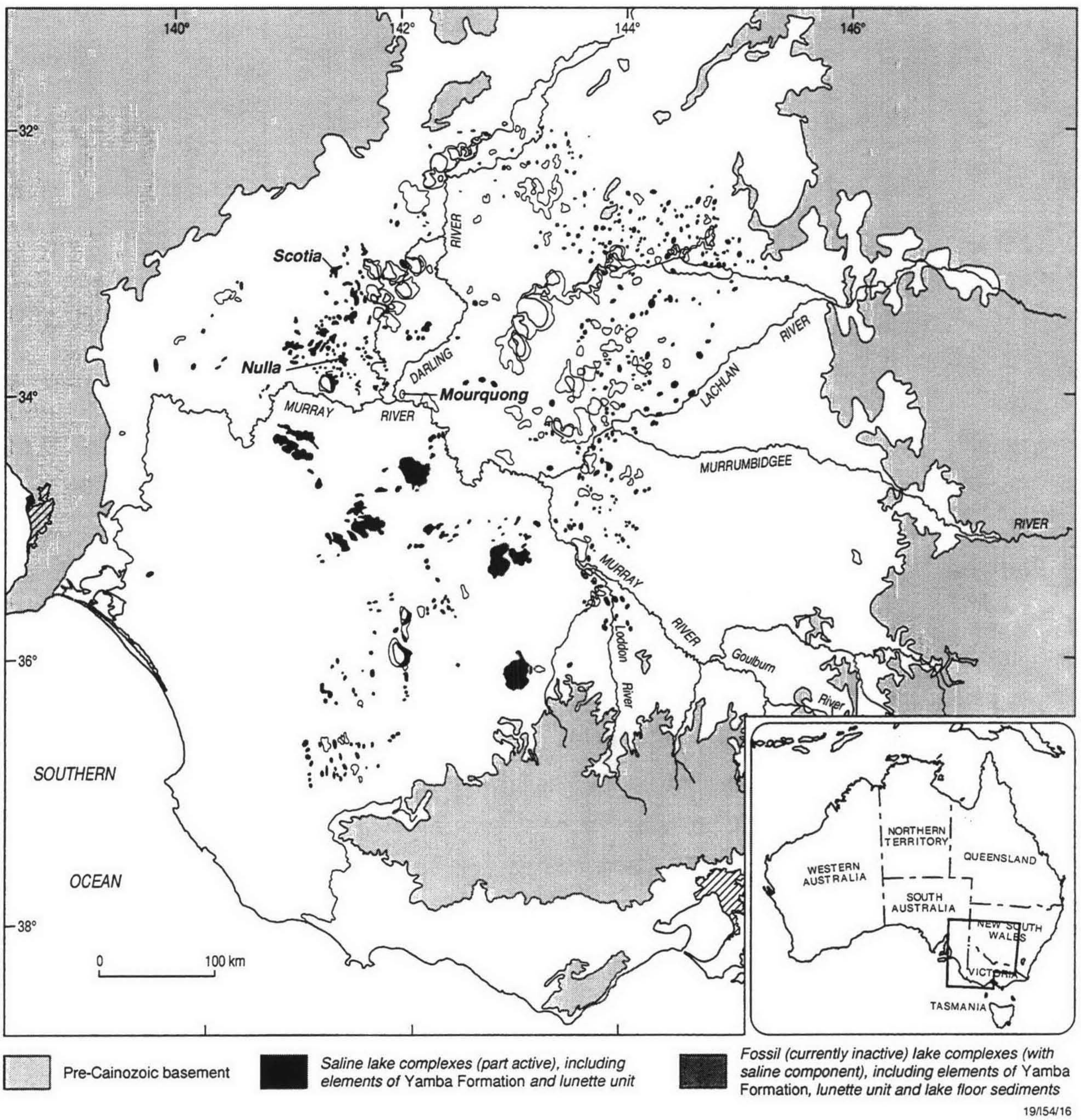


Figure 1. Location of Nulla Discharge Complex

The stratigraphic and hydrodynamic history of groundwater discharge complexes is accessible through information on the lithostratigraphy of the lacustrine sediments, and from the distribution and geochemistry of saline waters retained from previous regimes. The method has been to reconstruct the pre-existing, regional hydrodynamic context and the processes of discharge development. This has been done by using the results of a detailed stratigraphic study to help model the hydrodynamic history of each complex from its initiation to present state.

THE NULLA GROUNDWATER DISCHARGE COMPLEX

INTRODUCTION

Natural groundwater discharge complexes in the Murray Basin are commonly used for the disposal of saline groundwater from salt interception schemes. A major factor in the siting and management of these disposal basins has been the need to understand and, if necessary, control the way in which brines generated by evaporation of the saline water leak laterally into adjacent areas and/or vertically into the underlying regional aquifer.

The fate of the vertically-moving brines which reach the regional aquifer can be a major factor in determining the efficiency and environmental impact of a disposal basin. The brines may be partly dispersed and swept down gradient, or they could form relatively stable brine pools which remain beneath the disposal site. Clearly, the latter situation is preferable because not only is the vertically leaking disposal water contained, but the capacity of the disposal basin would be increased many-fold if the evaporated disposal water could be stored mainly in the underlying aquifer. The potential extent of this increased disposal capacity is evident from the work of Macumber (1991), who showed that there is a highly saline brine in the regional Parilla Sand aquifer beneath Lake Tyrrell which contains about 1 to 2% of the total salt in the Murray Basin.

There is abundant evidence that the hydrodynamic processes in natural groundwater discharge complexes can increase the salinity in the underlying aquifers to various degrees, but the nature of the processes involved, and the factors which determine the extent of the increase in salinity are not well understood. Numerical models indicate that the situation should be relatively straightforward. Brine pools will develop where high sediment permeability favours advective reflux of lacustrine brines and, conversely, low permeability substrates restrict groundwater flow and salt moves by diffusion.

A preliminary examination of the situation at Lake Tyrrell suggests that application of this concept to natural systems requires some knowledge of the geological evolution as well as the present-day lithostratigraphy of the area because present-day conditions are not obviously conducive to brine reflux (Macumber, 1991). The hydraulic heads are currently directed upwards from the brine in the Parilla Sand aquifer to the lake, which suggests that the brine was emplaced during hydrodynamic regime(s) different to the present. In any event, the bed of Lake Tyrrell is not obviously permeable because most of the lake is underlain by 20m thickness of Blanchetown Clay. Two suggestions to resolve the discrepancy between the theoretical predictions and the inferred low permeability beneath of the lake are: (1) that brine reflux occurred through fractures in the Blanchetown Clay; and (2) that brine reflux occurred through a small area at the southern end of the lake where the Blanchetown Clay is missing and the underlying Parilla Sand is exposed at the lake surface.

To provide further information on the conditions necessary for advective brine reflux, a hydrodynamic, geochemical and lithostratigraphic investigation of a natural groundwater discharge complex at Nulla, in the Murray Mallee, N.S.W has been carried out. This discharge complex is sited well within the northern limit of the Blanchetown Clay and is therefore likely to have a high clay content and low permeability which, as indicated by the numerical models, should inhibit advective reflux and favour diffusion.

LOCATION and PHYSIOGRAPHIC SETTING

The Nulla Groundwater Discharge Complex is located in the Mallee region of the Murray Basin, some 70 km south of Scotia Discharge Complex (Figure **1**). It occurs within a small, broad and shallow, closed topographic depression which extends approx. 13 km N-S, and 10 km E-W. The southeastern extent is poorly defined by the erosional remnants of the oldest aeolian deposits which are partly interworked with, and overlain by active seif dunes established since Woorinen dune development.

The complex contains a distinctive suite of landforms. Active salinas occupy relatively small areas in the lowest parts of the complex and are entrenched within a fossil stranded lake complex. The elevations of active lake floors lie between 20.3 - 21m AHD in Nulla Spring Lake at the southern end, and are variable in individual lakes in the northern area; between 22 and 24 - 24.5m AHD in the ephemeral or small isolated lakes, and 23.5 - 24m AHD in the larger "permanent" northernmost lakes. Two terraces of surrounding stranded lake floors are recognized, a poorly-defined outer level at 29-31m AHD, and a central prominent level at 24-28m AHD.

Adjacent lunette ridges (crescentic leeward dunes), which flank the eastern margins of both active and stranded lake floors, rise to elevations of approx. 27-33m AHD for the youngest, approx. 31m AHD for the prominent central terrace, and approx. 38-42m AHD on the oldest peripheral lunette system. The lunettes are generally concave to the west. In comparison with the large clay lunettes such as at Lake Tyrrell, they form low, sinuous source-bordering ridges, several hundred metres long, only 20 - 40 metres wide and a few metres in elevation above the surrounding terrain. Locally, lithologically-similar deposits form mounds at the top of, and against the western flanks of stranded lake pedestals. Crests are generally rounded and smoothed by erosion. Minor erosional gullies occur adjacent to the modern lakes.

Modern lunettes closely parallel the eastern margins of the active salinas while older lunettes, which form a discontinuous series of roughly north-south oriented ridges, were at one stage located adjacent to active salinas, but are now stranded some distance from and higher than the modern lakes. Their orientation reflects the prevailing winds at the time of deposition. The older lunettes are characterized by the presence of cream-coloured earthy gypsite, with local horizons of purer, white, fine-grained gypsite which have been interpreted as a weathering product of aeolian millet seed gypsum (e.g. Jack, 1921). Remnant pedestals of Blanchetown Clay, often with veneers of aeolian dune sand, rise to around 27-33m AHD. The surrounding aeolian dunefields and sand plains have an elevation of approximately $\geq$ 33 m AHD.

Active lakes represent only the most recent of a number of past salinisation/deflation events, each of which has left an imprint on the landscape and vegetation cover of the discharge complex, as well as on groundwater salinity.

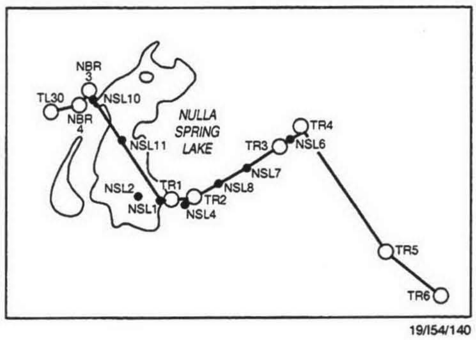
The regional dunefields of the Woorinen Formation locally form low-lying east-west oriented, linear seif dunes, separated by broad swales and extensive sand plains. These consist of red-brown silty sand, with a high clay content, and are modified by pedogenesis. With the exception of local deflation hollows, the dunes are stabilized by vegetation at the present day. Older components have well-developed brecciated calcrete hardpans, as well as carbonate rhizoliths and pisolitic concretions. Calcrete is generally lacking in younger, remobilized components of these dunes.

METHODS

For this investigation, the regional setting of the Nulla Discharge Complex was established using data from nearby sites at Coolamon (aka NSL 9) and Talgarry (Figure 2). The Coolamon and Talgarry sites are located in a Woorinen Dunefield to the northeast and southwest of the complex, respectively. The area around Coolamon is not obviously salinized but near Talgarry interdunal salinisation occurs nearby. Studies of the discharge complex are centered on Nulla Spring Lake, which is the largest active lake. A transect (Figure 2) has been established from a large Woorinen dune on the western margin of the complex, across Nulla Spring Lake and terminating in lacustrine-derived lunette deposits to the west (Figure 2).

Drilling was undertaken along the transects shown in Figure 2. Playa bed conditions are soft and wet, and for this project we used a specially designed tripod-mounted rig assembled on site, with a hovercraft to transport the rig components. In addition, rotary rigs were used at sites on land, to drill to a depth of 60 m and install nests of deeper piezometers in order to investigate the regional groundwater regime.

The drillholes were cased as piezometers, and subsequently levelled relative to the Australian Height Datum (AHD). Salinity and geochemistry was measured on porewater from the base of each core section. The sections were then split for lithostratigraphic examination.



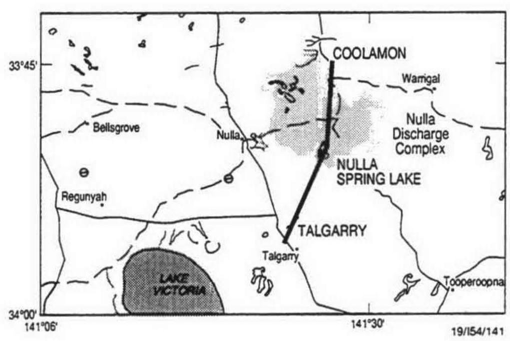


Figure 2. Location of regional and local transects centred on Nulla Spring Lake in the southern area of the Nulla Discharge Complex.

Groundwater samples from the deep drill-holes were obtained from the piezometers after removing at least two casing volumes of water.

Measurements of surface water salinity and geochemistry were limited to a few samples taken in winter, when local rainfall and runoff temporarily floods some of the active lakes.

Lateral and vertical hydraulic gradients have been determined separately using freshwater and environmental water heads, respectively. The concepts used are those developed by Lusczynski (1961) and Lusczynski and Swarenski (1966).

Additional information on the methods is in the Appendix.

STRATIGRAPHY

Regional Structural and Palaeogeographic Setting

Small active salinas are abundant in the northern area of the Nulla complex and align with broad lineaments (pronounced on TM imagery) interpreted as a relict Parilla Sand strandline complex (Figure 3). This lake elongation and orientation is not seen to the south, away from the strandline complex, where Nulla Spring Lake is the only significant salina. The position of Nulla Spring Lake appears to relate to a pronounced north-south lineament (Figure 3). The westward thickening of the Blanchetown Clay sequence below the lake, the fractured and disrupted sequence (varying dips) in NSL 10 (Figure 4) on the western side of the lake, and the disparate higher level of the top of the Blanchetown Clay in the dune to the west of the lake (about 37 mAHD) compared to the upper level to the east (between 27 to possibly 33 mAHD) suggests a possible displacement of as much as 10 metres. Subtle differential deposition with tilting on the downthrown eastern side is apparent. All Blanchetown units indicate small but consistent thinning eastwards. Springs in the eastern floor of Nulla Spring Lake align parallel with this structure.

The Nulla Discharge Complex is distinctively terraced and most of the older terraces that are preserved as stranded pedestals within younger deflation surfaces, have dissected and eroded outlines that reflect this regional lineament set (Figure 5). This upper terrace is understood to be partly eroded into and overlies Blanchetown Clay. Fracture of the Blanchetown Clay by subtle basement movement is apparent, influencing fracturing on the localised erosion of the Blanchetown Clay. The easterly limits of the main terrace and its embayments also have northeast and northwest sublinear margins also influenced by this structure.

Regional Stratigraphy

The surrounding area to the Nulla Discharge Complex is almost entirely masked by sands of the Woorinen Formation except where deep dissection exposes Blanchetown Clay. The

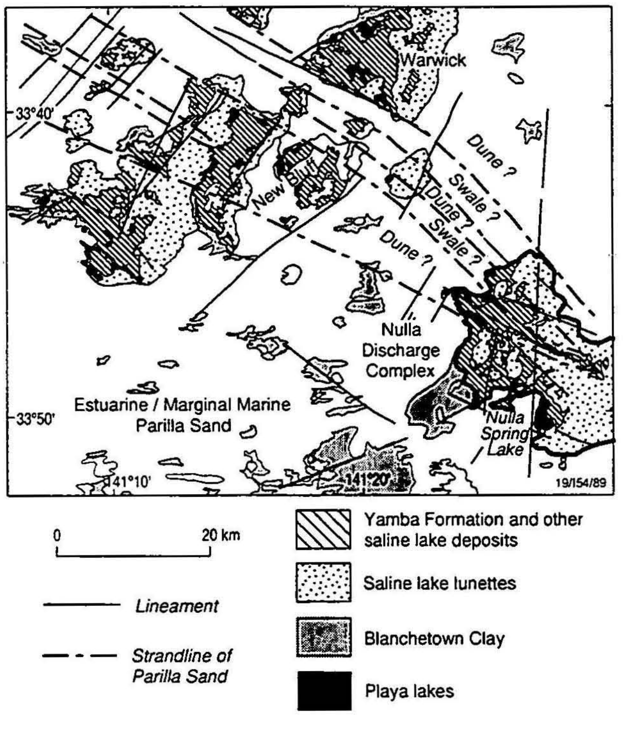


Figure 3. Regional structural and interpreted palaeogeographic setting of the Nulla Discharge Complex.

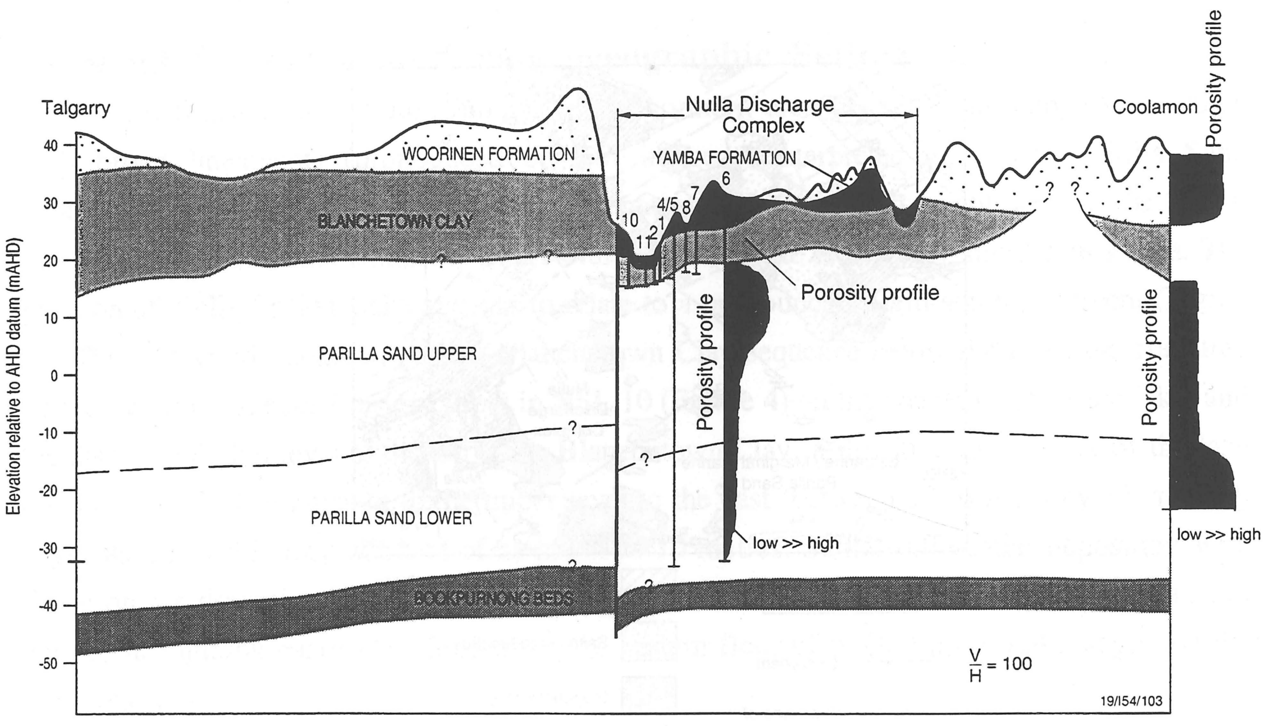


Figure 4. Regional stratigraphic setting and porosity of the Nulla Discharge Complex.

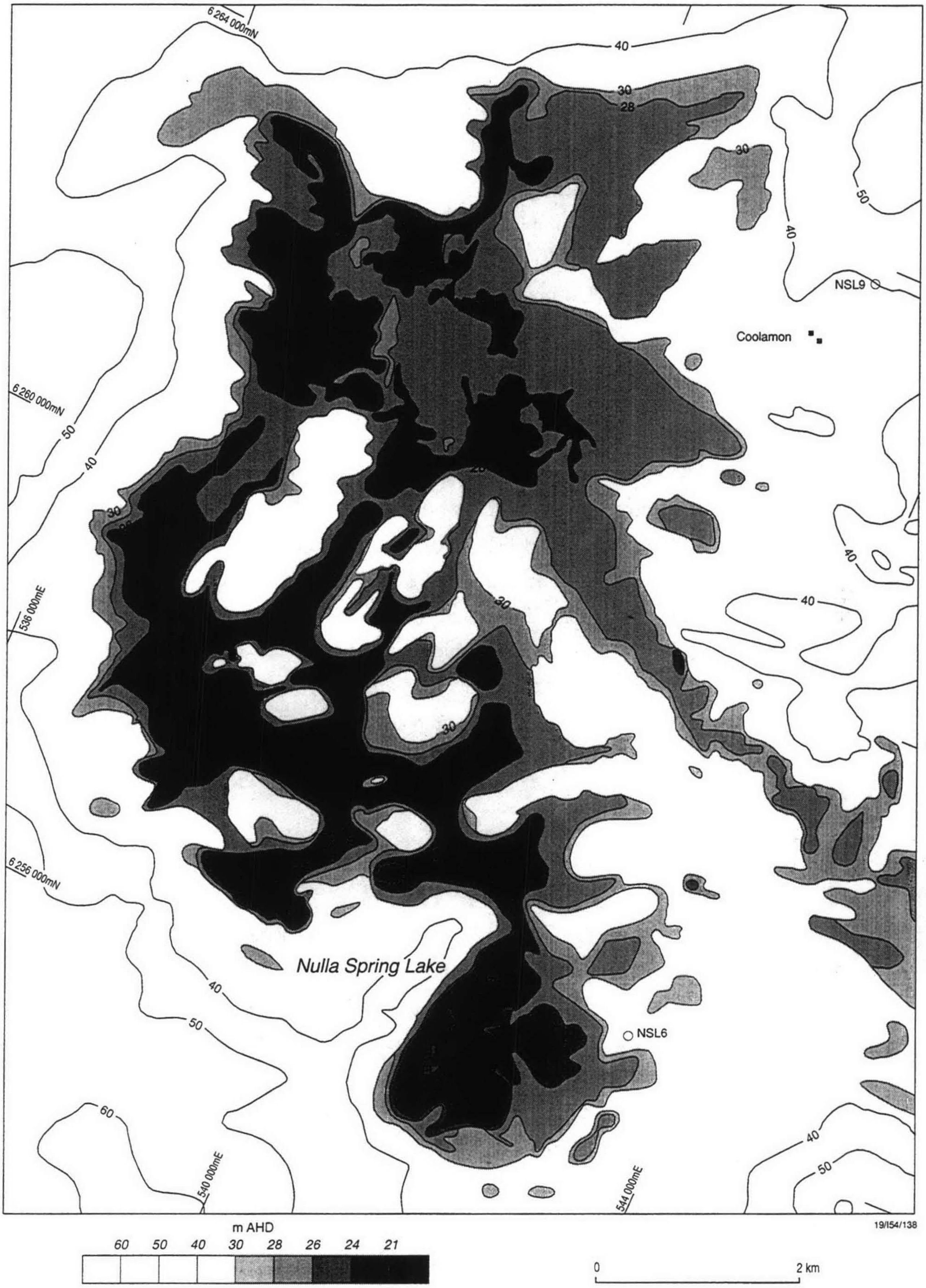


Figure 5. Topography of the Nulla Discharge Complex.

spatial distribution of the stratigraphic units is shown in Figure 6.

Parilla Sand

The Pliocene Parilla Sand aquifer underlies, and is confined from the discharge complexes by the overlying Blanchetown Clay. It remains conjectural whether the Parilla Sand is exposed around the discharge complexes. At Nulla Discharge Complex, the Parilla Sand may be exposed beneath the northernmost lakes, on the basis of outcrop and on regional Parilla dune strandline trends identified on TM imagery.

The Parilla Sand is described in Lithofacies Unit N1.

Blanchetown Clay

The Blanchetown Clay and the occasionally associated Bungunnia Limestone are restricted to the inter-ridge zone of the Parilla Sand topography (Lawrence, 1975). Its distribution is consequently a series of strips oriented NNW-SSE in the same direction as the strandlines of Parilla Sand. Brown (1991) recognized stranded pedestals of Blanchetown Clay throughout the complex. At Nulla Spring Lake, Blanchetown Clay extends beneath the salina. In subsurface, this unit is lithologically similar to the clay lithofacies of the Yamba Formation. Because of this similarity, earlier stratigraphic interpretations did not recognize Blanchetown Clay below Nulla Spring Lake (Brown, unpublished; Radke, 1992). Subsequent thermoluminescence dating and a lithostratigraphic comparison with Mourquong Discharge Complex confirm that the sequence below Nulla Spring Lake is almost entirely Blanchetown Clay.

Woorinen Formation

The Woorinen Formation (Lawrence, 1966) forms a regional thin to superficial cover around Nulla and Mourquong discharge complexes and comprises mainly red-brown to pale reddish brown (10R4/4-5/4) siliceous silty sand which is variably sorted to bimodal (very coarse to very fine sand and silt), light pink-brown (5YR7/4) to moderate brown (5YR4/6) calcareous loamy sand with irregular calcite glaebules, red calcareous silty clay, and sandy clay. It characteristically contains one or two well-developed horizons of platy and nodular calcrete, 0.7 to 0.3 m thick. The pisolitic nodules range from centimetre to decicentimetre size, and are small rounded to larger irregular to subangular shapes. These form an unconsolidated but close-fitted fabric. Fragmented segments of calcareous rhizoliths (up to 15 mm D) may be *in situ* or scattered with the nodules

The formation forms extensive and isolated patches of longitudinal dunes, morphologically featureless sand sheets, and locally less distinctive low hummocky dunes. The latter morphological forms are probably younger phases of mobilization and reworking of the regionally pervasive longitudinal dunes, especially around and on the eastern side of the discharge complex. Longitudinal dunes have a distinctive east-west orientation superimposed on

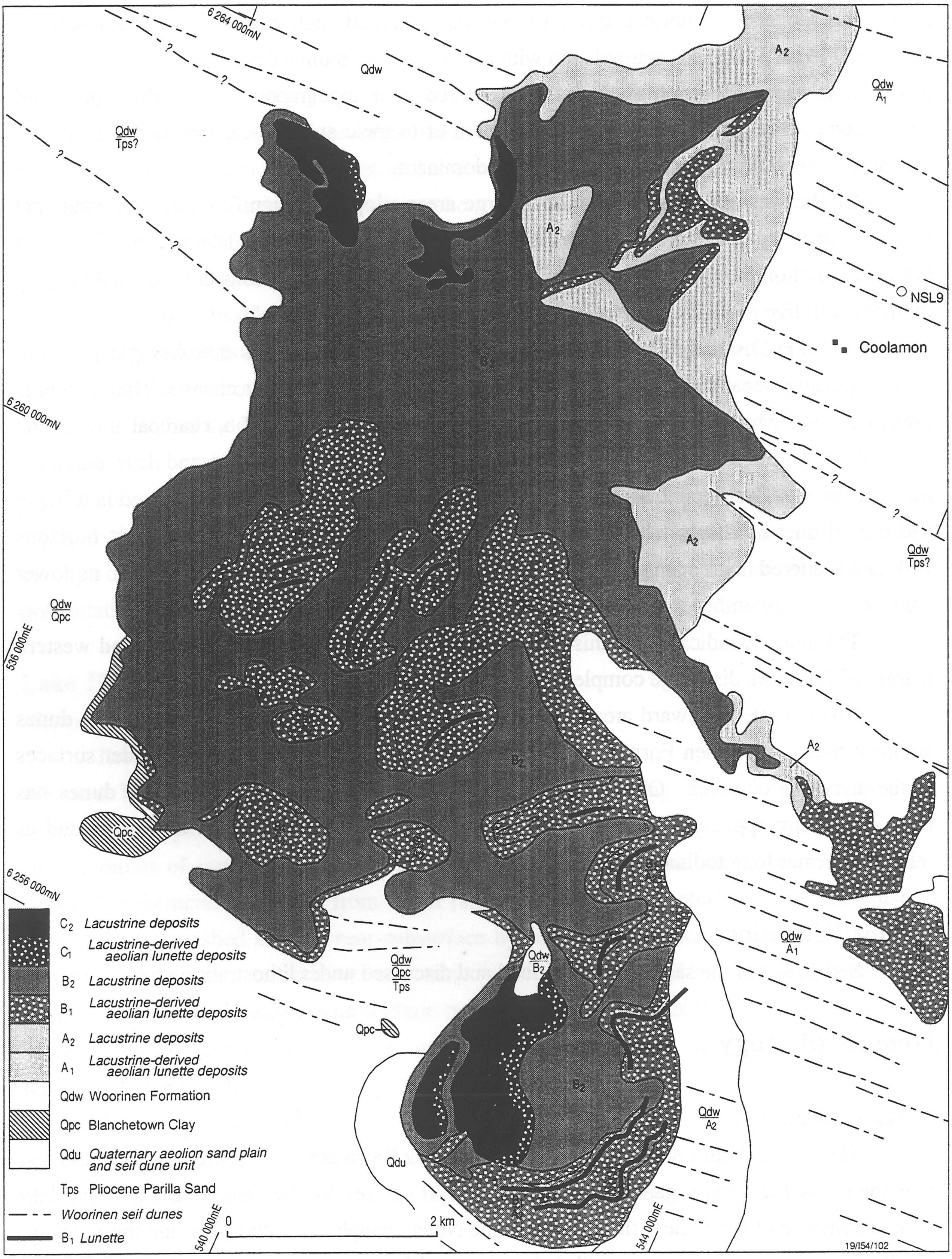


Figure 6. Morphostratigraphy of the Nulla Discharge Complex.

a variable local terrain which suggests several possibilities: gentle local tectonic uplift of the underlying sequence; Woorinen cover of preexisting broad high ridges (Parilla dunes?); or significant local Woorinen accumulation with a surficial longitudinal fabric.
Longitudinal dune morphology is better preserved over topographic highs while in broad depressions which are derived by either deflation or tectonic subsidence, this fabric is almost absent and low hummocky dunes are more predominant.

On the western margins of the discharge areas, slopes are significant and an additional younger reworked body demarks the base of slope adjacent to the active lake margin. The sand is a relatively homogenous light reddish-brown sandy soil becoming compact with depth, faintly mottled, with live rootlets and organic matter.

At Nulla Discharge Complex there are two sand bodies in this morphologic position, stratigraphically separated by an erosional surface and distinctive colour change. The additional lower body is a white to very pale green friable sand with faint lamination, charcoal flecks, and a pervasive colour mottling from vertical-dominant and horizontal finer and less dominant rhizome traces. These root traces may be filled with rust brown sand. Superimposed is a larger and less distinct but larger mottling pattern in bright red and orange. Thin indistinct horizons with rare scattered black manganiferous? speckling and faint mottling may occur near its lower contact.

TM imagery indicates that this lighter-coloured unit extends along the dissected western margin of the Nulla discharge complex.

On the eastern leeward area of the discharge complex, low indistinct hummocky dunes are identified as Woorinen Formation. These have an irregular cover over upper older surfaces of the discharge complex. On the interpreted "A" surface the distribution of these dunes has more anisotropy approaching lineation in a west north-west orientation and are interpreted as relicts of former longitudinal dunes.

Yamba Formation

Sediments of the salinas are described and discussed under lithostratigraphy.

Geomorphology

Surface Drainage

The regional dune sands of the Western Murray Basin are highly porous, much drainage is in the subsurface, and organized surface drainage is of only local extent. Consequently, there is little evidence of fluviatile influence within the Nulla Complex, which lies within the relatively small basin of endoreic drainage, with only minor and local ephemeral runoff. Erosional gullies which developed around the western margin of the complex are generally only a few hundred metres long. In winter, most of the water in the lakes comes from local precipitation, and includes runoff and seepage from the adjacent dune systems. The lakes contain salts derived from evaporation of groundwater and runoff.

Vegetation

Lake margins are primarily vegetated by low halophytic samphire vegetation (mainly *Salicornia* sp.). Downwind of the lakes, the samphire is interspersed with tussock grasses. In the elevated areas within the complex, and in the surrounding landscape, the vegetation consists of grasses, saltbush, clumps of casuarinas, she-oaks, and mallee trees. Most trees are relatively stunted and have preferentially colonized well-drained aeolian dunes. The presence of salts, redistributed from lake complexes within the region, is indicated by the widespread occurrence of halophytic `blue-bush' vegetation. The adjacent land is used primarily for grazing of sheep.

The characteristic landforms of groundwater discharge complexes have resulted from the interaction between groundwater systems and surface processes. These show that the extent of salinisation within the Nulla discharge complex has varied in the recent geologic past, and at times has been considerably more widespread than at present. Active and fossil saline playa lake complexes and gypsum hardpans are scattered in low-lying areas throughout the lower Darling region of the western Murray Basin. At Nulla, where the groundwaters are neutral to alkaline, the hydrochemical processes which are active in the spring zone have resulted in the precipitation of carbonate at the surface, and gypsum within the upper sediment.

Lake Floor Deposits

Modern

The salinas dry during the summer months, leaving an ephemeral crust of halite bordered by gypsite and other efflorescent minerals- including thenardite, epsomite, and hexahydrite. In places, the desiccated lake floors are flanked by `fluffy' and `puffy' crusts and small mounds of creamy-brown, clay and gypsum pellets, with fine sand grains. The area is subject to ephemeral inundation from winter rains with resultant re-solution of the salt crust. At times, halite is washed into the near-subsurface by summer rains, converting a salt-pan into a clay pan. When a halite crust is present, there is usually rafting and development of shrinkage polygons, but the immediate near-surface remains moist in the capillary zone. On the lake margins, insects (especially ant nests) are more abundant at the lake margins, presumably tapping into the moisture.

A layer of black anoxic mud rich in sulphate-reducing bacteria and complex sulphides underlies the salt crust. The thickness and extent of this layer varies as the lake expands and shrinks with the seasons. As with all the lake sediments, the presence of re-cycled fine-grained aeolian quartz sand grains is ubiquitous.

Small-scale lake-margin deltas, occur at the mouth of gullies and are confined in distribution to the western margin of the lake complex, particularly prevalent along the western margin of Nulla Spring Lake and adjacent lake to the west (which intercepts clastic debris entering the complex via gullies in the southwest. These sites of fluvial discharge onto the lake floor have deposits up to a few tens of centimetres above the lake floor and comprise red quartz sand. The size of the deltas varies from a few metres to 30-40m in radius. They are ephemeral features, being washed over and reworked with higher fluctuations of lake level.

Ancient

Extensive, near-planar terraces have massive gypcrete crusts or hardpans of variable thickness in the near-surface of their stranded lake floor sediments. The hardest layer is 20-30cm thick but locally may be up to several metres thick, consisting of large bladed crystals of translucent gypsum, clouded by mud inclusions. The presence of these mud inclusions suggests formation within the sediment. This layer forms a bench where undercut by the modern playa lake, particularly along the western margin. For example, a distinctive bench rims the western margin of Nulla Spring Lake and where it has been undercut, the lake margins are blanketed by oligomictic breccias of corroded gypsum crystals.

Lunettes

Modern

These landforms are vegetated by low samphire on the lower slope, with scattered colonization adjacent to the lake; the healthiest (greenest, higher density) colonize adjacent to the lower slopes flanking the lake, presumably intercepting run off and local groundwater. On the higher slopes, grass as well as samphire is present. A grey powdery silty sediment and soil forms on the upper slopes and ridge crest. The lunettes are formed by the accumulation of deflated sand-sized gypsum and clay pellet (grapestone) aggregates from the lake surface.

Ancient

Older lunettes adjacent to the stranded lake floors, appear to be more gypsiferous than the modern equivalent, and comprise earthy gypsite. These lunettes have distinctive stunted vegetation. Some of the smaller and lower ridges have the appearance of strandlines of gypsite.

Stranded Pedestals

Pedestals of Blanchetown Clay generally exceed 29-30 mAHD elevation (Figure 5), They are mainly buried beneath aeolian sand deposits, and have approximate north-south and northeast-southwest elongation that reflects a fracture pattern within the Blanchetown Clay inherited from a deeper structural fabric. Pedestal distribution within the discharge complex is in bands that reflect former Parilla swale? topography (Figure 6), but not adjacent to western lake margins. At times of high groundwater table and lake levels in the past, these would have formed islands with steep banks and beaches. Erosional development of these features was most probably by parallel scarp retreat to account for the relatively steep slopes. Areas of white gypsite within the pedestal areas are possibly due to leaching of gypsite down to hardpan with subsequent deflation. Alternatively, and more likely, this surface reflects an earlier and higher deflation/lacustrine level. The cores of the pedestals are not known but a gully incising a pedestal to the west of a lake in the northeast appears to expose Blanchetown Clay containing gypsum in pods and veins.

Aeolian Dunes and Deflation Hollows

Extensive root systems of modern Mallee and Acacia vegetation are exposed in recent deflation hollows. Delicate filamental and ornate tubular rhizoliths are preserved in gypsite. Nodular hummocky gypsite, with crusts containing minor calcrete, are also exposed in these hollows. Some have a distinctive type of stunted vegetation and an absence of extensive calcrete development. Aboriginal fireplaces are a relatively common occurrence distinguished by hard to very hard blue-grey clay, often with a white siliceous coating, siliceous scraping tool artefacts, but a paucity of ironstone artefacts. Remnant dune sand is red to orange-red in colour, with only a minor clay content as red cutans on the quartz grains.

Erosion Gullies

Erosion gullies occur in most steep-sided banks including modern unconsolidated lunettes on lake margins where they drape an eroded bank. Here they are up to one metre deep and extend short distances 10 to 15 metres upslope.

On the western margins of the complex, especially adjoining the active lakes, erosion gullies extend upslope from the deltas, cutting into Woorinen Formation, and Blanchetown Clay. These gullies are approximately 2 to 3 metres deep and may have flat or V-shaped floors, with vertical walls, and are dendritic in plan view. The better exposures of these units are to be found in these gullies which can extend almost to the crests of ridges.

Palaeosols

Stranded lake floors, particularly around the western margin, are weakly modified by pedogenesis, with minor red-brown soil development with calcareous content; partly unvegetated; desiccated crust with polygons, crumbly soil, and patches of efflorescent salts - gypsum, halite, and others. In the subsurface these are recognized by a compact blocky texture, mottled rusty colouring usually controlled by the fracture fabric, rootlet traces and fenestrae, solution - enlarged fenestrae, sometimes with infill by very fine sucrosic gypsum. Generally these features are thin and subtle, probably either as a result of erosion of most of the former surface, or the brief nature of the event.

Stratigraphy

The sequence beneath Nulla Spring Lake and its surrounds comprises Blanchetown Clay overlying the Parilla Sand. This lacustrine sequence is considered to be entirely Blanchetown Clay. It has been eroded by several deflation events to produce a complex of lunettes and terraced former lake levels.

Lithostratigraphy

Lithological correlations, the distribution of ostracod faunas, carbonates, sulphates, and sulphides, and features of erosion, exposure, and salinity are documented in Radke (1992). The selected lithostratigraphic units are delineated in Figure 7. This sequence is described on the basis of lithostratigraphic units.

Unit N1 Parilla Sand

Location in lake complex: Unit N1 underlies the entire discharge complex.

Geometry and thickness: This unit is approximately 52m thick below Nulla Spring Lake but has variable thickness up to 80m immediately to the west. On a regional scale it is a tabular body with a horizontal lower boundary. The upper surface has significant topographic relief (and localised erosional relief), giving the highly variable thickness under and around the discharge complex. It comprises a lower, muddier sand unit (21m thick) and an upper cleaner sand unit. Only the upper interval of this upper sand unit is described.

Description: `Clean' light-coloured unconsolidated quartz sands, with grainstone to packstone textures, have variable colours from dusky yellow to very pale orange (5Y6/4 to 5YR8/1), medium olive grey (5Y5/1), and medium light grey (N6). The particulate components are predominantly quartz - coarse to medium and fine, sorted, well-rounded sand, with traces of opaque grains (rutile, and tourmaline?), and white clay matrix varying from <10 to >30%. Subtle erosional surfaces with undulose relief of 1 cm are overlain with cross-stratified sand grading up into homogenous sand. These sands have medium to high interparticulate porosity, and variable but minor framboidal pyrite which is usually in localised clusters, probably around residual organic matter associated with bioturbation.

The sands in the upper 0.25 - 1.9m of this unit thin towards and are nonexistent in NSL 8 and NSL 7. The sands are muddier, compact to friable, and darker: light brownish grey (5YR6/1), light (5Y6/2) to dark olive grey (5Y3/6). They comprise coarse to fine quartz sand with rare traces of opaque minerals, and muddy matrix in packstone and wackestone textures. Intraparticle porosity is lower and more variable. There is some cross-stratification in better sorted sands in NSL 1. A trace carbonate matrix, predominantly dolomite, is present in NSL 10, 7, and NSL 1 but absent in NSL 6. Traces of very fine framboidal pyrite accentuate sedimentary lamination and some bioturbation features.

Stratigraphic relationships: The Parilla Sand conformably overlies the Miocene-Pliocene Bookpurnong Beds, and is overlain by Units N2, 3 and 4 of Blanchetown Clay.

Depositional Environment: The Parilla Sand was deposited as a regressive marginal-marine dune sand unit with interbedded paralic swale lenses of muddy sands. The lower unit comprises shallow-marine subtidal muddy sands while the upper unit was deposited under southwest prograding shallow marine, beach, and coastal dune environments with intercalated paralic lagoon or estuarine deposits.

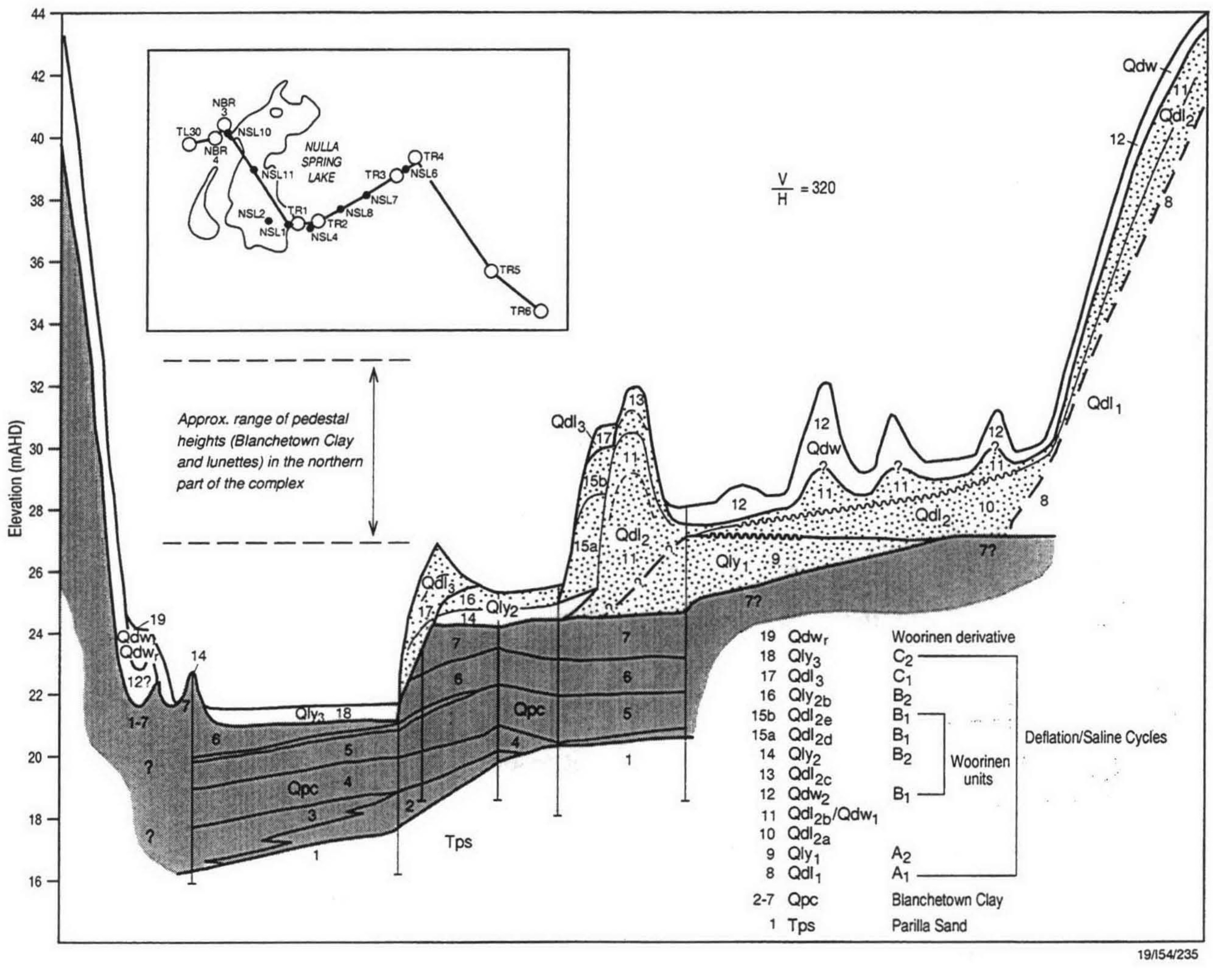


Figure 7. Lithostratigraphic units of the Nulla Discharge Complex in a section through Nulla Spring Lake.

Discussion: The Parilla Sand is the significant aquifer underlying the discharge complex. Only the upper levels have been intersected by coring. 'Clean' light-coloured sands in NSL 7, 8, and 6 are interpreted as an eroded dune crest. The absence of carbonate in NSL 6 suggests that the dolomite, where present, is diagenetic.

Unit N2

Location in lake complex: Unit N2 is intersected in NSL 1, 4, and 8, and overlies the Parilla Sand.

Geometry and thickness: This is a thin lens with maximum thickness of 1.5m in NSL 1, and dips westwards off Unit N1 lying to the east.

Description: The sequence is compact to friable and comprises interbedded muddy and clayey sands, and sandy muds. Sands are greenish grey to dark greenish-grey (5G6/1, 5GY6/1, 5G4/1), dusky yellow grey (5GY5/2), and moderate olive grey (5Y4/2). Wackestone to packstone textures predominate, and comprise coarse to medium to fine quartz sand, millimetre-sized pinkish calcrete clasts, traces of opaques (ilmenite?), and green kaolinitic and montmorillonitic clay. The matrix of quartz silt and clay varies from <20 to 50%. Faint lamination is defined by graded fining-up cycles and cross-stratification is occasionally apparent.

The muddy sands exhibit efflorescence of halite and possible fibrous gypsum, are slightly calcitic, and pyritic. The carbonate content (mostly dolomite) increases to the top of the unit in NSL 1. In NSL 10 the muddy sands are dolomitic.

Stratigraphic relationships: Unit N2 disconformably? overlies the Parilla Sand (Unit N1), draping westwards off it and ?interdigitating with unit N3.

Depositional Environment: Most probably this unit resulted from the reworking of the Parilla Sand during the initial filling of Pleistocene Lake Bungunnia.

Discussion: Without intersection of the unit between NSL 1 and NSL 10, the interpretation remains equivocal but implies that the Blanchetown Clay exists below the complex.

The preferred interpretation is that Unit N2 is a Parilla Swale which drapes a dune structure (Unit N1).

An earlier interpretation of the evolution of the complex implied the formation of Unit 2 by colluvial/fluvial action during and after deflation of the Blanchetown Clay and reexposure of the Parilla Sand (Radke, 1992).

Unit N3

Location in lake complex: The unit is only recognized on the western side of the complex, intersected in NSL 10.

Geometry and thickness: It forms an apparent wedge 1.55m thick in NSL 10, with a lateral facies which is transitional laterally and is not recognized in NSL 1.

Description: N3 comprises sandy muds (33%), dolomitic muds (27%), dolomitic sands (25%), and dolomicrite (15%), in an upward succession of alternating mud and sand with a 37 cm thick dolomicrite band below the uppermost dolomitic sand.

The plastic sandy muds are faintly-laminated dark bluish grey with thin lenses and laminae of dark yellowish orange porous sand. The sand in both the muds and lenses is medium to coarse, quartzose, with traces of lignitic flakes and very fine pyrite.

Sandy dolomitic muds with a plastic consistency comprise two beds. The upper bed is dark bluish grey (5B4/1) with faint sandy laminae and contains quartz, micaceous flakes, and lignitic flakes. The lower bed comprises faintly laminated medium grey (N5) to light olive grey (5Y6/2) muds with coarse-medium - fine quartz sand, with traces of lignite, and very fine disseminated friable pyrite.

Calcareous and dolomitic sands comprise the uppermost 25 cm thick semi-indurated bed and a lower 30cm bed of compact grading downwards to unconsolidated sand. The upper bed is dark greenish grey (5G5/1) to light olive grey (5Y6/1) fine to coarse clear quartz sand in clay matrix (approx. 20%), and with predominantly grainstone texture. They overlie the dolomicrite and also contain traces of dolomitic clasts. The sands generally fine upwards and have traces of framboidal pyrite.

The lower sand is light brownish grey (5YR7/1) in very thin cross-stratified sets and comprises fine-medium-coarse rounded to subangular clear quartz, traces of ilmenite, and minor pyrite. The dolomite is present in the matrix as dolomicrite.

The dolomicrite, approx. 37 cm thick, is plastic with an upper 5 cm indurated crust that has repeated irregular erosional surfaces and infill. The carbonate is greenish grey (5GY6/1) sandy (clear medium quartz sand) with a clotted texture and lightens tonally up to the indurated crust (5GY7/1). Very fine pyrite is disseminated ubiquitously.

Stratigraphic relationships: The unit disconformably overlies Unit N1 and is laterally transitional with and possibly overlies Unit N2. It is overlain conformably by Unit N4.

Depositional Environment: Deposition was in a freshwater lacustrine environment with highly alkaline conditions, and with a continued influx of sand from exposed Parilla. To the east, a sandier lithofacies (N2), closer to a source of Parilla Sand, accumulated concurrently.

Discussion: Clastic deposition predominated over dolomite precipitation.

Unit N4

Location in lake complex: The unit extends beneath the entire part of the complex that has been intersected by drilling.

Geometry and thickness: It is a tabular-wedge-shaped body thinning eastwards from 1.35m in NSL 10, 0.95m in NSL 1, 0.8m in NSL 4, 0.75m in NSL 8, to 0.15m in NSL 7 and 0.3m in NSL 6.

Description: This unit has laterally uniform facies. A basal non-dolomitic mud is overlain by dolomitic clays and muds with interbedded dolomite bands. Dolomites increase upwards in abundance and thickness. The uppermost dolomite is thicker to the east where erosional and

reworking features on the upper surfaces of the beds are prolific.
The basal muds are approx. 0.25m thick. In the section from NSL 10 to 4, the lowermost 10 cm have a sand/mud interlamination of medium greenish to bluish grey colour (5G5/1 & 5B5/1). The basal muds are plastic, medium to dark greenish and bluish grey (5G5/1-4/1; 5B5/1-4/1) with localized rusty oxidation, and are faintly laminated with numerous horizontal burrows. Pyrite framboids are concentrated in siltier laminae.
The overlying dolomitic clays and muds are plastic, light greenish grey (5GY7/1) and light grey (N7) in colour with an indistinct light/dark mottling. Their lighter character results from the dolomitic mud content. Some lamination indicates plastic deformation in certain horizons. Bioturbation and desiccation cracks, as well as dolomitic clasts and flakes are present. Dolomite-rich laminae and bands are fractured, and bioturbation structures are highlighted by framboidal pyrite.
The interbedded dolomites are semi-indurated, vary from laminae to 8 cm thick bands, and are light olive grey (5Y6/1) to yellowish grey (5Y8/1) to light greenish grey (5G8/1). These have a clotted texture with prominent microfracture porosity. The uppermost dolomite bed, especially in NSL 7 and 6 has additional pelleted to ooid structures, macro fractures, breccias, and erosional features. Much of the fracturing appears to have been created through volume changes as the dolomite precipitated within the sediment, initially producing clotted textures, microfractures, then breccias and macrofractures. Because of their internally-stressed nature, the beds exfoliate and spall readily on exposure to create dolomitic flakes and clasts.
Stratigraphic relationships: Unit N4 is conformable over Units N2 and N3, with probable disconformity over Unit N1. It is overlain with unconformity to the west, and with disconformity to the east by Unit N5.
Depositional Environment: Shallow, episodic freshwater lacustrine conditions with periodic to continuous high alkalinity waters prevailed. The recurring bioturbation and paucity of clastic gypsum laminae indicate periodic lower salinities. Traces of gypsum occur randomly throughout the unit except in NSL 6 to the east. The associated presence of plant material is suggestive of higher rainfall and more vegetation around the complex during this time. Numerous desiccation and small-scale erosional surfaces and features, especially in the dolomites, suggest that the lake was very shallow or that the dolomicrites precipitated during or prior to the drying up of the lake.
Discussion: Thickness variations of this unit suggest that the underlying Parilla dune in NSL8 and 7 still has had some subtle topographic expression and that the western side of Nulla Spring Lake has continued to subside. The upper dolomite of this unit is distinctive in its laminated and erosional character. In NSL10 at this horizon there is a distinct change of dip apparent in the core, steeper below. This suggests that the upper surface is a diastem and possibly marks the end of a phase of differential subsidence.
The proportional increase in dolomite abundance with thinning of the sequence is suggestive that either that allochthonous sediment could only accumulate in areas of subsidence below

deflationary base level while autochthonous carbonate precipitation was relatively uniform, but with erosion of these deposits more apparent to the east. Alternatively, the lake floor may have been still asymmetric, deeper to the west as could be expected also for the underlying units N3 and N2.

Unit N5

Location in lake complex: Unit N5 extends below the entire breadth of Nulla Spring Lake and eastwards.

Geometry and thickness: The unit is stratiform and tabular with variable thickness: slightly thicker to the east (0.99m in NSL10; 0.88m in NSL 1; 1.15m in NSL 4; 1.35 in NSL 8; 1.47m? in NSL 7 (top at 3.53m) and ?1.65m in NSL 6. Picking the top in NSL 7 is equivocal because of the absence of ostracod faunas. The NSL 6 section is not readily correlated but an oxidized and weathered surface at 5.3m, with subvertical fractures and ochreous infill, may be the same surface.

Description: The sequence of Unit 5 shows a gradual thickening eastwards and an associated increased homogenization of sediments. In NSL10, 1 and 4 there is a very distinct lower interval, 23 to 30 cm thick, of silty clays and muds with interlaminated porous thin sands and silts. These sediments are medium bluish grey (5B5/1) to dark greenish grey (5G4/1), comprising quartz silt, traces of fine to medium sand `floating' in kaolinitic and montmorillonitic clays with flecks of black carbonaceous plant matter. The interlaminated silts and fine to very fine sands, sometimes bimodal, form lensoidal laminae resembling flasers. Pyrite framboids are abundant and thin gypsum laminae occur in the basal zone at NSL 8.

Overlying are compact to plastic sandy muds and muddy sands which are darker and more dolomitic to the west in NSL10 and 1, dark bluish grey (5B4/1), greenish black (5GY2/1) and yellowish grey (5Y6/2, 5Y7/1), apparently lightening to yellowish grey and greenish grey (5GY7/1) in NSL 7 and 6.

The sand content is characteristically variable from very fine to very coarse, with bimodal sands in places. In NSL10 this unit has ubiquitous traces of carbonaceous plant flakes, is faintly laminated, occasionally bioturbated with traces of pelleted mud, and is very dolomitic (nodular concretions and thin interbeds). Pelleted textures in the muds are more common in NSL 7 in two horizons, and in NSL 6 where oxidized pyritic framboids delineate this texture. In the eastern part of the section, sandy mud, dolomitic in places, comprises almost the entire unit. In NSL 7 and NSL1 a thin soil zone with mottling, root molds, and a lightly-developed coarsely-crystalline gypsum overprint characterizes the upper part of this unit. NSL 7 also contains a few laminae of clastic gypsum.

Stratigraphic relationships: Unit N5 appears to be disconformable over Unit N4. The unit is overlain with conformity by Unit N6 on the western side.

Depositional Environment: To the west, apparently near continuous lacustrine conditions were predominantly freshwater. Eastwards, conditions were more cyclic towards the top of the unit,

with apparent increases in salinity and repeated brief aeolian events (as indicated by pelleted textures, lighter sediment colour, oxidation of early diagenetic pyrite and preservation of thin laminae of aeolian quartz sands).
Discussion: This unit had significant lateral changes in depositional environment. The poorer definition of sediments to the east is compatible with more aeolian reworking and oxidation of the sediment.

Unit N6

Location in lake complex: Unit N6 extends below Nulla Spring Lake and eastwards.
Geometry and thickness: The unit is tabular, stratiform, thinning to the east from 1.29m in NSL10 to approx. 1.05m, 1.0m, and 0.85m in NSL 4, 8, and 7 respectively, and 0.7m in NSL 6.
Description: The lower boundary is defined by the lowest ostracod horizon, a distinctively white speckled dolomicrite of variable thickness and colour. The upper boundary is not clearly-defined lithologically, being based on the cessation of the combined abundance of clastic gypsum horizons, erosional surfaces and weathering zones, and ostracod abundance.
Lithologically, the unit generally has a lower interval of dolomitic mud and dolomite, a transition zone of mixed dolomitic clay and dolomitic mud, and an upper clay with clastic gypsum.
The lower dolomitic muds are plastic to subindurated locally, especially with dolomite bands. The muds are medium dark to medium light grey (N4-6) and dark bluish grey (5B4/1-5/1). Locally where oxidized, they become dark yellowish-brown (10YR4/2). The dolomites vary from medium olive grey (5Y5/1) to very light grey (N8).
Ostracods are distinctive in dolomite and dolomitic mud bands. Carbonaceous plant debris is ubiquitous. Micro-erosional surfaces over dolomites and dolomite-rich muds are a common association.
The middle transitional zone of mixed dolomitic muds and clays is predominantly semi-indurated and pervasively fractured in NSL10. The muds and clays are medium dark to light grey (N4-N7) to dark bluish grey (5B4/1) with ubiquitous carbonaceous flakes of plant matter and may feature ostracod bands, rootlet traces, lamination and desiccation cracks.
The upper plastic clays, with interlaminated clastic gypsum, have a relatively oxidized appearance with light olive grey (5Y6/1), greyish orange (10YR3/6), and moderate brown (5YR3/6). The preserved abundance of thin clastic gypsum laminae is greatest in NSL 7 with a density of up to 11 discrete laminae in a 7 cm interval. Traces of carbonaceous plant material, rootlet traces and desiccation cracks and features are also recurring.
This sequence is more distinctly laminated in NSL 4, and the intervals are most pronounced in NSL10. Only an erosional remnant of the unit survives in the NSL1 section. In NSL 4, dolomite is present throughout but clay and gypsum horizons predominate in the upper section. In NSL 7, apart from muds in the lower 20 cm, the unit is almost entirely clay with clastic gypsum, and marked by prominent gypsum nodules coated in magnesite at the base of this clay.

Laminae of clastic gypsum, erosional surfaces, and weathering zones are most prolific in this section. Eastwards, the unit is represented by muds which are slightly calcitic.

Stratigraphic relationships: The unit overlies Unit N5 with apparent conformity, and is generally continuous into the overlying Unit N7.

Depositional Environment: This sequence has the most sustained alternations of conditions from `freshwater' (at least below 15‰) to gypsum precipitating conditions (>100‰), desiccation and deflation, sustained exposure and oxidation. During conditions of lower salinity and proliferation of ostracods, the Mg/Ca ratio was in excess of 30 as implied by the absence of *Chara* (Patrick DeDeckker, pers. comm., 1992). The gradual predominance of more saline conditions eastwards is indicated by the absence of ostracods beyond NSL8 and the presence of magnesite and gypsum nodules within the same horizon.

Discussion: Ostracod faunas from within a 0.55m interval in NSL 10/1 are correlated generally with a 10 centimetre interval in both NSL 1 and 4. Lithological correlation suggests that the lower ostracod-rich horizon in NSL 10/1 correlates with the top of the narrow horizon in the other two holes.

Unit N7

Location in lake complex: The unit extends below the complex and beyond and east of NSL 6 and Trench 5.

Geometry and thickness: It is an irregular tabular body due to an erosional upper surface. Thickness varies from 1.16m in NSL10 to 0.8m in NSL8 and 4, to 1.45m in NSL 7 and 1.2m in NSL 6. East of here, only East of here, only the upper surface is intersected and it remains speculative whether the unit thickens to the east. NBR 1 has 0.5m+ on the west side of the lake.

Description: In NSL10 the unit has a basal clay and an upper intermixture of dolomitic sands, clays and muds. A similar pattern is apparent in NSL8 but in NSL 4 and 7 the sequence is variably dolomitic and gypsiferous throughout.

The basal clay is plastic, light olive grey (5Y6/1) and greenish grey (5GY6/1) with some mottled light brown (5YR3/6) horizons. Sandy clay intervals are uncommon.

The upper intermixed zone comprises semi-indurated yellowish grey (5Y7/2), greyish orange (10YR7/4), and very pale orange (10YR8/2) dolomitic sands, dolomitic muds and dolomitic clays. The sands have a packstone texture with fine to medium clear quartz sand. Limestone and dolomitic bands comprise approx. 15% of this interval. Structures include sand-filled rootlets, erosional surfaces and overlying dolomitic flakes. Pedogenic overprints are more common.

In NSL 4, 8, and 7, the unit is entirely overprinted with coarse diagenetic gypsum which masks and even obliterates much of the original sediment and structure.

In NSL 6 this unit comprises subcompact to plastic, yellowish grey (5Y5/2) to light olive grey (5Y7/2) mottled sandy mud locally speckled to moderate yellowish brown; and thin bands of semi-indurated white (N9) calcisiltite. The mud contains coarse to fine and very fine clear quartz sand in a wackestone texture. The sediment has an earthy crumbly fracture suggestive of a pelleted microtexture. Rootlet porosity and an associated clotted appearance occur with pervasive short and blocky fracture with some slickenslides in the upper 0.8m of the unit. Bioturbation? or compacted pellet texture is present in the lowermost 10 cm. The thin calcisiltite bands are indurated to chalky with numerous very fine dark-lined rootlet pores. This porosity appears to be lined with concentrations of microspheroidal purple-black manganese and iron sesquioxides.

Stratigraphic relationships: Unit N7 is apparently conformable over Unit N6 except on the western side of the lake in NBR 1, 2, and 3 where the contact appears unconformable due to tectonic subsidence during/between deposition of the units. The upper surface of unit N7 is erosional to the east and rises from 25m AHD in NSL 6 to almost 27m AHD in Trench 5. The unit is overlain with unconformity by the lunette sequences, Units N8, 10, 12, 15, and 16.

Depositional Environment: Conditions were variable but not to the same degree as in the underlying unit. Freshwater lacustrine sedimentation initially occurred in NSL10 and possibly NSL 4 while elsewhere lacustrine conditions were sufficiently saline to precipitate gypsum. Complete evaporation and sustained emergence are recorded with pedogenic calcrete overprints, especially to the eastern side.

This interval in NSL 6 is interpreted as a weathered lunette deposit that has had calcrete development within a pedogenic overprint.

Discussion: Because of the pervasive and disruptive late diagenetic gypsum overprint it is not possible to be more specific except in NSL 6 where this overprint is absent.

Unit N8

Location in lake complex: This is the highest and easternmost unit of the complex, and is intersected in Trench 6. Unit N8 is interpreted as extending north-south along the entire eastern margin of Nulla discharge complex.

Geometry and thickness: N8 is a lensoidal dune deposit with a minimum thickness of 1.3m in the bottom of Trench 6, but here it may possibly be up to 14m. The probable maximum thickness is in excess of 14m, and may be up to 34m.

Description: The unit is predominantly massive, homogeneous, lightly indurated and porous, and comprises light red brown quartz sand with approximately 15% white millimetre- to centimetre-sized gypsum crystals. Near the top of the dune, the sands grade upwards to light pink orange mottled quartz sands with a calcitic matrix and exhibit faint overprint features such as subvertical mottling. This unit has a calcrete influence from the above unit N11.

Age: Unknown, presumed 600 Ka, equivalent to early Woorinen deflation.

Stratigraphic relationships: Unit N8 is assumed to be erosionally disconformable over Unit N7, and overlain and blanketed disconformably by Units N10 and N11.

Depositional environment: Unit N8 is considered to be the first or at least the major lunette sequence to be formed in the complex, establishing the broadest easterly extent of the complex.

The unit may comprise a mixed source; gypsiferous sediments from the uppermost Blanchetown Clay (Unit N7 and ?) and quartz sands mobilized at the onset of aridity when Woorinen dunes began to accumulate.

Discussion: This unit has only been intersected in Trench 6 and there the original relationships have been overprinted by a subsequent calcrete development in it and the overlying unit N11.

Unit N9

Location in lake complex: Unit 9 is apparently disconformable over the erosional surface on Blanchetown (Unit N7) on the eastern margin of the complex. It is intersected only in Trench 4 (2.8 to 1.0m depth) and NSL 6.

Geometry and thickness: The unit is an apparent erosional wedge with its lower surface rising to the east. An upper near-horizontal weathered and bioturbated surface. The western upper surface appears to be steeper and erosional. The sequence apparently reaches maximum thickness westwards but has 1.8m intersection in Trench 4 and NSL 6.

Description: The unit has a basal 25 cm thick indurated white gypsite with a millimetre-sized sugary texture. This gypsite is transitional upwards into alternating light brown (5YR5/6 to 5YR6/6) quartz sand interlaminated with white semi-massive gypsiferous bands. The upper 70 cm becomes increasingly gypsiferous with root tubule mottling. The tubules and large irregularly ovoid holes (centimetre-sized) are infilled with red sand. A wavy erosional surface 30cm from the top of the unit separates a lower band of smaller bioturbations and an upper band of larger bioturbation. Gypsum is dominant above this erosional surface.

Age: Unknown, but relatively younger than unit N8, therefore ca. 500 Ka.

Stratigraphic relationships: It is apparently unconformable over underlying Unit N7 (Blanchetown Clay) and is overlain disconformably by Unit N10 eastwards. The unit appears to be eroded and overlain by lunette unit N11 to the west of NSL 6.

Depositional environment: There is probably a lake sequence with seasonal alternations of lake gypsum and aeolian-introduced sand. Lacustrine conditions were variably hypersaline, and later emergent when bioturbation and or vegetation root invasion modified the upper part of the unit.

Discussion: This unit is considered to be the first lacustrine deposit of the newly-formed salina and had a significant input of Woorinen aeolian sand. The interpretation is tenuous considering the limited stratigraphic evidence.

Unit N10

Location in lake complex: Unit N10 is present on the eastern margin of the complex, adjacent to and onlapping the western side of Unit N8 and observed only in Trench 5.

Geometry and thickness: This is an apparent wedge with a subhorizontal base and an upward-sloping upper surface, onlapping Unit N8. In Trench 5 the unit is 1.6 metres thick but may thicken to in excess of 2 metres eastwards.

Description: The lower 70 cm is a distinctive wavy alternation of white sugary crystalline (millimetre to centimetre-sized crystals) gypsite and light green compact sandy clay. The clay occurs in thin beds and wavy lenses which attenuate within the gypsite. Some of the upper gypsite surfaces appear to be irregular and erosional.

The upper 90 cm is almost uniformly pinkish-white gypsite with rare thin and irregular laminae of green gypsiferous clay. The uppermost 30 cm is increasingly sandy, with clay clasts and bioturbated, and has an upper hummocky surface with regular cracking that extends 40 to 60 cm down into the unit. The uppermost hummocky surface is indurated by massive gypsum.

Age: Unknown, but relatively younger than unit N9, therefore circa. 400 Ka.

Stratigraphic relationships: Unit N10 probably disconformably overlies Unit N9 and N8, and is unconformably overlain by Unit N11, above the distinctive erosional surface.

Depositional environment: This unit is considered to be transitional from shallow saline lacustrine to lunette deposits of thin alternations of gypsite and sandy clay-pellet aggregates.

Discussion: The geometry of the unit is speculative and there are distinct lithological similarities with the underlying Unit N9 to the west. The distinctive erosional surface with large ovoid borings and ferruginous staining at the Base of Unit N10 and at the top of N9 indicates the chronological relationship between these units even though they have not been observed in the same section.

Unit N11

Location in lake complex:

This unit, comprising at least two cycles, forms the dune complex that rims the outer margin of the B terrace. on the eastern palaeoshoreline of the discharge complex. It is widespread on the eastern side of the discharge complex. In the section line, it extends from between NSL 7 and NSL 6 eastwards to beyond Trench 6.

Geometry and thickness: Unit N11 has a series of steep-sided asymmetric lenses with ribbon-like extent, connected by a thin tabular body. In Trench 3, 1.3m of the unit was intercepted but it may be 4.6m thick at this site. Eastwards it is variable in thickness, 0.2m in Trench 4, 0.3m in Trench 5, and 2.4m in Trench 6.

Description: The unit comprises two or more cycles, each overlying a karstic gypcrete, erosional or palaeosoil surface. Each cycle is about 1.2 metres thick. The base of each cycle has friable and porous light red-brown stratified gypsiferous quartz sand. Gypsum crystal content increases steadily upwards and stratification is caused by fluctuating relative abundance of quartz and gypsum. This friable pale yellowish-brown (10YR6/4) to greyish-orange (10YR7/4) sand is stratified because of fining up laminae with gypsum discoid crystals decreasing upwards and quartz sand apparently increasing upwards. The sequence culminates in a white to light grey orangish-pink (5YR8/2) friable to semiconsolidated floury gypsite which has scattered dense gypcrete nodules.

The upper surface of the gypsite is typically irregular with 0.4-5 m relief. This surface comprises residual indurated planar surfaces with a microkarstic to brecciated form, deeply channelled to a relief of about 0.4 - 5 m, with near vertical and overhung sides. The upper surface is the most indurated and may comprise nodular indurated patches. Induration decreases rapidly downwards, as the gypsite increases in chalky porosity. Below the irregular upper surface, the sediment gradationally increases in red quartz sand content.

The sands are calcareous and frequently mottled from vegetation rootlets where the gypsum is not dominant. This bioturbation forms a prominent fabric in the lower part of the unit and below calcrete profiles where developed.

In Trench 6, this unit includes a well-developed calcrete profile. Here there is an indistinct transition from unit N8 upwards into a pinkish orange calcareous sand with scattered calcrete nodules. This has a distinct upper transition into a 30cm thick band of compact interlocked centimetre to decicentimetre-sized calcrete nodules. Above is a 20 to 30 cm band of smaller pisolitic (40%) sand, over which is a light pink-brown loamy sand with scattered calcrete nodules (<20%).

Age: Unknown, but relatively younger than Unit N10, say circa. 300 Ka.

Stratigraphic relationships: The unit is disconformable over Units N8, N7, N9, and N10. It is overlain disconformably by Unit N12.

Depositional environment: Accumulation was in an arid climate with active deflation of discoid gypsum crystals and minor sediment from salinas in the complex. Quartz sand migrated across the surface by aeolian activity, and gypsum crystals grew from evaporation of groundwater. Gypsum precipitation varied by some mechanism to produce finer floury efflorescence at times when quartz sand supply was relatively reduced.

Discussion: Unit N11 has internal cycles showing shorter-term changes in relative aeolian and lake-derived sediment. These cycles terminate in hiatuses evident as karst on the uppermost gypsite bands.

These lunette cycles are widespread in distribution on the eastern margin of the complex. They indicate a distinctly different set of conditions of sediment supply during deflation, to the clay pellet lunettes. Such conditions are unique to this period of deflation.

Unit N12

Location in lake complex: This unit is present along the eastern side of the complex, extending from NSL 6 eastwards. It is observed within the gypsite lunettes in Trench 4 at 1.60 - 1.85 metres and in Trench 7 at 1.575 - 2.10 metres.

A thin veneer of this unit indicated on the western margin of Nulla Spring Lake.

Geometry and thickness: It is a blanket deposit with localised low hummocky dune accumulations. The unit varies from 70 cm in Trench 4 to 40 cm in Trench 5 and Trench 6.

Description: The deposits comprise light brown (5YR5/6) to reddish quartz sand with white gypsum flecks and red brown sand. Numerous subvertical rootlet traces are infilled by darker sand or gypsum. Darkest colouration is at the surface and is gradationally lighter with depth.

A uniform friable red quartz sand about 25 cm thick overlies and smooths out this irregular gypsite surface of unit N11 to a gently undulating surface with local relief variations of 10 cm. This red sand appears to follow the terrain.

Age: Unknown, but relatively younger than unit N11, say circa. 250 Ka.

Stratigraphic relationships: Unit N12 is disconformable over, and blankets the underlying unit N11. It forms the present terrain surface in this area.

Depositional environment: Depositional conditions appear to have been extremely arid environment in which vegetation could not readily survive and the sands remained mobile.

Discussion: There is difficulty in distinguishing the sediments of this unit from Woorinen Sand as a genetic source from Woorinen mobilization is envisaged.

This surface is recognized mainly within the gypsite lunettes in the B1 sequence, rimming the palaeoshoreline of the B terrace. Extrapolation of this surface has yet to be attempted. Most probably correlates to a Woorinen surface.

The indicated occurrence on the western side of Nulla Spring Lake is questionable because of its elevation and relationship overlying an incised surface on Blanchetown Clay which is probably much younger. Lithologically, the sequence at this site has close similarities with Parilla Sand and it may be a reworked derivative of Parilla Sand upthrown with the conjectured fault on the western margin. The significance of this interpretation is that the Parilla Sand was topographically higher than the present Nulla Spring Lake.

Unit N13

Location in lake complex: This unit is only recognized in the major lunette cluster between NSL 7 and NSL 6.

Geometry and thickness: This forms a steep-sided lens overlying an existing lunette. Unit N13 is 1.6m thick in Trench 3.

Description: The unit has close similarity to Unit N11 and comprises a basal thin, very coarse friable sand which fines upward through cross-stratified pale pinkish orange quartz - gypsum sand to an upper white floury friable gypsite.

The basal sand has laminar stratification defined by alternations of gypsum crystal size and quartz sand content. The overlying low-angle cross-stratification is distinct and delineated by gypsum crystal size and abundance. The upper loose gypsite has an irregular gradational lower contact with the cross-stratified sands.

Age: 110±22 Ka, based on one thermoluminescence date in Trench 3.

Stratigraphic relationships: Unit N13 disconformably overlies unit N11 and a thin cover of N12. Where present, it is exposed at the surface.

Depositional environment: Like unit N11, this cycle accumulated from deflation of salina gypsum deposits as well as trapping Woorinen aeolian quartz sand.

Discussion: This unit has been differentiated on stratigraphic position but it has nearly identical features to Unit N11. However, it lacks the induration and karstic erosion of the upper gypsite, and is not covered by a red quartz sand blanket deposit.

Unit N14

Location in lake complex: This unit extends over the raised " B " terrace to the eastern side of Nulla Spring Lake and presumably further north over this same surface. It is intercepted in drillholes NSL 7, 8, 4 and possibly in Trench 1. On the western side of the lake, NSL 10 is spudded into an erosional remnant of this unit.

Geometry and thickness: Unit N14 is a relatively uniform blanket deposit over the B terrace and ranges in thickness from ?1m in NSL 7 to about 40 cm in NSL 4 and approximately 20 cm in NSL10.

Description: The sediment is yellowish grey (5Y6/2) and semi-indurated, with a dense indurated gypsum hardpan about 5 cm below this change of induration. The hardpan is approximately 15cm thick, with underlying variable semi-indurated to compact gypsite. In this upper indurated band of gypsite, interparticle and intercrystal porosity is still significant, with additional fenestral porosity from decayed rootlets.

In the NSL 7 sequence which is not significantly overprinted by coarse gypsum, the sediment is a gypsiferous sand. It has a pedogenic overprint and sediment colour is mottled and highly variable from yellowish grey (5Y6/2) with white gypsum mottling, to pale yellowish brown (10YR7/2), and greyish orange (10YR7/4), to moderate brown (5YR4/6). The coarse overprint comprises centimetre-sized euhedral pyramidal gypsum with clear overgrowths over a muddier core. Finer sucrosic gypsum infills subvertical root tubule fenestrae, usually 0.5 mm diameter, which comprise about 20% of the sediment. Limonitic traces in clayeyer patches delineate these fine tubules. Rootlet traces are ubiquitous in NSL 7 section, forming bifurcate and diagonal solution-enlarged fenestral porosity. Where secondary coarsely-crystalline gypsum hemispheroids are well developed, clay argillans are present in the interstitial clayey sediment.

Quartz in this gypsarenite is variably coarse sand to silt-sized. Packstone textures suggest original pelletal clay matrix, at least locally, and relict traces of cross-lamination are associated.

Age: Presumed to be between 110±22 and 37±7 Ka on the basis of its onlap with Unit N11, and probably being overlain by Unit $N15_a$.

Stratigraphic relationships: The unit unconformably overlies the Blanchetown Clay (Unit N7) and onlaps Unit N11 to the east. It has a pedogenic overprint and is partly indurated with gypsum infill of porosity. The upper surface is mesoscopically irregular, and eroded with a thin overlying unit (N16) of sandy pelleted soil with dolomite clasts. This unit is also presumed to be overlain to the east by $N15_a$.

Depositional environment: Unit N14 is an accumulation of lacustrine and aeolian sediments. Sediment cover of this deflationary surface is thin, and thinner to nonexistent further north. Conditions were predominantly semiarid and deflation was active from a damp surface which was locally undergoing partial induration as well as pelletization.

Discussion: The sequence, as well as the underlying units, has a significant gypsum overprint, especially across the eastern terrace and consequently the lower contact is difficult to recognize.

The correlated occurrence in NSL 4 is arbitrary and awaits elucidation with thermoluminescence dates from Trench 2.

Unit N15a

Location in lake complex: Unit N15$_a$ is the basal component of the lunette complex that lies to the southeast of Nulla Spring Lake. This lunette is crossed by the access road to the lake, and extends northeastward to near NSL 6.

Geometry and thickness: The unit is probably wedge-shaped to lensoidal, onlapping older lunette deposits, N11, and is probably 3.5 metres in its thickest section, although it forms a western and southern cover to older lunettes.

Description: The unit comprises greyish orange pink (5 YR 7/4) variably gypsiferous rounded quartz sand. The gypsum occurs mainly in the upper coherent part of the unit as coarse millimetre-sized crystals and decreases in content down to a lower friable greyish orange (10 YR 7/4) quartz sand.

The uppermost surface is irregular with 20 to 30 centimetre relief, and comprises a light brown (5 YR 5/6) quartz sand with subvertical rootlet traces filled with gypsum. A white (N9) gypsite underlies this uppermost sand, and has an irregular indurated upper karst-like surface of up to 10 centimetres relief. This gypsite has a rapid gradation down into very fine friable gypsite, and then into the gypsiferous quartz sand. The unit has high intraparticle porosity, especially in the lower friable sands.

Age: 37±7 Ka based on 2 TL dates from Trench 7.

Stratigraphic relationships: Unit N15$_a$ is presumed to overlie units N11 and N14, the earlier deflation/lacustrine deposition cycle.

Depositional Environment: Presumed initially a beach sand dune environment and changing in time to lunette cumulates of evaporitic gypsum and aeolian quartz sand, derived from winnowing of the lacustrine unit N14.

Discussion: The lower stratigraphic relationship of this unit is assumed from morphological associations. The unit is overlain by subsequent lunette deposits, separated by the described palaeosol. The lunette complex of this age has a distinct northeast -southwest orientation, different to the more irregular remnants of the much older lunette of N11 (110±22 Ka) which appears to have undergone structural fracturing and karstic modification. However, the very close levels and general paleoshoreline similarities of these units suggests they are of the same megacycle of deflation. The comparative abundance of quartz sand to pelletal clays is probably more a result of the predominance of Woorinen sand landforms available locally as source material at this time.

Unit N15b

Location in lake complex: This unit is the upper component of the lunette feature to the southeast of Nulla Spring Lake, and is younger than but genetically related to Unit N15$_a$.

Geometry and thickness: Unit N15$_b$ acquires a maximum thickness of about 1.2 metres in the crest of the lunette, forming a westerly wedge-shaped to lensoidal unit, against an older lunette sequence.

Description: The unit is a pale yellowish brown (10 YR 6/4) gypsiferous quartz sand, mottled with larger gypsum crystals, and light to dark grey charcoal stains after rootlets. The rootlet traces have elongate subvertical fabric. Like Unit N15$_a$, the sand grades up to a more gypsiferous sand and then light greyish orange pink (5 YR 8/2) gypsite of increasing coherence. This culminates in an upper karst-like surface of indurated white gypsite with a sharp cuspate upper surface. Small subhorizontal tubular? traces, filled with moderate brown quartz sand are probable infilled root traces.

Age: 23±5 Ka on the basis of one TL date from the middle of the unit in Trench 7.

Stratigraphic relationships: N15$_b$ overlies unit N15$_a$ with disconformity, with an apparent hiatus of 15 Ka

duration. It is overlain by a young surficial sand (1 Ka). Both units 15 lie against the south westerly side of the older lunette unit N11.

Depositional Environment: As with the underlying unit, there was a probable change from high-water stand sand dune accumulation to more evaporitic conditions on a sand-floored salina.

Discussion: Units N15$_a$ and N15$_b$ comprise a deflation cycle of the broader Nulla Salina prior to the development of the lower Nulla Spring Lake. Quartz sand dunes were the predominant land surface and the floor of the broad salina complex was apparently predominantly sand during this phase of deflation.

Unit N16

Location in lake complex: N16 forms the surficial deposit over the "B" lake surface due east of Nulla Spring Lake at 26 metres AHD. It was intersected in drillholes NSL 7 and 8. On the basis of terrace level, this unit in all probability extends across the entire "B" terrace surface in the complex.

Geometry and thickness: The unit is a very thin tabular body of some 30 centimetre thickness.

Description: Unit N16 comprises loose sandy pelleted gypsiferous and clayey soil with scattered small dolomitic flakes.

Age: Presumed between 6±1 Ka (the age of the most recent lunette deposits) and 23±5 Ka (the former deflation deposits of Unit N15$_b$. Within this age window, the older end of the range is more probable.

Stratigraphic relationships: N16 overlies N14 with disconformity (age difference of about 87 Ka). It is overlain on its Nulla Spring Lake margin by the younger lunette unit N17.

Depositional Environment: Sandy lake floor of a salina with only moderate clay sediment available. This surface is comparable to that existing on Scotia Scott Lake today.

Discussion: This unit is exposed at the surface of the "B" terrace or "B" deflation level and is presently stabilized by low halophytic samphire vegetation. Most probably it has suffered continued but fluctuating winnowing of lighter gypsum and other evaporitic efflorescences which have accumulated as cappings on the downwind lunettes.

Unit N17 Modern Lunettes, lunette deposits

Location in lake complex: This unit extends eastward from the shoreline of Nulla Spring Lake, over the upper terrace to the base of the lunette cluster (Units N11 and N13).

Geometry and thickness: N17 is a lens with a thinning wedged eastern margin. In NSL 4 and 5 the unit has a maximum thickness of 2.1m. It thins gradually to 40 cm at NSL8 and 30cm at NSL 7

Description: This unit has an active soil profile overprint characterized by gypsiferous reddish quartz sands. The upper 0.4m is light brown (5YR4/6) to very pale orange (10YR8/2) unconsolidated gypsiferous clayey sand with a sucrosic loose clotted texture. The coarse to medium quartz sand has reddish clay cutans, and is scattered with small dolomitic fragments and small friable lumps of white very finely sucrosic gypsum.

In NSL10, the semi-indurated to friable dark greyish orange sand is dolomitic, calcareous and gypseous, with apparent pelleted texture. Generally, pelleted textures are only readily apparent in the surface unconsolidated sediment. Interparticle porosity is high and accentuated by rootlet-derived fenestral porosity, especially where some induration bonds the particles.

The secondary millimetre- and centimetre-sized hemispheroidal gypsum coincides with the horizon of partial induration and has variable but generally increasing abundance down section.

At least three deflation cycles are recognized within this unit, with quartz-dominant sands at their base and grading up to gypsiferous pelletal clayey sand.

Age: The base of the oldest of these cycles is 6±1 Ka (one TL date in Trench 1). The base of the middle cycle is dated at 2 Ka (one TL date in Trench 1).

Stratigraphic relationships: Disconformable over Units N16, N14, N7, and $N15_b$. At least three generations of lunette development are indicated in NSL 4.

Depositional Environment: There has been aeolian transport of quartz sand and pelleted lacustrine sandy clay. Quartz sand was most probably derived from a Woorinen source on the western side of the lake. The sand has probably been continually migrating into the lake, and during higher lake stands, has been transported across the lake by wave action to form a leeward beach from where it has been dispersed onto the eroded margin and has blanketed pre-existing lunettes. As evaporative conditions became dominant and the lake dried, pelletization of the marginal surfaces provided clayey material for aeolian transport and different lunette deposits accreted. The sequence indicates at least three lake cycles of high water level to evaporative conditions.

Discussion: Cross-stratification with foreslope angles of approx. 10^o are seen in two horizons in NSL4 and appear to be in the basal zone of a new lunette phase. Pedogenic features overprint these primary aeolian features higher in the profile.

Unit N18 Present lake floor

Location in lake complex: Unit N18 occurs within the active Nulla Spring Lake and probably in active lakes at the northern extent of the complex.

Geometry and thickness: The sediment body is tabular and approximately 0.57m thick.

Description: This unit comprises a lower plastic gypsiferous mud (78%) and an upper friable sandy gypsiferous mud (20%), with two thin dolomicrite bands at the base and between the different muds (2%).

A thin basal lamina of medium greenish grey (5G6/1) plastic clay contains fine lenticular fenestrae filled by very fine gypsum. This is overlain by a very pale orange (10YR8/2) silty dolomicrite with blocky fracture.

The lower gypsiferous muds are greenish grey (5G6/1), with mottling in moderate yellowish orange (10YR5/4) grading up to yellowish grey (5Y8/1) mottled with dark yellowish orange (10YR6/6). Most lamination is disrupted to a chaotic fabric by the displacive large discoidal gypsum crystals scattered subhorizontally in the sediment. Clay argillans are developed in the chaotic intervals. Some clay lamination, discrete thin and wavy, and with fine fenestrae filled by soluble salts, alternates with or is random within the displacive gypsum areas.

The upper dolomicrite is 2 cm thick, dark yellowish orange (10YR6/6), and friable to compact with an blocky earthy texture.

This is overlain by 2 cm of coarse and finely crystalline gypsum, with large discoidal crystals and argillans in a pale yellow grey (5Y8/1) mud.

The uppermost 10 cm interval is yellowish grey to medium olive grey (5Y8/1-5/1), and medium light grey (N6) sandy gypsiferous mud with a chaotic fabric containing argillans, large discoidal gypsum crystals (40%) in a matrix of bimodal medium to fine quartz sand (50%) and halite.

Age: Being relatively younger than Unit 17, this unit is considered to range from the present back to 6±1 Ka.

Stratigraphic relationships: N18 unconformably overlies and is contained within Unit N6 (Blanchetown Clay).

Depositional Environment: Semiarid hypersaline to evaporitic lacustrine conditions are continuing at present.

Discussion: There appears to be active but very slow accretion of this unit at present. The lunette derived from this present deflation surface indicates several deflation episodes so the lacustrine accumulation is a nett accumulation between these aeolian erosional episodes.

Unit N19

Location in lake complex: On the western dune slope down to the lake, Unit N19 forms a superficial blanketing deposit.

Geometry and thickness: The unit forms the uppermost part of the section in NBR 3 (1.2m) and NBR 4 (1.4m).

Description: A light reddish brown sand to sandy loam is friable to compact and has a bioturbation-mottled basal 30 to 40 cm. Where the unit is thicker, a lower, compact 80 cm of bioturbated sand has a more distinct transition into an upper homogeneous light brown sandy loam.

Age: Undated, but postdates Unit N12, and could therefore range from 250 Ka to the present.

Stratigraphic relationships: Unit N19 is a surface deposit on the western side of the complex, and overlies the light-coloured sands of Unit N12 disconformably.

Depositional environment: Aeolian reworking of existing Woorinen dunes and transportation of sand down the lee slope has occurred in subarid conditions when the Woorinen dunes and depositional area remained partly vegetated. Colluvial processes were and are also contributing to transport of these sediments.

Discussion: This unit is difficult to differentiate from Woorinen sands except by its stratigraphic and morphological position.

Morphostratigraphic Synthesis

Subsequent trenching and thermoluminescence sampling (Figure **8**) and a comparison of Nulla with the Mourquong Discharge Complex (Figure **1**) confirms that the clay sequence below Nulla Spring Lake is Blanchetown Clay except for the uppermost N18.

Regional interpretation of the discharge complex (based on interpretation of AUSLIG 1:27,200 Black and white photography (flown 29/9/89)) identifies three morphostratigraphic assemblages. These are interpreted to be 3 major phases of nett deflation and subsequent lacustrine deposition, and annotated as A - oldest, B - middle, and C - youngest, with deflation episodes (subscripts 1 and 2) and lacustrine. The extent and distribution of these events is presented in Figure **6**, and the interrelationship of lithofacies units with these events is apparent in Figure **9**.

Sequence A

Geomorphological evidence for the first phase of playa development, denudation and lunette accretion is based on air photo interpretation (Radke, 1992) and regional mapping (Ray, in prep.). The elevation of the A features suggests that the Blanchetown Clay was not completely stripped by deflation in this phase. In the northern area, where the Parilla dune complex - strandline/interdune, deflation of this contributed to a large dune complex east of Nulla with a distinctive dune morphology recognized by Ray as a Parilla derivative. One small area in the eastern high dunes has a surface expression of a jointed partially-indurated sand (Woorinen calcrete in Parilla jointing?).

The remnant A_2 lacustrine sequence is thin and is known to be present east of Nulla Spring Lake (Unit N9) where it has significant gypcrete cementation. The sequence probably extends the entire eastern side of the complex. On this highest sand-covered surface of

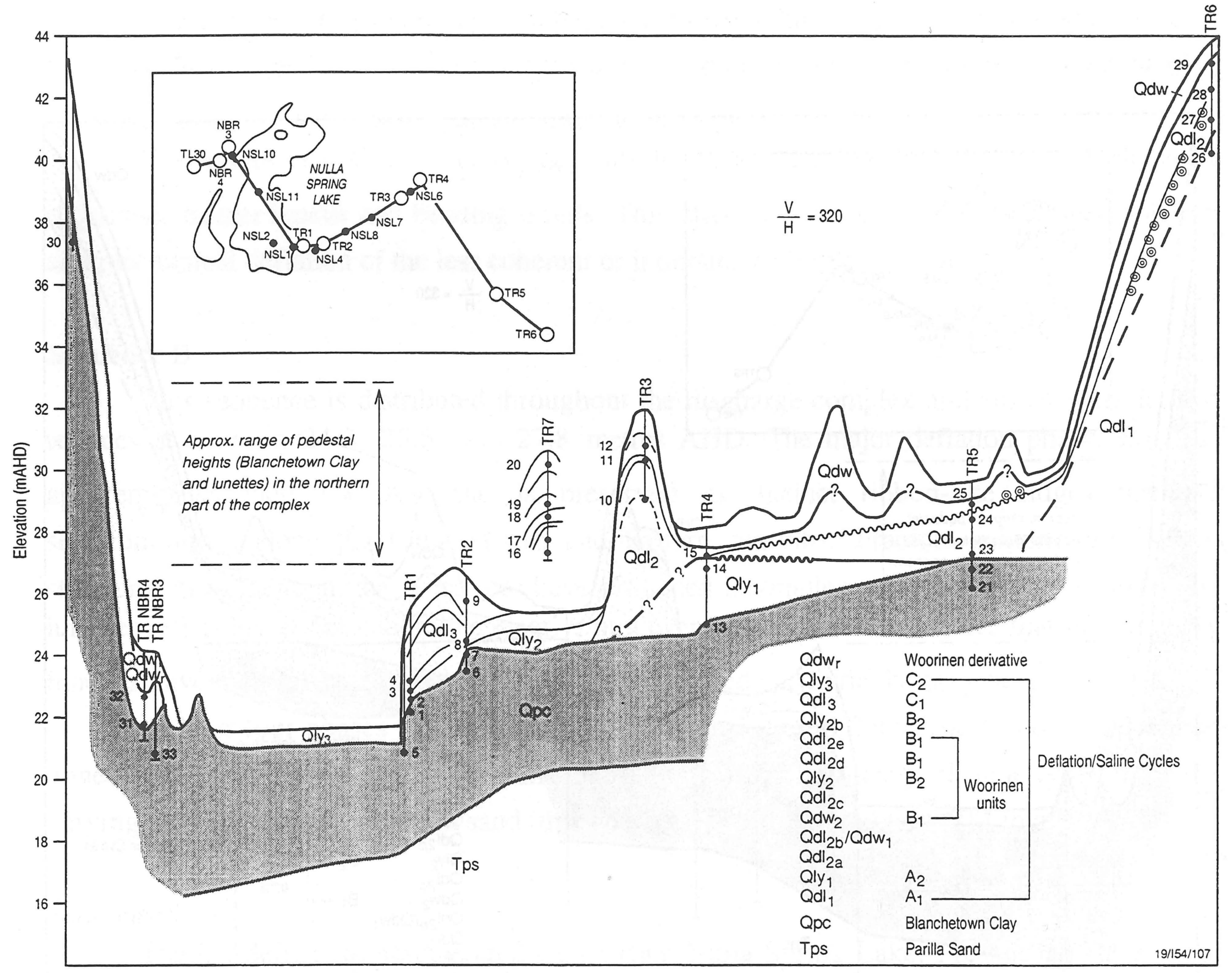


Figure 8. Stratigraphic interpretation of Nulla Discharge Complex and location of thermoluminescence sampling.

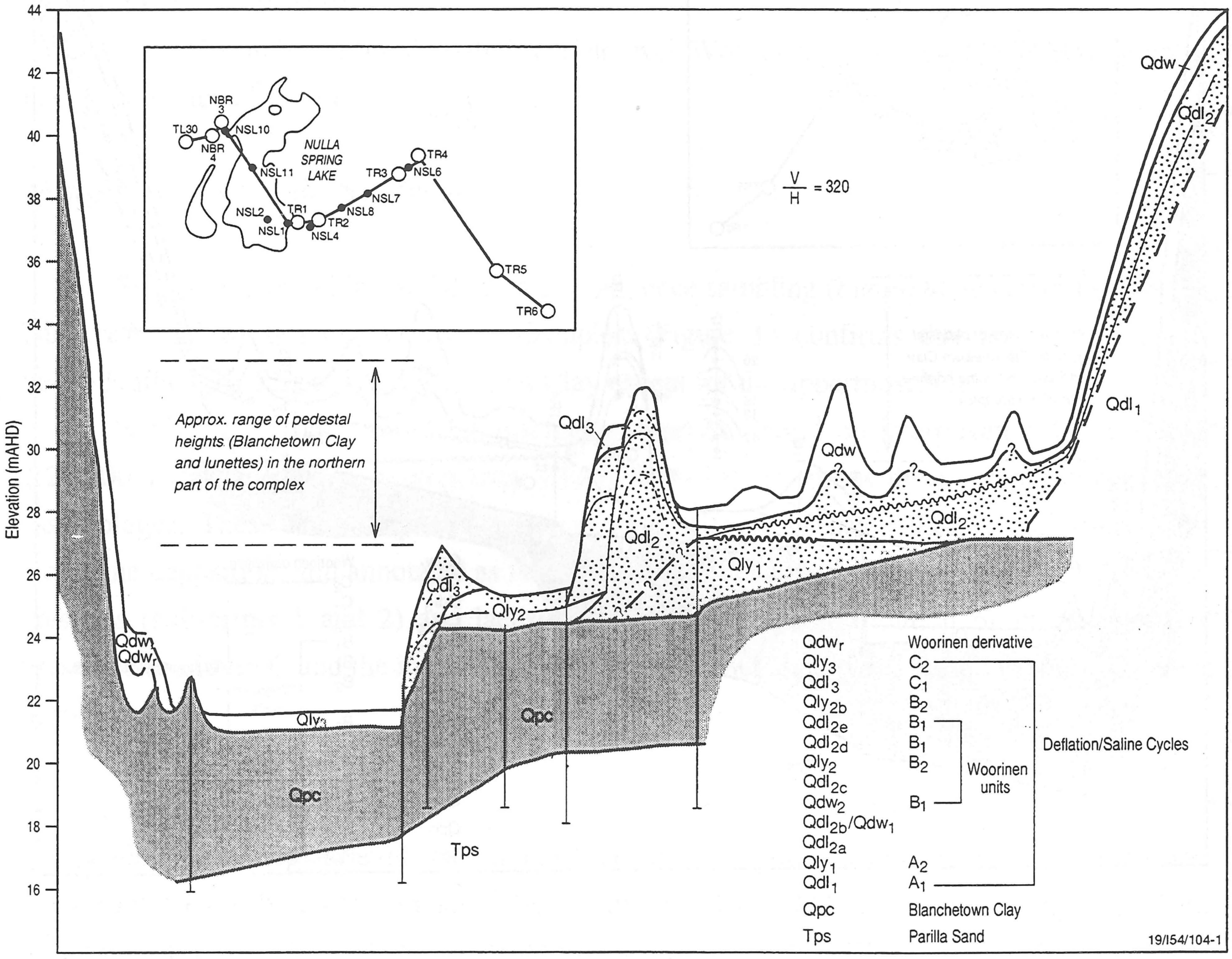


Figure 9. Interpreted stratigraphy of the Nulla Discharge Complex.

approximately 27 to 33 metres elevation AHD, linear and parallel vegetation patterns are spaced identically to those of existing Woorinen dunes further to the east beyond the A_1 lunette zone. These linear features are interpreted as the basal remnants of Woorinen dunes which now have surface expression either as the original quartz sand-rich gypsiferous sediments, or as subtle vegetation differences influenced by substrate variations. That these lineaments are recognized only over A_2 surfaces, indicates the extent of deflation that occurred before Woorinen dune development. The subsequent B1 phase of deflation is more intrinsically related with Woorinen dune development.

The lunette component, A_1, is interpreted as extending along the entire eastern side of the Nulla Discharge Complex. Topographically, A_1 comprises a semi-continuous arc of high dunes blanketed by Woorinen sand and longitudinal dunes.

The terrain of both A_1 and A_2 deposits has a low hummocky character which partly obliterates former lunette and bedding trends. This effect is probably due to combined solution and mechanical deflation of the less coherent or indurated sediments.

Sequence B

This sequence is distributed throughout the discharge complex and forms well-defined terraces at between 24.3, 25.5, and 27.8 metres AHD. The major deflation phase, B_1, has apparently spanned 100 Ka, and is preserved as distinct ribbon-like ridges that are semicontinuous along the south-eastern and eastern margins. Fracture jointing and subtle structural movements in the A terraces have produced a complex shoreline to the B lake. The lunettes reflect the eastern shoreline clearly, however, there is some evidence that the older B_1 lunettes have themselves also been subsequently fractured and variably karstified.

At least four phases of lunette accretion are apparent in Trenches 3 and 7. Woorinen dune development was active at this time and there is a greater variety of dune types from the varying intermixture of Woorinen sand (this character is pronounced with TM imagery).

Sequence C

The C_1 deflation phase created the existing Nulla Spring Lake. Present lake level is at about 21.3m AHD, about 3m lower than the B terrace. Lunettes of this event rim the eastern margin of Nulla Spring Lake and also form a thin veneer on the southeastern B_1 lunettes. C_1 lunettes are dated at mid-Holocene to present (6 to 1 Ka).

Lunette C_1 clearly marks the edge of the steep eastern lake margin with a rise of about 2 metres above the B terrace. Locally the relief of this lunette unit is variable, and greater in the southeastern quadrant, presumably a result of a longer fetch for the prevailing wind across the lake in a northwest - southeast direction.

The C_1 sequence comprises loose to compact calcareous pelletal sediment of bound quartz sand, gypsum and clay. A pedogenic overprint below the lunette, at the top of B sequence, indicates a long transition from B accumulation to C_1 deflation.

This C_2 sequence forms the floor of the existing Nulla Spring Lake. Stratigraphic interpretation of the cored sequence in NSL 1 suggests that the accumulated sediments following the acme of this deflational phase is only about 0.57 metre thick.

Diagenetic Characteristics

Carbonates

The distribution of carbonate within the sequence is summarized in Figure **10.**

Dolomite

Dolomite is the most abundant carbonate in the complex, present as indurated bands, concretions, and varying component in the lacustrine muds and clays.

<u>Dolomite beds</u>

Prominent exposed flaggy beds of white to orange indurated dolostone rim the western margins of northern active salinas and Nulla Spring Lake. Stratigraphically these are correlated, lying on the contact of Units N6 and N7 and higher in N7.

At Nulla Spring Lake, these horizons comprise thin flags, 0.5 - 3 cm thick, of dolomicrite with well preserved bottom structures, predominantly burrow tubules 3 to 5 mm thick filled with dolomicrite, subhorizontal to vertical, bifurcate, and random to closely intermeshed, especially where subhorizontal.

In the northern lake occurrence, beds are medium to very thick (30 to 90 cm), and show distinct facies variation over only tens of metres from dolomitic bioturbated sandstones to massive dolostone low mounds with palimpsest gypsum hardpan crystal meshwork textures, to nodular and lenticular bedded dolomite concretions.

The dolomitic sandstone has laminar stratification, differentially weathered by dolomite induration, with vertical burrows, 2 to 5 mm diameter, and slightly thinner subvertical burrows. These are interpreted as escape and feeder structures. The upper surface of this lithofacies has distinctive polygons 30 to 90 cm diameter. These polygons have central and randomly interconnected solution basins (decicentimetre-sized).

However in the subsurface, there are numerous dolomite beds from Unit N3 up to N7. In addition to discrete bands, dolomite has diminishing abundance as concretions and as a component of clastic sediments. It is almost ubiquitously micritic and in sufficient concentration, imparts a lighter tone to the sediment and a chalky to clotted texture with micro intercrystalline porosity, and small fracture porosity.

Dolomites in the subsurface are consistently non-stoichiometric with a compositional range of 43 to 48 Mole% $MgCO_3$ (XRD analyses from NSL1 2.275m to 2.765m and NSL10 0.22m to 6.67m). Variations in the $MgCO_3$ content correlate with isotopic trends.

Three genetic categories of this dolomicrite are LP (Lake precipitates), NSP (near

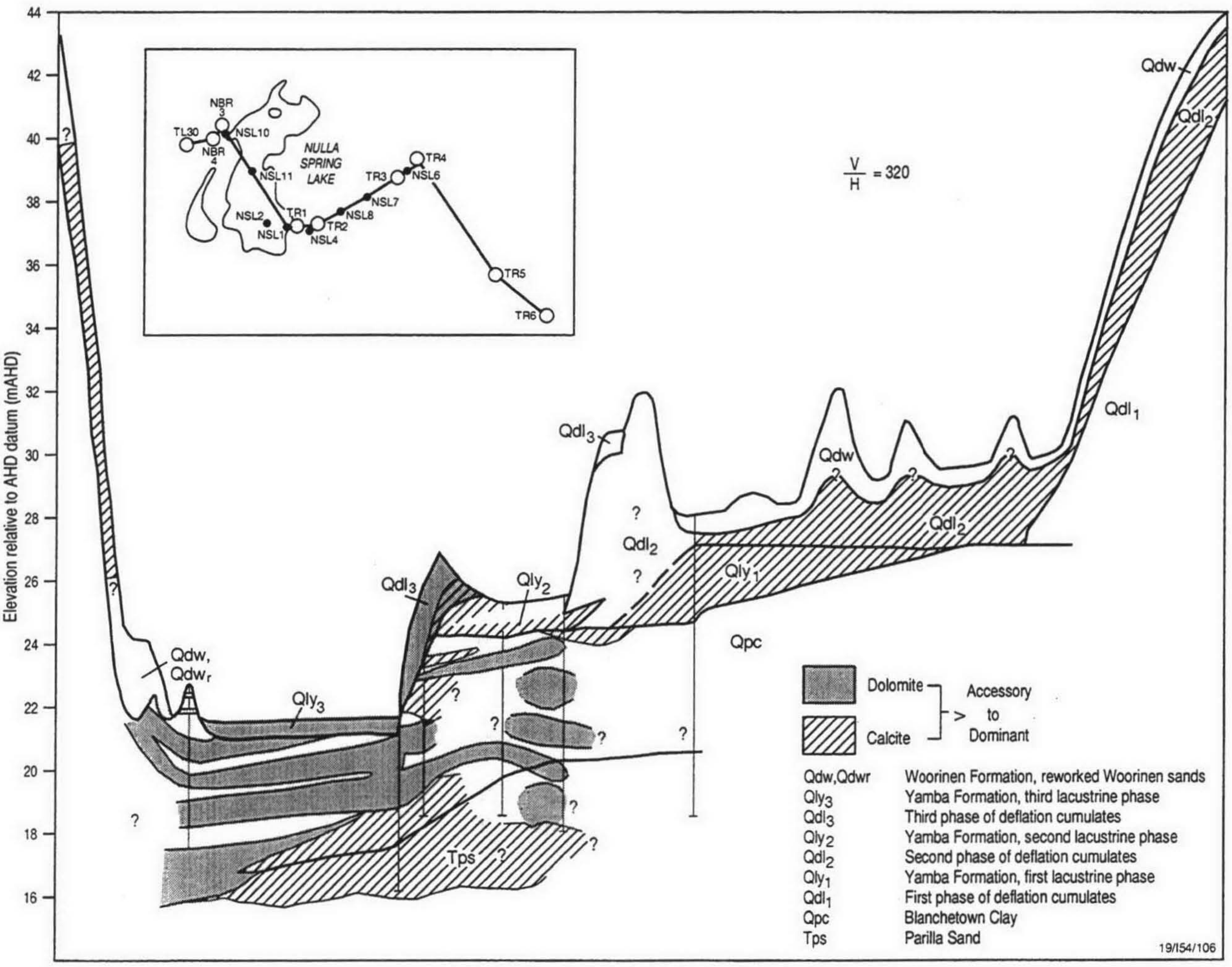


Figure 10. Distribution of carbonates in the Nulla Discharge Complex.

surface precipitates) and NSC(near surface concretions). Intermediate forms are to be expected.
LP lake precipitates are regular to irregular crusts and varves with erosional or depositional features bounding the dolomitic laminae, eroded and reworked clasts, and spherules of the dolomite into the overlying sediment.

The process of precipitation of irregular crusts is active today around the groundwater springs on the eastern side of Nulla Spring Lake, forming a nodular tufa crust over gypseous muds. This dolomicrite precipitate forms thin but densely-interconnected crusts around the spring perimeter, which thin and sparser concentrically away from the localized discharge, forming metre-sized discs with gradational perimeters on the host gypseous mud.

NSP near-surface precipitates have gradational margins to variable concentrations of dolomitic mud within a mud or clay matrix. These indistinct patches are randomly present within their host and appear to transgress sediment laminae and other depositional features within the fine-grained host.

NSC near-surface concretions are gradational with the NSP and are distinguished by sharper boundaries. Within these concretions, the microcrystalline texture is noticeably chalky and porous with intercrystalline porosity. Commonly, areas of highest dolomite concentration may be variably indurated. Microfracture and microbrecciation is characteristic of this texture where fracture porosity becomes as significant as the chalky (intergranular) porosity.

Dolomite abundance is greatest within the lacustrine sequence and within that, abundance varies between stratigraphic units as well as laterally. On the western side of the complex, the dolomite is more abundant in both thickness and frequency of intervals. A noticeable and gradational reduction occurs from NSL 10 to NSL 6. Nodular concretions are most abundant in NSL10.

Discussion: The varves and intricate association of alternating laminae with sands, erosional surfaces with overlying dolomite flakes and clasts demonstrate dolomite precipitation to be a surface or very near-surface phenomenon. Additionally in horizons with preserved ostracod fauna, the sediment is usually dolomitic but no *Chara* is present as would normally be expected. This indicates surface waters with Mg/Ca in excess of 30. Salinity estimates based on the character of the fauna suggest a range from <15‰ to 50‰. (P. DeDeckker, pers.comm., 1992).

Calcite

Calcite has only a minor presence in the complex; as a fine component of unconsolidated lunette sands, as calcretes in lunette deposits (NSL 6), as calcite cements in Parilla Sand; and scattered distribution throughout the lacustrine sequence in trace amounts.

Thin centimetre-thick bands of semi-indurated to chalky calcisiltite alternate with muds and sandy muds in unit N7, an older lunette deposit in NSL 6. The bands are very light grey (N9) and preserve fine fenestral porosity after rootlets. In the other occurrences it is almost exclusively a fine or micritic component of the sediment matrix in porous Parilla quartz sands where it is admixed with kaolinite-montmorillonite matrix. In the lacustrine sequence, calcite has only scattered occurrence, presumably as fine micrite.

Loose and friable lunette soils have a high calcite component in the finer fraction, closely associated with gypsum and quartz sands. This recent occurrence seems anomalous to the apparent paucity elsewhere in the sequence.

Magnesite

Magnesite is present in a thin interval within Unit N6, at the eastern extent of the main ostracod horizon. Here it occurs as millimetre-thick white chalky bands around gypsum nodules and as small millimetre-sized irregular pellets. These pellets may be partially compacted, indicating their accumulation as softer muds. In bands of abundant pellets, the sediment superficially appears identical with the ostracod-rich sediments.

Discussion: The eastward diminution of dolomite, the transition from a lower salinity ostracod interval laterally into an evaporitic playa suggests a unique situation of possibly gentle dip and therefore more exposure eastwards. This is consistent with the overall lithostratigraphy and geometry of units, indicating continued subsidence to the western side of the complex and uniform tilting. Subsurface dips (Figure 7) and surfaces of the exposed raised terrace adjoining Nulla Spring Lake collectively support this model.

Sulphates

Gypsum is ubiquitous in the sequence and the most abundant sulphate species. Mirabilite, fibrous gypsum, is observed as an ephemeral efflorescence in core sections with sulphate-saturated porefluids. Powdery yellow efflorescence of jarosite is limited to the underlying deeper sections of Parilla Sand rich in probable unstable very fine monosulphides. Possible traces of celestite are rare, and anhydrite is absent.

Gypsum has distinctly variable volumetric abundance, diagenetic type and emplacement time throughout the complex. As a generalisation, primary and early forms are low volumetrically. A distinct and late diagenetic overprint of the upper lacustrine sequence has mixed types but late centimetre-sized hemispheroidal crystals range upwards from 10% to commonly 80%. Where exhumed, this overprint forms a distinctive hardpan surface. In the lunette deposits, gypsum may be abundant, 30-70%, but in finer form.

The distribution and characteristics of gypsum are discussed under the sequence categories and are summarized in Figure **11**. Classifications of characteristics documented by Bowler and Teller (1986) and gypsum petrofacies of Magee (1991) have been applied in the distinction of lacustrine and diagenetic overprints in this study.

Parilla Sand

Gypsum is rare in the lower Parilla, only observed at 51m in NSL 6 as traces of discrete crystals (<<1%) from large (millimetre-sized) corroded translucent yellow to clear colourless discoidal forms.

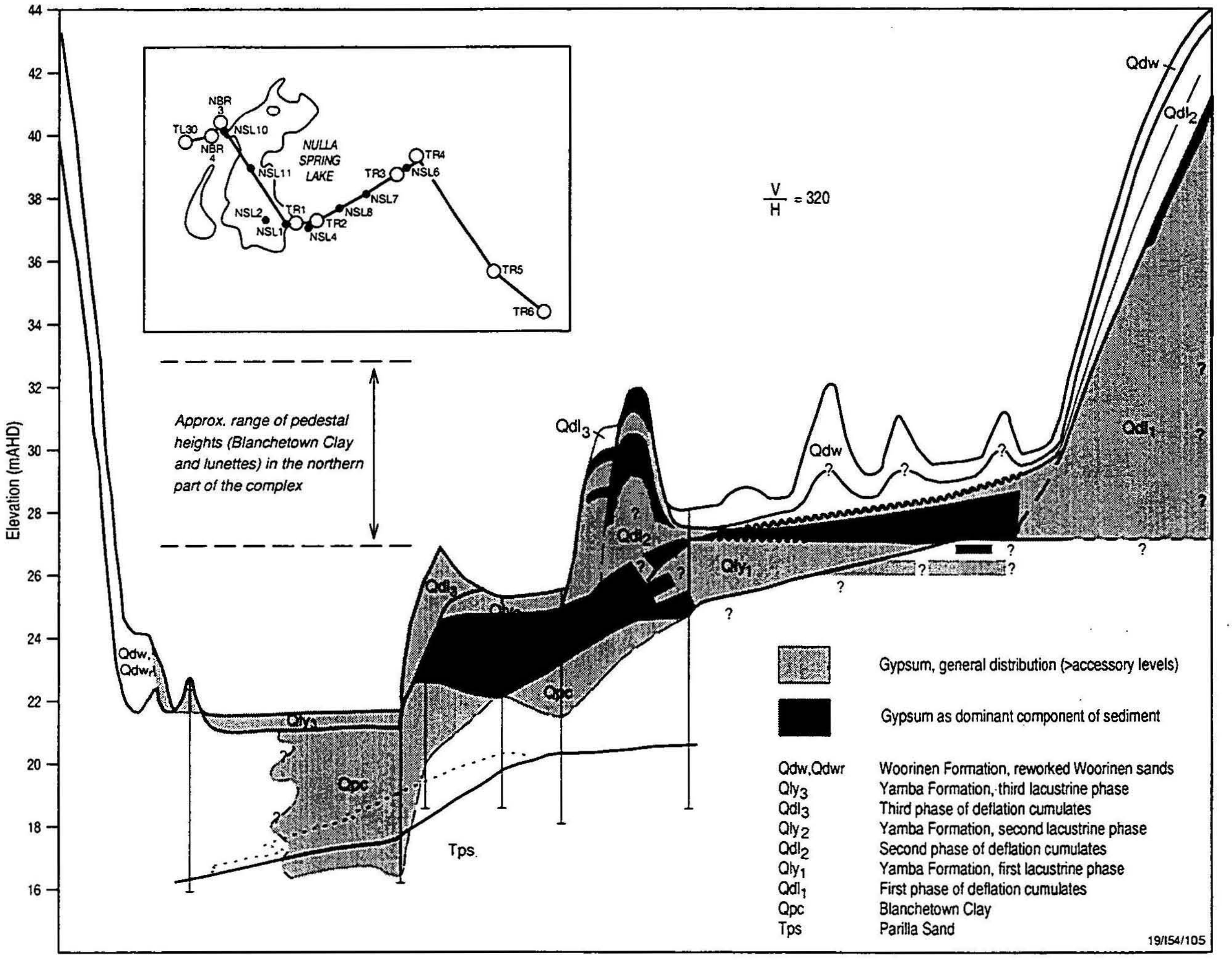


Figure 11. Distribution of gypsum in the Nulla Discharge Complex.

Jarosite is present in trace amounts in the lower unit of the Parilla in the intervals NSL 6 50-60m depth, and NSL 9 47-56m. Here it occurs as bright yellow plastic clots and sugary cements and efflorescence in association with sulphurous odour attributed to unstable sulphides. It is uncertain if the jarosite has developed only since drilling.

The upper porous sands of the Parilla, just below the muddier infiltered zone, contain traces (<5%) of early? diagenetic vertical to subvertical millimetre-sized hemispheroidal crystals with a displacive habit. Smaller hemispheroidal crystals, <1mm, constitute late? diagenetic porefill cements in some interparticle porosity.

Blanchetown Clay "lunette" units

Lunettes comprise between 30 and 70% gypsum and have variable late diagenetic overprint. Pellet textures are not recognized. Gypsum crystals are very small early diagenetic displacive hemispheroids and later diagenetic replacive forms.

Blanchetown Clay (Units N3 to N7)

Lateral and vertical changes in gypsum type, frequency of occurrence, and abundance is significant in the sequence. As a generalisation, the frequency of primary and early diagenetic gypsum horizons increases up sequence, and increases in abundance as well as frequency from west (NSL10) to east (NSL7). Late diagenetic overprints are prolific in the upper sequence. Largely because of subsequent deflation/erosion pattern, this overprint is thickest and most pervasive to the east.

In the lower sequence (NSL10), thin and infrequent fine laminae comprise fine(<1mm) hemispheroidal and prismatic clastic particles and crystals, ranging from primary to early diagenetic modification and enhancement. Early diagenetic timing is more apparent where this hemispheroidal habit is displacive in the sediment, especially within desiccation fractures and cracks. Upwards in the sequence, the crystal habit becomes predominantly hemispheroidal in either primary clastic or early diagenetic displacive occurrences. In NSL1, displacive early diagenetic hemispheroidal habit predominates. East of NSL1, it is a variety of occurrences from primary prismatic/hemispheroidal habit and early millimetre-sized displacive hemispheroids to early diagenetic centimetre-sized vertical displacive hemispheroids in another host sediment.

In the eastern end of the sequence, gypsum occurrences up section become overprinted with 10 to 80% overprint (or recrystallization) to late diagenetic vertical and subvertical centimetre-sized clear displacive and sandy replacive hemispheroidal crystals. In higher abundance the crystals become subhedral through growth interference and host sediment becomes a mere outline between crystals. The relative significance of volumetric displacement versus recrystallisation of host primary/early diagenetic gypsum is equivocal without petrographic information.

C Sequence lunette

In these younger lunettes which rim the eastern margin of the present Nulla Spring Lake, the gypsum is also very finely crystalline. Volumetric proportion of the sediment is undetermined but probably comparable to the B lunettes. Fabrics are predominantly small (<1mm sized) primary fragments and abraded/corroded clastic hemispheroids, and small late-diagenetic replacive hemispheroids. Haloturbation most prevalent in the recent developing soils, homogenizing and disaggregating surface soil profiles.

Lacustrine C Sequence - Unit N16

Gypsum in this unit, the present lake floor, is predominantly primary small clastic hemispheroidal, with an overprint of early diagenetic large (millimetre-sized) vertical displacive crystals. The latter have created argillans within the host and contorted but not generally penetrated interlaminated clay laminae.

Active springs are associated with low gypseous mounds near the eastern margin of Nulla Spring Lake. Within the surface muds surrounding spring outlets, a zone of centimetre-sized gypsum hemispheroidal mush has and is developing by displacement in the near-surface muds.

Sulphides

Pyrite has wide distribution but low abundance (generally <<1%) in the lacustrine sequences as disseminated framboidal clumps and microspheroids.

The stratigraphic distribution indicates pyrite to be most abundant in the lower part of the western section (Units N4, and to a lesser extent N3 and N5, in NSL10) and to a lesser extent in these units eastwards. Unit N7 has only traces in the western section. The lunette deposits are devoid of sulphides. Mesoscopically, pyrite distribution in the sediment is influenced by porosity variations in laminated sediment, bioturbation, and interparticle porosity of clean silts. Porous coarse sands are rarely pyritic.

The local control of pyrite accumulation appears to be porosity or a porosity differential and the proximity of organic carbon. Both reducing environments and a source of sulphates for sulphate reduction are common so it appears to be the limitation of either iron or organic carbon that controls emplacement.

HYDROGEOLOGY AND HYDRODYNAMICS

Hydraulic Conductivity

The hydraulic conductivities of the lacustrine sediments surrounding Nulla Spring Lake and the underlying Parilla Sand have not been measured, but some inferences can be drawn from a combination of indirect indicators and literature values.

(1) Nulla Spring Lake is enclosed by the Blanchetown Clay, some units of which are dominated by dense, plastic clays. These clays are likely to be at the lower end of the permeability range for this sequence.

(2) Further evidence of a very low permeability for the Blanchetown Clay comes from the observation that some piezometers set in the Blanchetown Clay or near the Blanchetown Clay - Parilla Sand interface had very slow response times compared with other piezometers in similar hydrodynamic situations. These slow piezometers had not reached equilibrium after several months.

(3) For very low permeability clay-dominated sediments the lateral and vertical conductivities are probably about equal (J. Kellett pers. comm.). Based on laboratory measurements of clay components of the Blanchetown Clay by Thorne et al. (1990), this suggests that Nulla Spring Lake is enclosed by an aquitard whose hydraulic conductivity is probably $\leq 1 \times 10^{-4}$ m/day.

Despite the very low hydraulic conductivity of the enclosing sediments, groundwater reaches the lake in the form of numerous small springs. These springs are not concentrated at the periphery of the lake but, when a salt crust has formed on the lake surface, are visible over most of the southern area. It therefore seems likely that the groundwater springs reach the lake by making use of higher permeability carbonate-rich horizons in the Blanchetown Clay as part of a fracture-based flow path from the underlying and adjacent Parilla Sand. This hypothesis is supported by salinity data from the Mourquong Discharge Complex (Ferguson et al., 1997), which show the presence of anomalously high areas associated with carbonate horizons within the clays and sandy clays of the Blanchetown Clay.

The Parilla Sand aquifer is divided lithostratigraphically into an upper unit and a lower muddier unit. The porosity below the discharge complex (NSL 6; Figure **4**) is consistent with higher permeability in the upper unit but beneath the Woorinen Dunes at Coolamon (NSL 9; Figure **4**), the porosity distribution is more complex.

Literature hydraulic conductivity data for the Parilla Sand indicate values in the range 1 to 5 m/day, with the lower values being associated with the lower Parilla and the higher values with the upper Parilla. J. Kellett (pers. comm.) has estimated that the ratio of the horizontal to the vertical conductivity in the Parilla Sand is 100 to 1000 with the higher values being associated with the lower Parilla, which is more laminated. Accordingly, an average lateral hydraulic conductivity for the Parilla Sand in the Nulla area is estimated to be 2m/day and an average vertical hydraulic conductivity is estimated to be 0.004 m/day.

The Woorinen Formation sediments at Coolamon (NSL 9; Figure **4**) have a high porosity, which is consistent with the generally high permeability of this unit known from other areas.

Physiography and Surface Water Hydrology

Nulla Spring Lake has a morphology which is irregular to the north and slightly more rounded to the south. This shape is indicative of a greater surface water influence in the southern part of the lake. Field observations that winter rainfall/runoff accumulates in the topographically lower southern area as a broad shallow pond are consistent with this view. Runoff enters the lake mainly through erosion gullies cut into the lunettes and lacustrine sediments which form the

Table 1. Lateral (Freshwater) Heads in the Southern Nulla Groundwater Discharge Complex

The groundwater pressures at other than the measured depths were obtained by interpolation between piezometer data.

Piezometer Location	Date	Estimation Method	Hif at 21mAHD mAHD Lacustrine Clays	Hif at AHD 17m mAHD Upper Parilla	Hif at AHD 8m mAHD Intermediate Parilla	Hif at AHD -12m mAHD Intermediate Parilla	Hif at AHD -32m mAHD Lower Parilla
Coolamon	Mar-92	Interpolation		24.55	24.75	25.21	25.67
NSL 6	March/April 92	Interpolation	23.42	23.70	24.04	25.01	25.76
NSL 7	Feb/Mar/April 92	Interpolation	22.95	23.62			
NSL 8	Mar 92/Jul 91	Assume NSL 4/5 slope for 17m	23.22	23.42			
		Assume NSL 4/5 slope for 17m & use max. Pact		23.74			
NSL 4 and 5	March/April 92	Interpolation	22.39	23.58	24.08	24.97	26.05
NSL 1	Aug-92	Assume NSL 4/5 slope for 17m	21.42	23.58			
NSL 2	Aug-92	Assume NSL 4/5 slope for 17m	21.47	22.79			
NSL 11	Aug-92	Assume NSL 4/5 slope for 17m		23.66			
NSL 10	Mar 92/Aug 92	Assume NSL 4/5 slope for 17m	20.93	23.24			
Talgarry	Nov-91	Estimated Talg. 2 salinity is 83,000 mg/L			24.56	24.31	24.07
		Estimated Talg. 2 salinity is 83,000 mg/L and assume NSL 4/5 slope					24.09
Warwick	Nov-91	Assume NSL 4/5 slope			25.15		
Cal Lal	?	Assume NSL 4/5 slope for both			22.49	23.48	

Table 2. Environmental Water Heads in the southern Nulla Groundwater Discharge Complex

Piezometer Location	Date	Piezometer	Aquifer/Aquiclude	Zi	Hip	Zr	(density)i	(density)a	(density)f	Hin
Coolamon	Mar-92	9/20m	Parilla	16.4	24.4	24.4	1.02067	1.0207	1	24.40
		9/40m	Parilla	-2.56	24.38	24.4	1.02288	1.0212	1	24.42
		9/60m	Parilla	-22.62	24.37	24.4	1.02306	1.0218	1	24.43
NSL 6	March/April 92	6/5m	Lacustrine Clays	22.71	23.16	23.16	1.00623	1.0062	1	23.16
		6/8.5m	Parilla	19.9	23.48	23.16	1.02931	1.0155	1	23.53
		6/20m	Parilla	8.21	23.47	23.16	1.03642	1.0291	1	23.59
		6/40m	Parilla	-11.69	23.35	23.16	1.04714	1.0363	1	23.74
		6/60m	Parilla	-31.73	22.28	23.16	1.06433	1.0434	1	23.37
NSL 7	Feb/Mar/April 92	7-Feb	Lacustrine Clays	21.73	23.03	23.03	1.0413	1.0413	1	23.03
		7-Mar	? Parilla	19.3	23.27	23.03	1.04045	1.0410	1	23.28
		7-Jan	Parilla	17.52	22.98	23.03	1.037	1.0403	1	22.96
NSL 8	Mar 92/May 91	8-Feb	Lacustrine Clays	21.53	23.11	23.11	1.0526	1.0526	1	23.11
		8-Jan	? Parilla	18.8	23.15	23.11	1.04313	1.0496	1	23.12
NSL 4 and 5	March/April 92	4;	Lacustrine Clays	19.3	22.78	22.78	1.04915	1.0492	1	22.78
		4/2;	? Parilla	17.5	23.28	22.78	1.04679	1.0487	1	23.29
		5/20m	Parilla	7.8	23.32	22.78	1.04982	1.0484	1	23.37
		5/40m	Parilla	-12.2	22.79	22.78	1.06243	1.0528	1	23.13
		5/60m	Parilla	-32.2	22.49	22.78	1.05531	1.0550	1	22.49
NSL 1	Aug-92	1/1.7m	Lacustrine Clays	20.67	21.52	21.52	1.1676	1.1676	1	21.52
	Aug-92	Mar-93	? Parilla	17.5	23.24	21.52	1.05448	1.1230	1	23.06
NSL 2	Aug-92	2/1.7m	Lacustrine Clays	20.34	21.43	21.43	1.2489	1.2489	1	21.43
		2/3	?Lacustrine Clays	17	22.52	21.43	1.04915	1.1736	1	22.02
NSL 11	Aug-92	11	? Parilla	16.36	23.3	23.3	1.05639	1.0564	1	23.30
NSL 10	Mar 92/Aug 92	Feb-93	Lacustrine Clays	19.8	21.38	21.38	1.06309	1.0631	1	21.38
		Jan-93	?Parilla	15.83	22.89	21.38	1.05905	1.0616	1	22.96
Talgarry	Nov-91	Talgarry 1	Parilla	7.3	23.97	23.97	1.03436	1.0344	1	23.97
		Talgarry 2	Parilla	-31.7	23.35	23.97	1.04614	1.0385	1	23.75

The following assumptions have been made:
(1) The top of the unsaturated zone is the SWL in the uppermost piezometer. This approximation is least likely to be accurate for the piezometers in the lake, where the top of the unsaturated zone will depend on the amount of surface water in the lake.
(2) The average density has been calculated by assuming: (a) that the salinity is constant from the midpoint of the slots of the uppermost piezometer to the top of the unsaturated zone; and (b) the salinity changes linearly between piezometers.

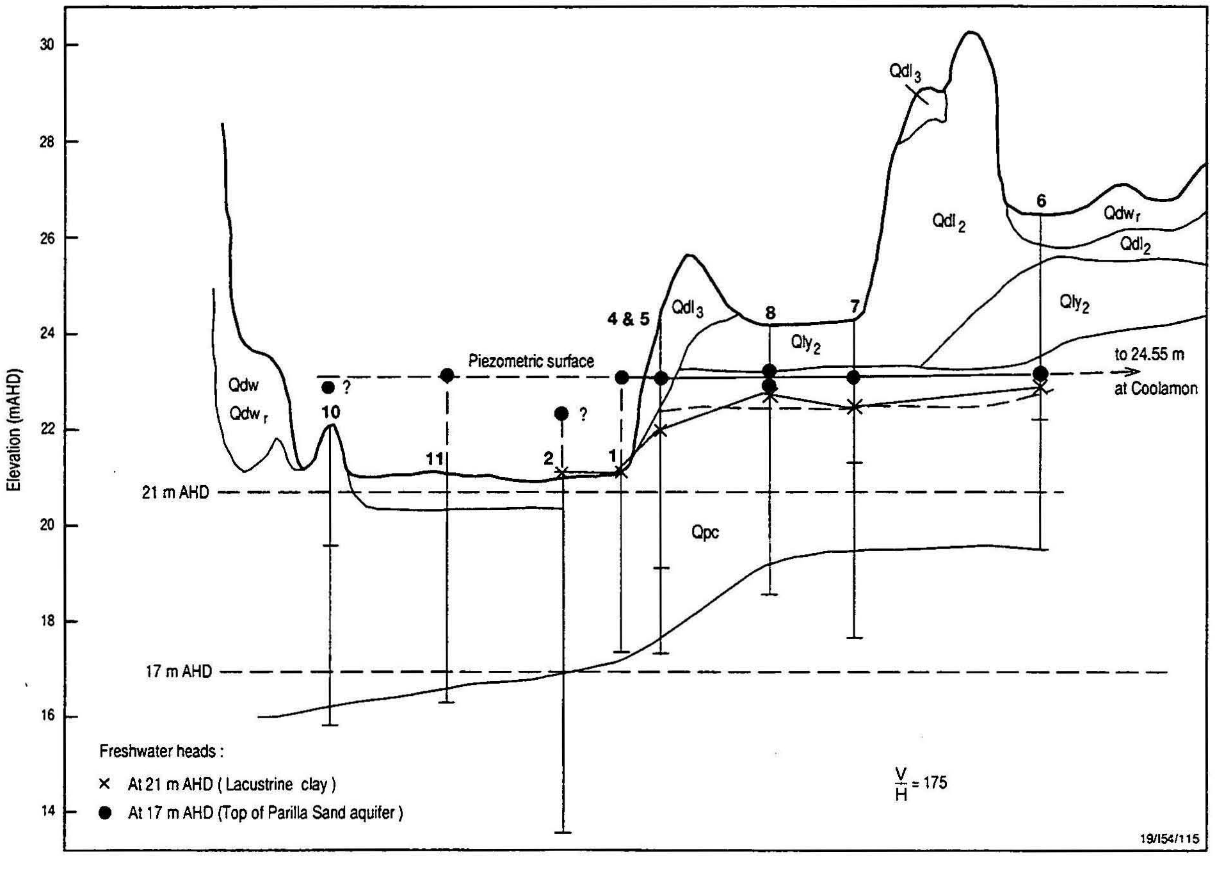


Figure 12. Lateral hydraulic heads associated with the top of the Parilla Sand and the lacustrine clays in Nulla Spring Lake and environs.

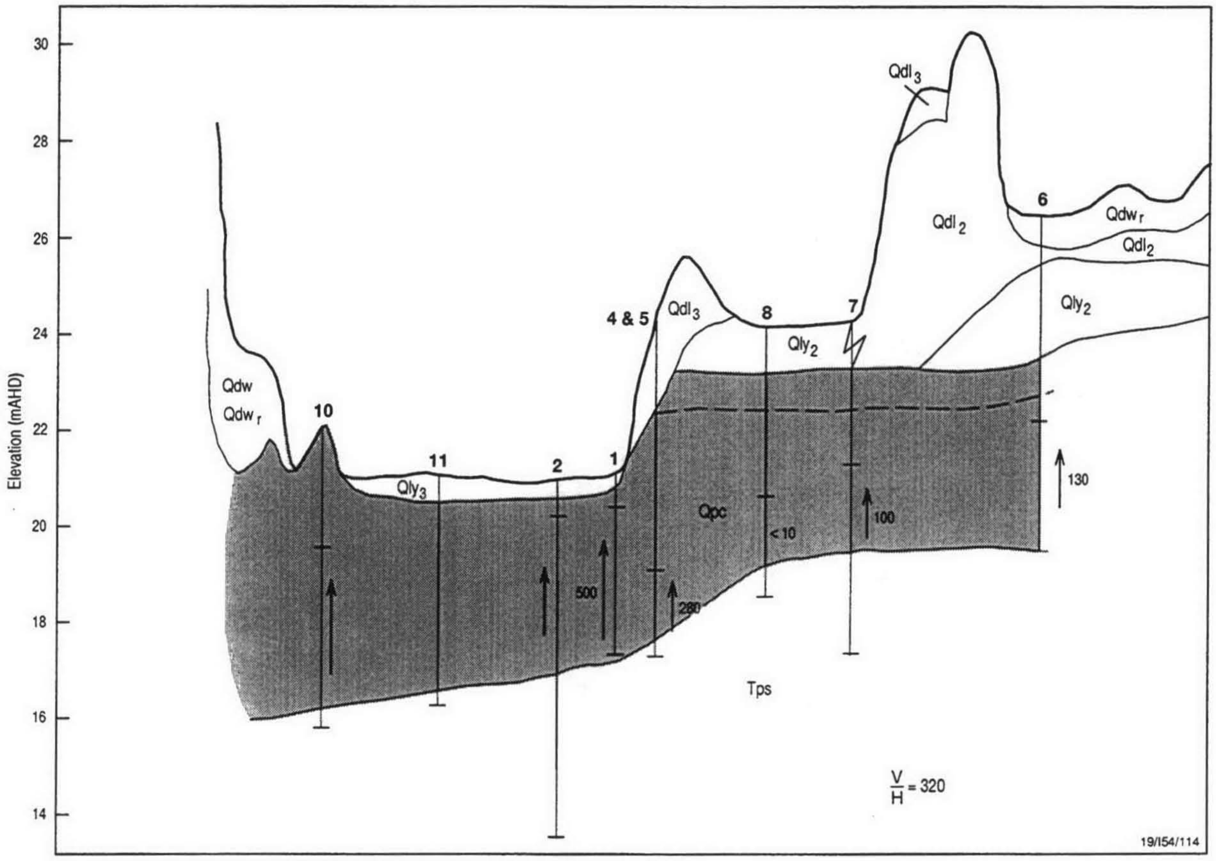


Figure 13. Vertical hydraulic gradients between the top of the Parilla Sand and the lacustrine clays in Nulla Spring Lake and environs.

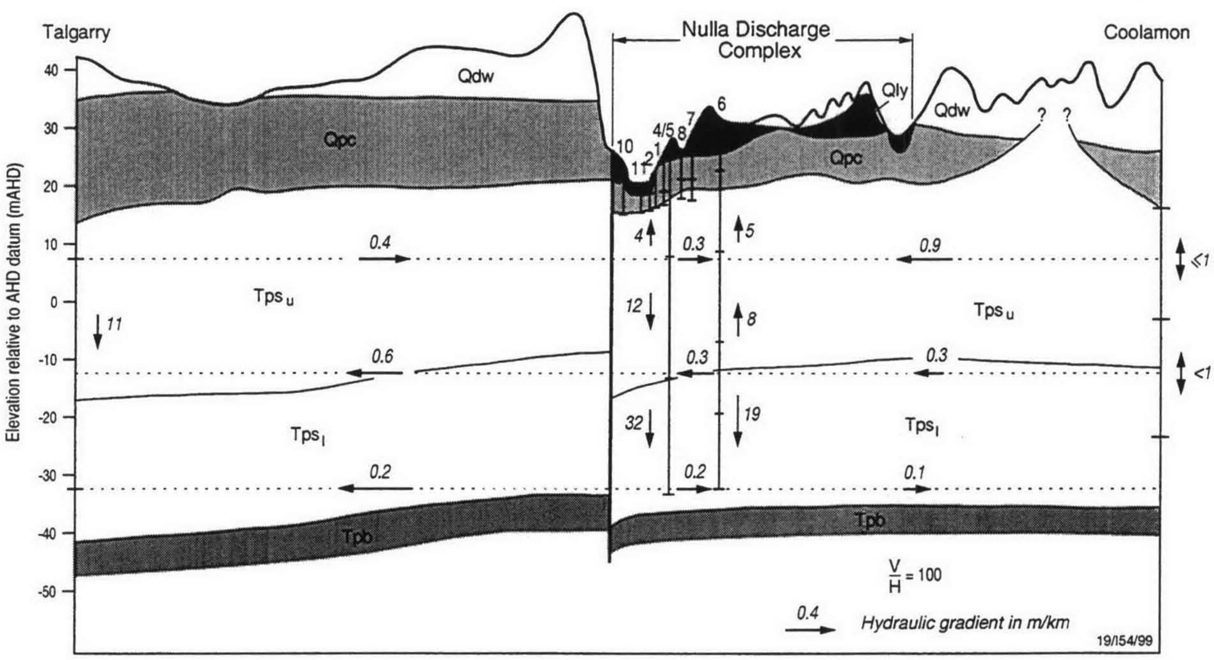


Figure 14. Lateral and vertical hydraulic gradients in the Parilla Sand aquifer on the Coolamon-Nulla Discharge Complex-Talgarry section.

perimeter of the lake. Sediment from these gullies forms small alluvial fans at the lake margins.

The surface water component of the lake is strongly influenced by seasonal variations in rainfall/runoff. During the wet season most of the lake is covered by a broad shallow pond. This pond is usually surrounded by a 10 to 20 m broad, gently sloping margin which is regularly washed by rainfall and by the seiching of the pond by winds. As summer approaches the pond gradually dries leaving a salt crust dotted with ponds of surface water from small springs. During normal seasons the sediment beneath the salt crust remains moist and deflation is restricted to the 10 to 20 m wide lake margins. However, during extended droughts the lake may dry completely and the salt crust be removed by deflation. Under normal conditions, as summer progresses the lake margins are wetted with decreasing frequency, the surface dries out, salt crystallises and the resultant mixture of salt and clay pellets is deflated from the lake.

Groundwater Flow

Lateral (freshwater) and vertical (environmental water) heads have been calculated according to the methods of Lusczynski (1961) and Lusczynski and Swarenski (1966), as described in the Methods section in the Appendix. Lateral hydraulic heads (Table **1**) are only comparable if measured at, or interpolated/extrapolated to constant elevation. Vertical hydraulic heads (Table **2**) are comparable when measured in groups of piezometers set at different elevations at the same location.

Lateral and vertical head data for the lacustrine clays and the underlying shallow Parilla Sand were obtained for Nulla Spring Lake and the area of the discharge complex to the east (Figures **12** and **13**). Data for the Parilla Sand aquifer (Figure **14**) was obtained from two locations in the discharge complex east of Nulla Spring Lake, and from piezometer nests at Coolamon and Talgarry.

Hydraulic Gradients Associated with Nulla Spring Lake

Lateral Hydraulic Gradients

The lateral (freshwater) hydraulic heads associated with Nulla Spring Lake (Table **1**, Figure **12**) have been calculated for two elevations: (1) an elevation which approximates the top of the underlying Parilla Sand aquifer (17m AHD); and (2) an elevation which is in the lacustrine clays and close to the surface of the lake (21m AHD).

Lateral heads at the top of the Parilla Sand (17m AHD) beneath the discharge complex are about 1 m lower than that at Coolamon, indicating a potential for flow towards the discharge complex from this direction. This head difference corresponds to a gradient of about 1m/km. When combined with a lateral hydraulic conductivity of 2m/day and an estimated porosity of 30%, this gives a flow rate towards the discharge complex of 0.7 x 10^{-3} m/day. For Talgarry, data for 17 mAHD is approximate because it must be obtained by extrapolation of data from 8m AHD. Probably, the gradient is from Talgarry to the discharge complex but its magnitude is smaller than that from Coolamon.

Lateral heads within the discharge complex to the east of the Nulla Spring Lake (NSL 6, 8, 7 and 4/5) are similar to those at two locations in the lake (NSL 1 and 11). Heads are lower one other location in the lake (NSL 2) and a location on the western margin (NSL 10) but these low heads are probably an artefact caused by the extremely slow response of the piezometers. Based on the piezometers at NSL 1 and 11, it appears that leakage of groundwater from the Parilla Sand aquifer through the Blanchetown Clay into the lake is not sufficiently rapid to affect the groundwater heads in the underlying aquifer. This is consistent with qualitative observations that the springs are small and their discharge sufficient to create small ponds but not streams.

Lateral heads in the lacustrine clay (21 m AHD) within the discharge complex vary little across the eastern margin from NSL 6 to NSL 8 (Figure **12**). The slightly lower value at NSL 7 could be a result of higher evaporation at this site, which is in a salinized de-vegetated area. There is a decrease in the lateral heads from the area between NSL 8 and NSL 4/5 to the lake presumably due to evaporation of groundwater from the lake. Evaporation may be greatest at the lake margins because evaporation from the centre is restricted by accumulated rainfall/runoff in winter and by the salt crust in summer.

The "drawdown" effect of groundwater evaporation from Nulla Spring Lake extends for a distance of less than 300m from the lake margin, which indicates that the lake plays only a minor role in "protecting" the surrounding area from rising saline groundwater levels.

Vertical Hydraulic Gradients

The vertical gradients from the top of the Parilla Sand to the clay are all directed strongly upwards (Table **2**, Figure **13**) and range from <10 to 500 m/km. The reliability of the values is affected by the slow (non-equilibrium) response of the piezometers in clay. These slow responses will tend to give high values if the upper piezometer is affected and low values if the lower piezometer is affected, as probably occurs at NSL 2 and NSL 10). Low gradients will also be obtained if the upper piezometer is in a permeable zone hydrodynamically connected to the Parilla Sand aquifer, as possibly occurs at NSL 8. Disregarding data from these three piezometers, the remainder show a pattern of increasing vertical gradients towards the lake (NSL 6 and 7 < NSL 4/5 < NSL 1; Figure **13**).

The vertical gradient within the lake (500 m/km) corresponds to an artesian head of at least 1m above the lake surface. This high artesian head in the lake is related to the low permeability of the surrounding Blanchetown Clay sediments, which allows the development of large vertical heads without large volumes of groundwater being discharged into the lake. Under these circumstances, increases in the hydraulic head of the surrounding Parilla Sand groundwater which occurred since the deflation event which excavated the present Nulla Spring Lake are reflected in the lake hydrology only in a very attenuated form. Consequently, rises in the lake levels have been relatively small, high artesian heads have developed beneath the lake, and development of lacustrine sequences overlying the Blanchetown Clay substrate in the lake has been severely limited. In this sense, Nulla Spring Lake is a hydrological and sedimentological "fossil" which has been unable to respond normally to increases in the Parilla Sand groundwater levels.

Hydraulic Gradients in the Parilla Sand Aquifer

Lateral Hydraulic Gradients

Lateral gradients at constant depth were calculated for the upper (8 mAHD), middle (-12 mAHD) and lower (-32 mAHD) parts of the Parilla Sand aquifer (Table **1**; Figure **14**).

An indication of the regional gradient in the area can be obtained by comparing the heads at Coolamon and Talgarry (Table **1**). At all three depths the gradient is from Coolamon to Talgarry and the magnitude increases with depth (0.1 to 0.45 to 0.8 m/km at 8, -12 and -32 mAHD respectively). The higher gradient at greater depths may not translate into a more rapid flow rate because, as discussed previously, the hydraulic conductivity is probably lower in the deeper Parilla Sand sediments.

Gradients from Coolamon and Talgarry are towards the discharge complex (Figure **14**) in the upper Parilla Sand. With increasing depth into the aquifer the Coolamon-discharge complex gradient decreases and then reverses so that the gradient is slightly away from the discharge complex in the lower Parilla Sand. The Talgarry-discharge complex gradient is away from the complex in both the intermediate and lower Parilla Sand. The range of lateral gradients associated with the discharge complex is from 0.1 to 2 m/km. Combined with an estimated average lateral hydraulic conductivity of 2m/day and a porosity of 30%, this translates to lateral flow rates of the order of 0.7×10^{-4} to 13×10^{-4} m/day.

Beneath the discharge complex (between NSL 4/5 and 6; Figure **14**) gradients are towards Coolamon near the top and base of the aquifer and towards Talgarry at intermediate depths, which is indicative of a complex circulation pattern.

Vertical Hydraulic Gradients

Vertical gradients in the Parilla Sand aquifer are in the range <1 to 32 m/km. The higher gradients in this range are associated with the lower hydraulic conductivity sediments of the lower Parilla. The vertical gradients are about 1 to 2 orders of magnitude higher than the lateral gradients (Table **2**; Figure **14**) but, as discussed previously, there is probably about 2 to 3 orders of magnitude difference in the lateral and vertical conductivity in the Parilla Sand. Assuming an average vertical hydraulic conductivity of 0.004 m/day and a porosity of 30%, the vertical gradients correspond to flow rates up to about 0.3×10^{-4} m/day. i.e. the vertical flow rates are probably slightly lower than the lateral flow rates.

At Coolamon, vertical gradients are negligible but at Talgarry the one value available indicates a significant downwards gradient.

Beneath the discharge zone, the vertical gradient is upwards in the shallower parts of the upper Parilla Sand, presumably reflecting both the discharge of groundwater into Nulla Spring Lake and, in some areas of the surrounding exposed older lake sediments, loss of groundwater by evaporation from topographically lower areas. At intermediate depths gradients are either upwards and downwards. Those in the lower Parilla Sand are downwards.

Flow Directions

Likely groundwater flow directions based on the lateral and vertical gradients described above are presented in Figure **15**.

SALINITY OF SURFACE AND GROUNDWATERS

Surface Water in Nulla Spring Lake

Salinity measurements were obtained for surface water on three occasions, two in late winter (August/September) and one in late summer (March). During late winter most of the lake is usually flooded by a large shallow pond formed from rainfall/runoff. The the salinity of this pond was 348,000 and 365,00 mg/L, which is close to halite saturation and confirms field observations that the salt crust does not dissolve completely during normal winter conditions.

During summer the lake is covered by a salt crust which is locally dissolved by emerging spring waters. The spring waters increase in salinity away from the spring source as they dissolve the salt crust and mix with residual brine in the underlying semi-liquid sediments. The lowest salinity obtained from these springs is about 60,00 mg/L, which is probably indicative of the salinity of the emerging spring water. A sample obtained for analysis (Table **3**) had a salinity of 81,000 mg/L, indicating that it contains some surface salt and/or brine.

Groundwater in the Lacustrine Clays

Salinity in the lacustrine clays beneath Nulla Spring Lake and the adjacent area of the discharge complex to the east are shown in cross-section in Figure **16**. Salinity versus elevation profiles for individual sites are also shown in Figure **16.**

Nulla Spring Lake

Beneath the area of the lake normally covered by the surface brine and/or the evaporite crust, different salinity profiles are associated with areas directly influenced by the emerging springs and those elsewhere. At sites near a spring there is a pronounced salinity minimum near the top of the Blanchetown Clay beneath the thin (0.45m) C_2 sequence (Figure **17**).

In areas away from the influence of springs the salinity decreases with depth from more than 300,000 mg/L near the surface to about 70,000 mg/L at the top of the underlying Parilla Sand (Figure **16**). The change in salinity with depth through the C_2 sequence and the underlying Blanchetown Clay be approximated by a single straight line (e.g NSL 1, Figure 13b), which is consistent with downwards diffusion of salt through the lacustrine clay into the top of the Parilla Sand aquifer.

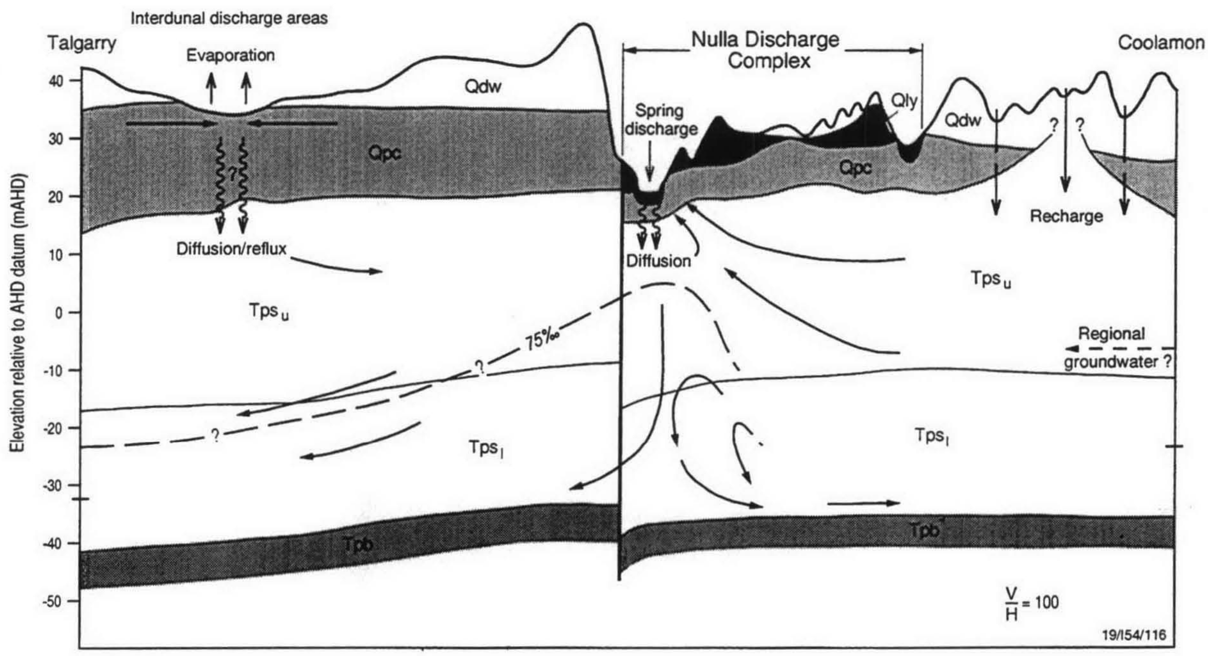


Figure 15. Interpreted groundwater flow pattern for the Parilla Sand aquifer on the Coolamon-Nulla Discharge Complex-Talgarry section.

Table 3 (a) Hydrochemistry of Nulla, Coolamon and Talgarry

Site	Description	Sample	Date	Lab Ref	Elevation (m AHD)	Salinity mg/L	pH	Alkalinity (meq/L)
Nulla Spring Lake	Surface water	NSL spring	Mar-91	910006		81000		5.6
Nulla Spring Lake	Surface water	NSL surface water	Mar-91	910007		333000		
Nulla Spring Lake	Surface water	NSL surface water	Sep-89	890344		348000	7.45	
Nulla Spring Lake	Surface water	NSL surface water	Sep-89	890345				
Nulla Spring Lake	Surface water	NSL surface water	Nov-91			365000		
Nulla Spring Lake	Surface water	NSL surface water	Aug-92	920180			7	
Nulla Spring Lake	Beneath salt crust	Nulla brine (below salt)	Mar-92	920066		350000	6.94	5.15
Nulla Spring Lake	Shallow Parilla Sand	NSL 1/3	Mar-92	920067	17.5	78000	7.25	4.3
Nulla Spring Lake	Shallow Parilla Sand	NSL 2/3	Mar-92	920068	ca. 17	76000	7.03	7.4
Nulla Spring Lake	Shallow Parilla Sand	NSL 11	Mar-91	910010	16.36	72000		7.8
Nulla Spring Lake	Shallow Parilla Sand	NSL 11	Aug-92	920179	16.36	76000	7.18	6.6
Nulla Discharge Complex	Clays beneath lunette	NSL 6/5m	Nov-91	900941	22.71	10000	7.66	2.5
Nulla Discharge Complex	Clays beneath lunette	NSL 6/5m	Mar-91	910002	22.71			2.65
Nulla Discharge Complex	Shallow Parilla Sand	NSL 7/1 deep	Mar-91	910004	17.52	61000		6.1
Coolamon	Parilla Sand	NSL9/20m	Nov-90	900945		26000	6.790	7.5
Coolamon	Parilla Sand	NSL9/20m	Mar-91	910008		28000		7.1
Coolamon	Parilla Sand	NSL9/20m	Nov-91			34000		
Coolamon	Parilla Sand	NSL 9/40m	Nov-90	900946		36000	6.730	9.2
Coolamon	Parilla Sand	NSL 9/40m	Nov-91					
Coolamon	Parilla Sand	NSL 9/60m	Mar-91	910003		36000		9.2
Talgarry	Parilla Sand	Talgarry 1	Jun-90	900718		55000	7.08	6.71
Talgarry	Parilla Sand	Talgarry 2	Jun-90	900719		88700	6.86	5.44
Nulla Discharge Complex	Parilla Sand	NSL 6/20m	Nov-90	900942	8.21	53000	6.66	6.7
Nulla Discharge Complex	Parilla Sand	NSL 6/40m	Nov-90	900943	-11.69	78000	6.65	8.5
Nulla Discharge Complex	Parilla Sand	NSL 6/60m	Nov-90	900944	-11.69	98000	6.73	5.96
Nulla Discharge Complex	Parilla Sand	NSL 6/60m	Mar-91	910005	-11.69	96000		7.35
Nulla Discharge Complex	Parilla Sand	NSL 6/60m	Mar-91		-11.69			
Nulla Discharge Complex	Parilla Sand	NSL 5/20m	Nov-90	900938	7.8	72000	6.85	5.44
Nulla Discharge Complex	Parilla Sand	NSL 5/20m	Mar-91	910009	7.8	72000		5.4
Nulla Discharge Complex	Parilla Sand	NSL 5/40m	Nov-90	900939	-12.2	94000	6.79	6
Nulla Discharge Complex	Parilla Sand	NSL 5/60m	Nov-90	900940	-32.2	106000	6.83	7.4

Table 3 (b) Hydrochemistry of Nulla, Coolamon and Talgarry

	Lab Ref	Ca	Mg	Na	K	Sr	Li	Cl	SO4	NO3	Br
NSL spring	910006	850	2820	27800	146	16.6	0.45	43400	7020	<100	96.3
NSL surface water	910007	96.3	35700	81900	785	2.08	2.29	165000	68800	<100	403
NSL surface water	890344					8.48	0.93				
NSL surface water	890345					14.27	1.036				
NSL surface water											
NSL surface water	920180	220	19300	110000	681	4.13	2.56	186000	48400		274
Nulla brine (below salt)	920066	40.9	28400	88300	820	4.5	1.4	178000	51100	<20	286
NSL 1/3	920067	802	2740	26000	215	13	0.33	41400	8950		72.9
NSL 2/3	920068	704	2470	25700	220	15	0.32	42200	6660		72.7
NSL 11	910010	881	2480	24500	121	16.9	0.33	41100	7060		83.6
NSL 11	920179	818	2320	23300	192	14.2	0.61	41900	6940		78.1
NSL 6/5m	900941	560	256	3050	34	23.9	0.06	4240	3710	24.5	10.5
NSL 6/5m	910002										
NSL 7/1 deep	910004	1060	2400	19700	97.8	16.9	0.33	32400	7550	<100	83.5
NSL9/20m	900945	417	960	8550	67.5	13.2	0.18	14100	3190	16.7	32.7
NSL9/20m	910008	461	990	8980	79.7	12.5	0.27	14400	3320		32.9
NSL9/20m											
NSL 9/40m	900946	579	1330	11300	61.1	15.7	0.12	18700	4250	16	42.1
NSL 9/40m											
NSL 9/60m	910003	536	1430	11900	67	15.4	0.17	19400	4570	<10	46
Talgarry 1	900718	831	2070	17060	125	34.14	0.391	27700	5800	47	61
Talgarry 2	900719	904	3540	22640	179	33.68	0.749	44700	9700	59.5	96
NSL 6/20m	900942	766	2060	16700	82.7	18.6	0.37	28800	6170	43.4	70.7
NSL 6/40m	900943	663	3070	24400	107	14.9	0.49	42900	8920	58.5	102
NSL 6/60m	900944	551	3500	31800	214	13.7	0.77	56400	11400	<100	127
NSL 6/60m	910005	682	3714	31271	166	19.2	0.31	55600	9630		109
NSL 6/60m								56500	11700	<100	112
NSL 5/20m	900938	881	2740	22400	106	17.4	0.366	39600	8140	45.6	90.3
NSL 5/20m	910009	939	2790	24000	151	17.2	0.493	39500	7700		91
NSL 5/40m	900939	630	3170	30300	208	14.1	0.58	53400	11000	<100	106
NSL 5/60m	900940	694	3770	34300	229	14.4	0.79	61100	11800	<100	128

Table 3 (c) Hydrochemistry of Nulla, Coolamon and Talgarry

	Lab Ref	Ca/Br	Mg/Br	Na/Br	K/Br	Cl/Br	SO4/Br	Sr/Ca	Na/Cl	1/Br
NSL spring	910006	8.83	29	289	1.52	451	73	0.172	0.64	0.0104
NSL surface water	910007	0.24	89	203	1.95	409	171	0.005	0.50	0.0025
NSL surface water	890344									
NSL surface water	890345									
NSL surface water										
NSL surface water	920180	0.80	70	401	2.49	679	177	0.015	0.59	0.0036
Nulla brine (below salt)	920066	0.14	99	309	2.87	622	179	0.016	0.50	0.0035
NSL 1/3	920067	11.0	37.6	357	2.95	568	123	0.016	0.63	0.0137
NSL 2/3	920068	9.7	34.0	354	3.03	580	92	0.021	0.61	0.0138
NSL 11	910010	10.5	29.7	293	1.45	492	84	0.019	0.60	0.0120
NSL 11	920179	10.5	29.7	298	2.46	536	89	0.017	0.56	0.0128
NSL 6/5m	900941	53.3	24.4	290	3.24	404	353	0.043	0.72	0.0952
NSL 6/5m	910002									
NSL 7/1 deep	910004	12.7	28.7	236	1.17	388	90	0.016	0.61	0.0120
NSL9/20m	900945	12.8	29.4	261	2.06	431	98	0.032	0.61	0.0306
NSL9/20m	910008	14.0	30.1	273	2.42	438	101	0.027	0.62	0.0304
NSL9/20m										
NSL 9/40m	900946	13.8	31.6	268	1.45	444	101	0.027	0.60	0.0238
NSL 9/40m										
NSL 9/60m	910003	11.7	31.2	259	1.45	423	100	0.029	0.61	0.0218
Talgarry 1	900718	13.6	33.9	280	2.05	454	95			
Talgarry 2	900719	9.4	36.9	236	1.86	466	101	0.041	0.62	0.0164
NSL 6/20m	900942	10.8	29.1	236	1.17	407	87	0.024	0.58	0.0141
NSL 6/40m	900943	6.5	30.1	239	1.05	421	87	0.022	0.57	0.0098
NSL 6/60m	900944	4.3	27.6	250	1.69	444	90	0.025	0.56	0.0079
NSL 6/60m	910005	6.3	34.1	287	1.52	510	88	0.028	0.56	0.0092
NSL 6/60m						504	104			0.0089
NSL 5/20m	900938	9.8	30.3	248	1.17	439	90	0.020	0.57	0.0111
NSL 5/20m	910009	10.3	30.7	264	1.66	434	85	0.018	0.61	0.0110
NSL 5/40m	900939	5.9	29.9	286	1.96	504	104	0.022	0.57	0.0094
NSL 5/60m	900940	5.4	29.5	268	1.79	477	92	0.021	0.56	0.0078

Table 3 (d) Hydrochemistry of Nulla, Coolamon and Talgarry

Sample	Lab Ref	δD (ppt)	∂18O (ppt)	∂13C (ppt)	87Sr/86Sr	36Cl/Cl (10^-15)	36Cl (atoms/L)	Tritium (T. U.)	14C age (Years B.P.)	% Modern C
NSL spring	910006	-18.1	-0.22	-2.51	0.709296	27(3)				
NSL surface water	910007	6	7.61		0.70917			4.5(0.4)/4.2(0.3)		
NSL surface water	890344		3.19	2.79		20(5)	53300(14000)			
NSL surface water	890345									
NSL surface water		15								
NSL surface water	920180									
Nulla brine (below salt)	920066									
NSL 1/3	920067									
NSL 2/3	920068									
NSL 11	910010	-17.6	-1.59	-10.67	0.709146			0.5(0.3)/0.3(0.3)		
NSL 11										
NSL 6/5m	900941	-30.4	-5.14	-10.04	0.709233	25(3)		4.7(0.3)/4.8(0.3)		
NSL 6/5m	910002		-5.13	-10						
NSL 7/1 deep	910004	-24.4	-2.7	-9.57	0.70922	28(4)	13600(2100)	0.0(0.3)/).2(0.3)	8940	34.2
NSL9/20m	900945	-29.3	-3.43	-9		29(3)	7832(919)	1.6(0.3)/1.0(0.3)	5070/6980	42.2/55.1
NSL9/20m	910008		-3.01	-8.8	0.70945					
NSL9/20m										
NSL 9/40m	900946	-31.2	-3.8	-12.7	0.70913	25(3)				
NSL 9/40m										
NSL 9/60m	910003	-32	-2.47	-13.3	0.709298	23(4)	7100(1300)	0.4(0.3)/0.6(0.3)	9430	31.75
Talgarry 1	900718	-30.1	-3.29	-11.0	0.70916	26(5)	12233(1583)	0.0(0.3/0.5/(0.3)		
Talgarry 2	900719	-31.3	-1.96	-10.1	0.70900	15(?)	11389(2437)			
NSL 6/20m	900942	-23.8	-2.33	-10.52						
NSL 6/40m	900943	-25.8	-0.87	-11.05	0.70913	25(3)				
NSL 6/60m	900944		-1.4	-10.96	0.709083	30(5)	28200(5100)	0.1(0.3)/0.5(0.3)	7590	30.1
NSL 6/60m	910005		-1.08	-11.65						
NSL 6/60m										
NSL 5/20m	900938	-23.5	-1.18	-9.47	0.70908	26(3)				
NSL 5/20m	910009		-0.88	-9.42						
NSL 5/40m	900939	-19.3	-0.71	-10.01						
NSL 5/60m	900940	-19.2	-0.64	-10.83	0.70919	23(3)	23800(2000)			

NBS 87Sr/86Sr = 0.710257 (95% confidence limits)

Table 3 (e) Hydrochemistry of Nulla, Coolamon and Talgarry

SI = Saturation Index

Sample	Lab Ref	SI anhydrite	SI calcite	SI dolomite	SI epsomite	SI gypsum	SI halite	SImagnesite	SI mirabolite	pCO2 (atmospheres)
NSL 6/5m	900941	-0.3	0.38	0.91	-2.82	-0.06	-3.66	-0.3	-2.84	-2.63
NSL 6/5m	910002									
NSL 6/20m	900942	-0.43	-0.27	0.4	-2.24	-0.21	-2.16	-0.17	-1.75	-1.22
NSL 6/40m	900943	-0.44	-0.27	0.66	-2.04	-0.24	-1.83	0.09	-1.45	-1.11
NSL 6/60m	900944	-0.45	-0.39	0.57	-1.94	-0.26	-1.57	0.12	-1.24	-1.34
NSL 6/60m	910005	-0.43			-1.99	-0.24	-1.58		-1.33	
NSL 6/60m										
NSL 7/1 deep	910004	-0.26	0.13	1.13	-2.15	-0.05	-2.04	0.17	-1.59	-1.59
NSL 5/20m	900938	-0.36	-0.13	0.76	-2.1	-0.13	-1.89	0.05	-1.52	-1.5
NSL 5/20m	910009									
NSL 5/40m	900939	-0.41	-0.28	0.69	-1.98	-0.21	-1.63	0.13	-1.28	-1.41
NSL 5/60m	900940	-0.36	-0.1	1.09	-1.92	-0.17	-1.5	0.35	-1.21	-1.35
NSL 1/3	920067									
NSL 2/3	920068									
NSL 11	910010	-0.39	0.65	2.27	-2.21	-0.19	-1.84	0.785	-1.52	-2

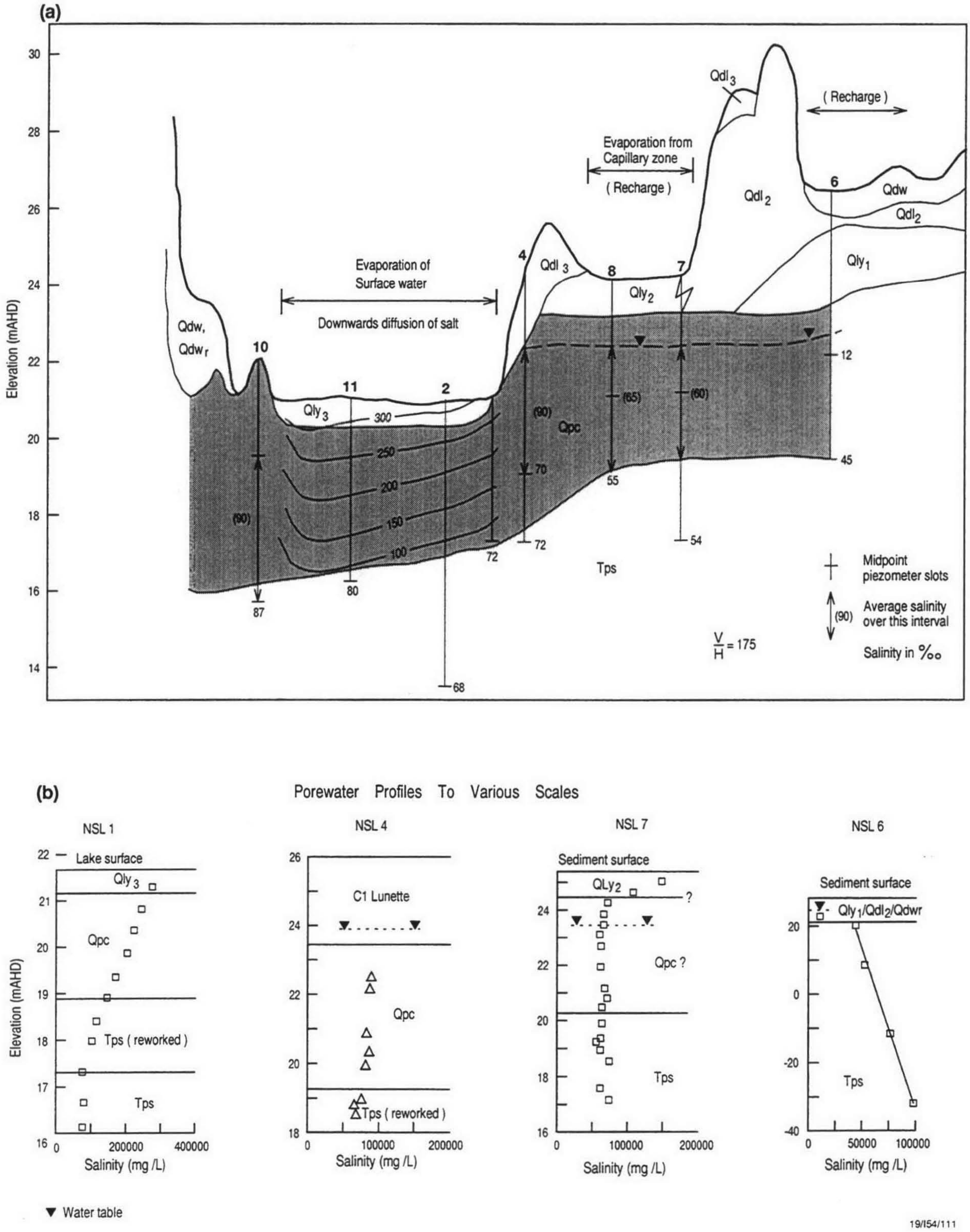


Figure 16. Iso-salinity contours and other salinity data for lacustrine clays in Nulla Spring Lake and environs.

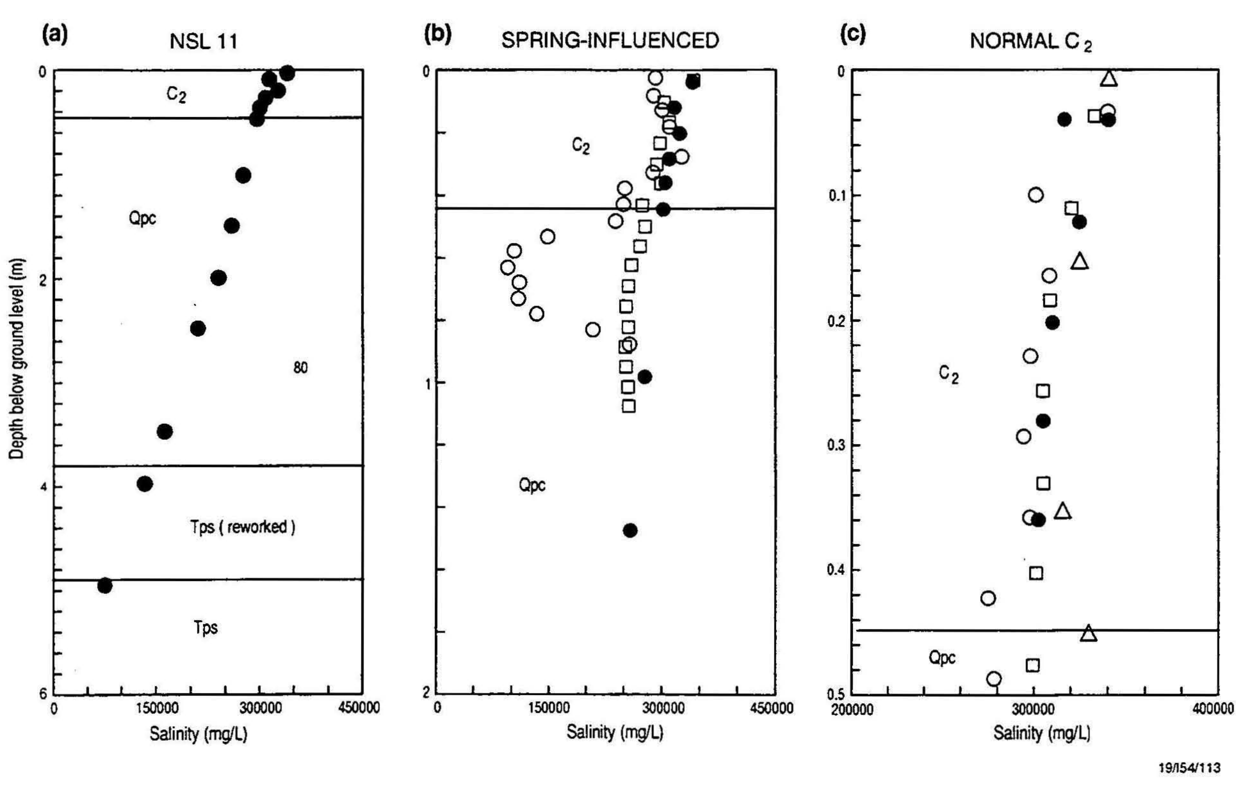


Figure 17. Detail of salinity changes in the C_2 unit and near the C_2 - Qpc interface. Comparison of NSL 11 with other sites in the lake.

For sites where more detailed information is available, the data is better described by separate lines of different slope for the C_2 and Blanchetown Clay sequences (NSL 11, Figure **18**). The salinity profile in the C_2 sequence shows an approximately linear change with depth from about 340,000 mg/L close to the lake surface to about 300,000 mg/L near the Blanchetown Clay - C_2 interface. Within the Blanchetown Clay the salinity decreases from about 300,000 mg/L near the C_2 interface to about 70,000 mg/L at the top of the underlying Parilla Sand. Closer inspection of the NSL 11 data indicates small deviations from linearity consistent with diffusional interaction between the two sequences. Most likely, the two salinity imprints result from the superimposition of the hydrodynamic regime associated with the deposition of the C_2 sequence on that associated with the preceding deflation event.

Lunette and Lacustrine Sequences to the east of Nulla Spring Lake

To the east of Nulla Spring Lake there is a partly devegetated area (around NSL 7) of gypsum hardpan which tops the older lacustrine sequence. In the lacustrine clays beneath this devegetated area the salinity is almost constant through the clay and is similar to that in the underlying Parilla Sand (Figure **16**). In the capillary zone above the water table at NSL 7 the salinity increases, presumably as a result of evaporation. This profile is consistent with net upwards movement of water from the underlying Parilla Sand through the clay. The higher salinity water produced near the top of the capillary zone does not reflux against this gradient and salt formed at the surface is continuously removed by deflation.

Beneath the active lunette (NSL 4) the salinity in the clay is almost constant and only marginally higher than that in the underlying Parilla Sand. This profile may have originated by the processes described for NSL 7 before the lunette was put in place. Since then, this profile has been preserved because clays in the lunette sediments have protected the underlying lacustrine sediments from evaporation or recharge.

The lacustrine clay east of NSL 7 is covered by older, more permeable lunette deposits which limit evaporation but allow the rapid infiltration of rainfall. About 1 m of lunette sediments overlie the clay at NSL 6. At this location water of relatively low salinity (about 10,000 mg/L) occurs near the lacustrine clay-lunette interface.

Salinity of the Parilla Sand Aquifer

The salinity in the Parilla Sand aquifer beneath the southern area of the Nulla Discharge Complex and its relationship to the salinity at Coolamon and Talgarry are shown in Figure **19**. There is a brine beneath the discharge complex (≥105,000 mg/L) which is considerably more saline than the regional Parilla Sand groundwater at Coolamon and Talgarry. Although the brine occurs beneath Nulla Spring Lake, it is unlikely to be a product of current conditions in the lake because there is a salinity minimum between the brine in the Parilla Sand and the brine the overlying lacustrine clay (Figure **16**). There is insufficient information to determine where the geometric centre of the brine pool is in relation the discharge complex as a whole, and the

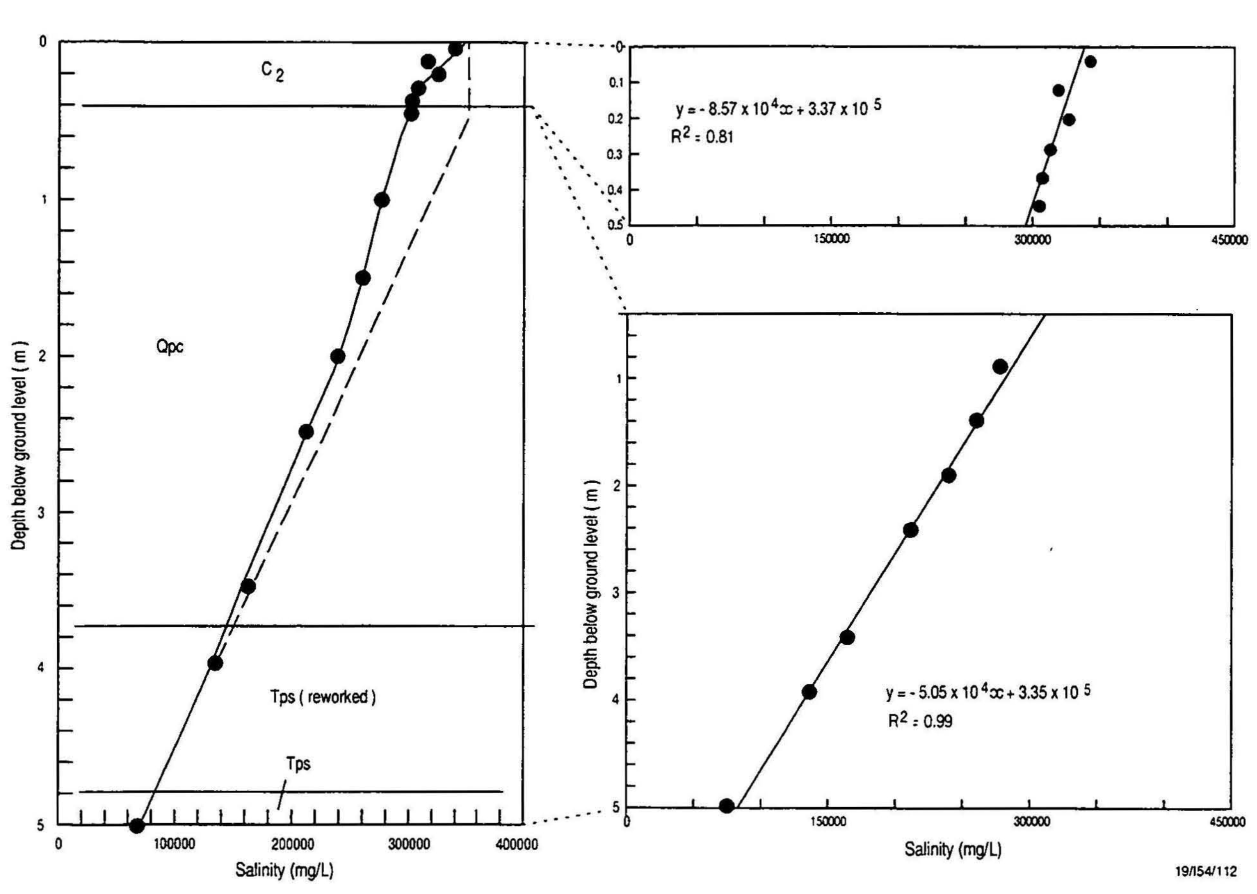


Figure 18. Detail of the salinity v depth profile at site NSL 11 in Nulla Spring Lake.

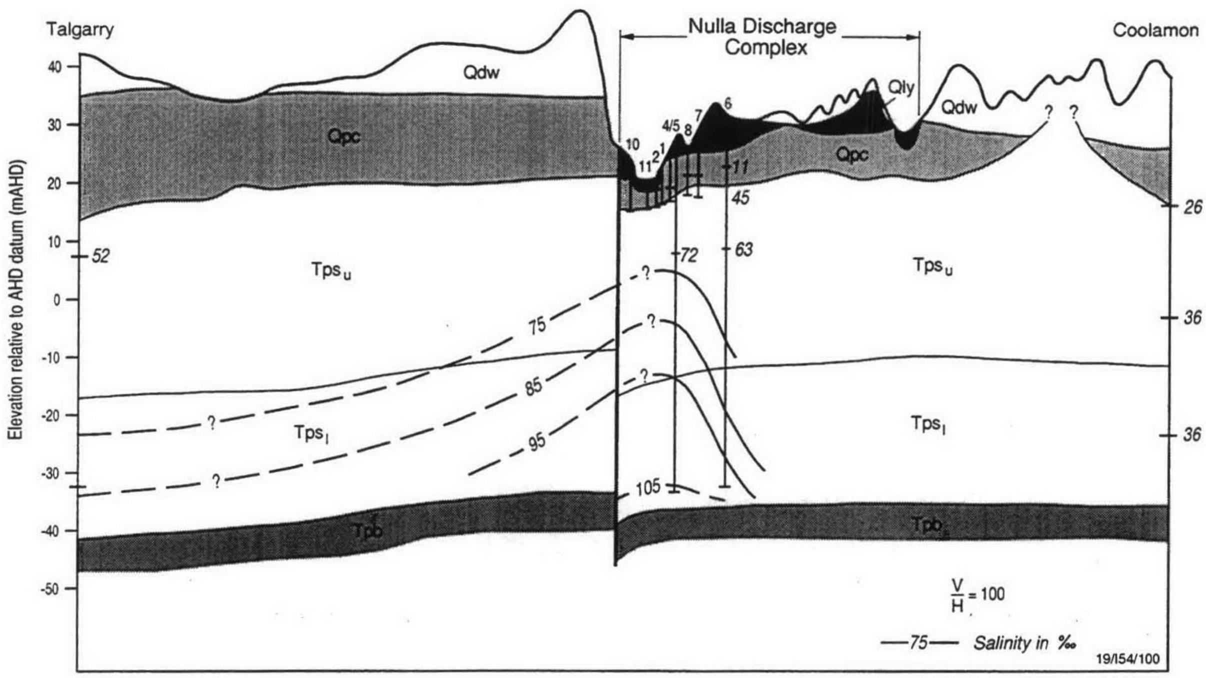


Figure 19. Iso-salinity contours for the Parilla Sand aquifer on the Coolamon-Nulla Discharge Complex-Talgarry section.

section at Nulla Spring Lake could have encountered the southern fringe of a large brine pond centered to the north. On the basis of information on the Mourquong Discharge Complex (Ferguson et al., 1997) it is speculated that there is an area of the discharge complex where the Blanchetown Clay is missing and that brine reflux occurred through this area.

There is a linear increase in salinity with depth at location NSL 6 (Figure **16**), which is consistent with upwards diffusion of salt from the brine to the lower salinity water in the upper part of the aquifer.

HYDROCHEMISTRY

Chemical analyses of the surface and groundwaters associated with the discharge complex and the reference sites at Coolamon and Talgarry are in Table **3**. A classification of the groundwaters in the Parilla Sand aquifer is in Table **4**.

Major Ion Chemistry

The geochemical relationships between the regional Parilla Sand groundwater, the brines in Nulla Spring Lake and the underlying lacustrine clay, and the brine in the Parilla Sand beneath the discharge complex have been examined by comparing: (1) the actual lacustrine surface and groundwater chemistry with that calculated for the evaporation path of the regional groundwater and the groundwater springs entering the lake; and (2) their Cl/Br or Mg/Br ratios.

Geochemical Calculations of the Major Ion Geochemistry of Nulla Spring Lake

The groundwater sample NSL 9/40m at Coolamon was taken as representative of the regional groundwater and the sample at NSL7/1 was taken as representative of the groundwater entering the lake in springs (Table **5**). These waters have been compared to shallow groundwater (< 1m depth) in the lacustrine clay at three sites (i1, i2 and i3) on the eastern margin of Nulla Spring Lake, between NSL 1 and the base of the active lunette.

Table 5 Composition of Probable Source Groundwaters for Nulla Spring Lake

molal	*NSL7/1*	*NSL 9/40m*
Na	0.8752	0.4980
K	0.0026	0.0016
Mg	0.1008	0.0554
Ca	0.0270	0.0146
Cl	0.9326	0.5339
SO4	0.0804	0.0449

Table 4. Chemistry of Groundwater in the Parilla Sand: Coolamon-Nulla Discharge Complex-Talgarry

Location	Salinity (mg/L)	pH	∂D (‰)	∂18O (‰)	$\partial^{13}C$ (‰)	Cl/Br (mass ratio)	$^{36}Cl/Cl$ (10^{-15})	$^{87}Sr/^{86}Sr$
RP_R Regional Parilla Groundwater diluted by Evaporated Local Rainfall								
Coolamon (NSL 9/20m)	26,000	6.8	-29	-3.4	-9	430	29(3)	(0.70945)
RP: Regional Parilla Groundwater								
Coolamon NSL 9/40m	36,000	6.7	-31	-3.8	-13	440	n.d.	0.70913
RP_E + TB : Regional Parilla Groundwater mixed with Talgarry Reflux Brine								
Talgarry 1	55,000		-30	-3.3	-11	450	26(5)	(0.70916)
TRB : Talgarry Reflux Brine								
Talgarry 2	89,000		-31	-2.0	-10	470	15(?)	0.70900
NRB: Nulla Reflux Brines								
NSL 6/60m	96,000	(6.7)	n.d.	-1.1	-11	510	30(5)	(0.70905)
NSL 5/60m	106,000	6.8	-19	-0.6	-11	480	23(3)	
NDG Nulla Diffusion-Influenced Groundwater								
NSL 11	72,000	(7.2)	-18	-1.6	-11	490	n.d.	0.70911

Values in brackets are from different samplings of the same piezometers.

The two groundwaters representing the source groundwater for Nulla Spring Lake behave similarly under equilibrium evaporation at 25°C (Figure **20**). Figure **20** also shows that the regional water is different from seawater, particularly with respect to SO_4^{2-} and Mg^{2+}. Equilibrium evaporation at 25°C would produce a sequence of minerals in which glauberite becomes saturated prior to halite precipitation (Figure **21**). This is reflected in the decrease of SO_4^{2-} with increasing Cl concentration prior to loss of Cl as halite (Figure **20**).

Ionic concentrations for the lake groundwater from different depths at sites I1 to I3 (Table **6**) are also plotted in Figure **20**. This shows their relation to the predicted molalities for evaporated regional waters and indicates that none have been derived simply by evaporation of the regional waters.

Table 6 Composition of Nulla Spring Lake Groundwater from Sites I1, I2 and I3.

	Depth cm	*Ionic Strength molal*	*Na molal*	*K molal*	*Mg molal*	*Ca molal*	*HCO3 molal*	*Cl molal*	*SO4 molal*
NSL I1 a	0-10	7.786	5.036	0.0184	0.7061	0.0028	0.0014	5.214	0.618
NSL I1 b	10-20	7.365	4.803	0.0160	0.6932	0.0049	0.0010	5.217	0.475
NSL I1 d	40-50	7.557	4.969	0.0164	0.7309	0.0042	0.0011	5.195	0.498
NSL I1 f	60-70	6.188	3.921	0.0138	0.6188	0.0096	0.0008	4.239	0.422
NSL I2 a	? 55-60	8.541	4.862	0.0179	0.9939	0.0019	0.0014	5.362	0.715
NSL I2 b	? 60-70	7.330	4.511	0.0142	0.7814	0.0055	0.0010	4.888	0.524
NSL I2 c	? 70-80	7.504	4.621	0.0151	0.7970	0.0047	0.0010	5.056	0.527
NSL I2 d	? 80-90	7.247	4.478	0.0157	0.7538	0.0057	0.0010	4.886	0.519
NSL I2 e	? 90-100	7.040	4.385	0.0148	0.7380	0.0071	0.0009	4.685	0.504
NSL I3 a	0-10	5.007	3.347	0.0121	0.3643	0.0105	0.0010	3.029	0.531
NSL I3 c	20-30	4.597	3.173	0.0111	0.326	0.0121	0.0009	2.894	0.441
NSL I3 g	60-70	4.046	2.803	0.0108	0.2769	0.0135	0.0009	2.588	0.382

Table **7** shows calculated excess ion concentrations relative to an evaporated regional water for samples below the level of glauberite ($CaNa_2(SO_4)_2$) saturation. I1 and I2 are similar to each other, with close-to-expected Na^+ concentrations and enhanced Mg^{2+} and SO_4^{2-} concentrations (relative to Cl^-) compared to an evaporated regional water. It should be noted, however, that Na:Cl is close to a 1:1 relationship, so that re-solution of halite could occur without showing major deviation from the evaporation path. Under these conditions additional Mg^{2+} and SO_4^{2-} can be underestimated because of the higher Cl concentration compared to the extent of evaporation. In I3 the enhanced SO_4^{2-} compared to regional water appears to be principally balanced by Na^+ (Table **7**).

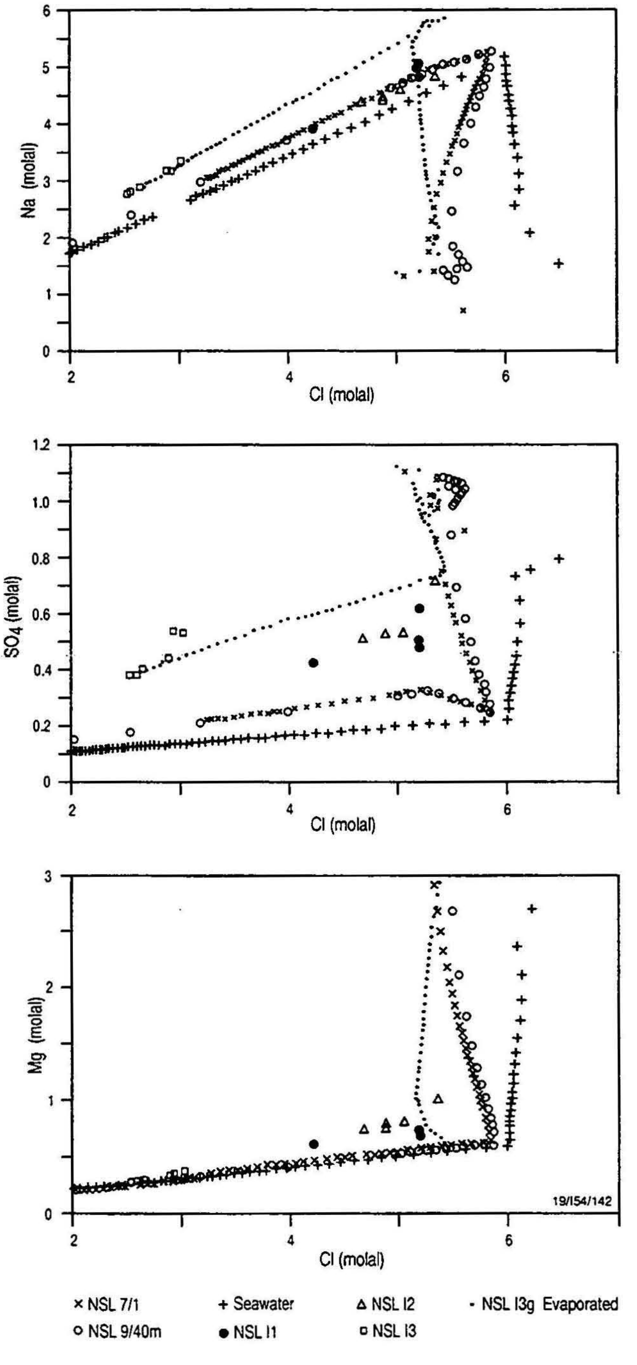


Figure 20. Na, SO_4 and Mg concentrations (molal) relative to Cl concentrations (molal) of brines from drill holes NSLI1, NSLI2 and NSLI3 compared to the predicted concentrations for equilibrium evaporation (at 25°C.) of regional waters (NSL9/40 and NSL7/1), seawater and a dilute brine from drill hole NSLI3 (I3G).

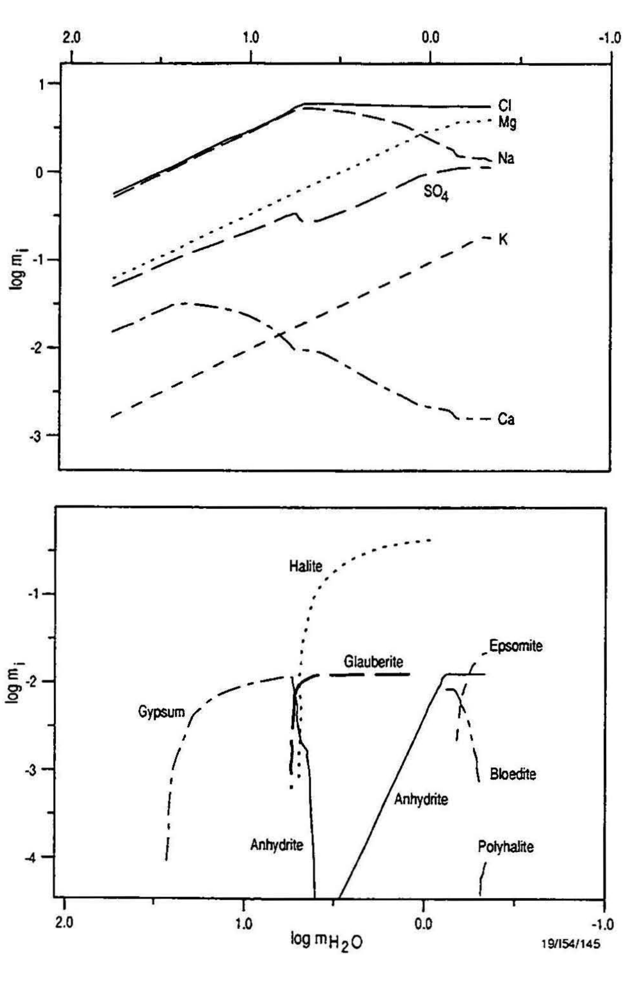


Figure 21. Equilibium evaporation of Nulla regional water . Upper portion shows molalities of major solutes and lower section shows solids in equilibrium from 1kg water as H_2O is removed in evaporation at 25°C.

Table 7 Differences in Actual and Predicted Concentrations of Groundwater in Nulla Spring Lake.

Water close to, or above the Cl concentration predicted for glauberite ($CaNa_2(SO_4)_2$) saturation were not considered.

	Cl molal	*Excess Na m molal*	*Excess Mg m molal*	*Excess SO4 m molal*
NSL I1 f	4.239		179	158
NSL I2 b	4.888		274	225
NSL I2 c	5.056		272	219
NSL I2 d	4.886		247	220
NSL I2 e	4.685		252	216
NSL I3 a	3.029	522	50	332
NSL I3 c	2.894	474	26	249
NSL I3 g	2.588	389	8	206

Since glauberite ($CaNa_2(SO_4)_2$), halite (NaCl) and epsomite ($MgSO_4{\cdot}7H_2O$) are predicted evaporation products, a mixture of these salts could be redissolved, and these would account for the ions in excess of an evaporated regional water.

Cl/Br and Mg/Br Ratios

The presence of redissolved salts can also be detected using ratios of the major ions to Br. Because Br is essentially conservative over most of the evaporation path, the presence of redissolved salts is indicated by major ion to Br ratios higher than those of the source groundwaters.

Surface Waters

The Cl/Br and Mg/Br ratios for the surface brine in winter and brine beneath the evaporite crust in summer in Nulla Spring Lake are shown in Table **3(c)**. The Cl/Br ratios of two of the three samples are in the range 600 to 700. This value is significantly higher than the regional Coolamon Parilla Sand groundwater range of 420 to 440 (Table **3(c)**), a probable spring source water in the shallow Parilla Sand near the lake margin (390: NSL 7/1; Table **3(c)**) and a Nulla Spring Lake groundwater spring (450; Table **3(c)**) The third surface water sample has a Cl/Br ratio of 410, but its Mg/Br ratio is comparable to that of the other two samples, which indicates that seasonal precipitation of halite has caused a temporary decrease in the Cl/Br ratio.

Groundwaters

The groundwaters in the lacustrine clay underlying Nulla Spring Lake have higher Cl/Br ratios than the likely source waters. For example at NSL 11 (Figure **22**) the ratio in the C_2-sequence the ratio is almost constant at 650 to 670, except for the uppermost sample. The ratio decreases in the upper part of the Blanchetown Clay (to 620) before rising to a maximum of 810. This implies that when the diffusion salinity-depth profile through the Blanchetown Clay was first established the Cl/Br ratio in the lake was higher than at present.

Slightly higher Cl/Br ratios occur at the top of the Parilla Sand beneath the lake compared to those beneath the discharge complex to the east (Tables **3** and **4**). For example, at NSL 7 the salinity in the shallow Parilla Sand is 61,000 mg/L and the Cl/Br ratio is 390. At NSL 11, the corresponding figures are about 72,000 mg/L and 490 (Table **3**) and at NSL 2 they are 68,000 mg/L and 450. These increased salinities and Cl/Br ratios are consistent with diffusion of salt from the clays underlying the lake into the underlying Parilla Sand.

The Cl/Br ratios of the brines in the Parilla Sand (Nulla Reflux Brines, NRB; Table **4**) are marginally higher than those of the regional Parilla groundwater at Coolamon (RP) and the mixture of evaporated regional groundwater and Talgarry Reflux Brine (RP_E) in the upper Parilla Sand at Talgarry. They are not significantly different from those of the brine in the lower Parilla Sand at Talgarry (TB).

δD and δ^{18}O

δD and δ^{18}O values of the regional groundwater at Coolamon, groundwaters at Talgarry and beneath the Nulla Discharge Complex, a spring in Nulla Spring Lake and the recharge-dominated groundwater beneath the lunette at NSL 6/5m are shown in Figure **23**, together with unpublished data of J. R. Kellett on the groundwaters of the Murray Basin and the Lower Calivil Formation.

The groundwater from beneath the lunette plots close to the meteoric water line, which is consistent with its low salinity and indicates rapid recharge of the permeable lunette sediments by rainfall. The remaining data scatter between lines I and III in Figure **23**, which are probably the evaporation lines for "free" (surface) water and capillary evaporation (groundwater), respectively. The large scatter of the points is consistent with the presence of several different types of brine and saline groundwater both in the discharge complex and at Coolamon and Talgarry.

The isotopic composition of the spring water indicates a mixed groundwater source for Nulla Spring Lake.

There is a general increase in δD with increasing salinity, which is indicative of an evaporation control (Figure **24**). However, the scatter is large, which is consistent with the involvement of two or more waters with different δD values.

δ^{18}O data for the brines in the lacustrine clays beneath Nulla Spring Lake (Figure **22**) indicate that the water near the top of the Blanchetown Clay is considerably more evaporated that the brine in the overlying C_2 sequence.

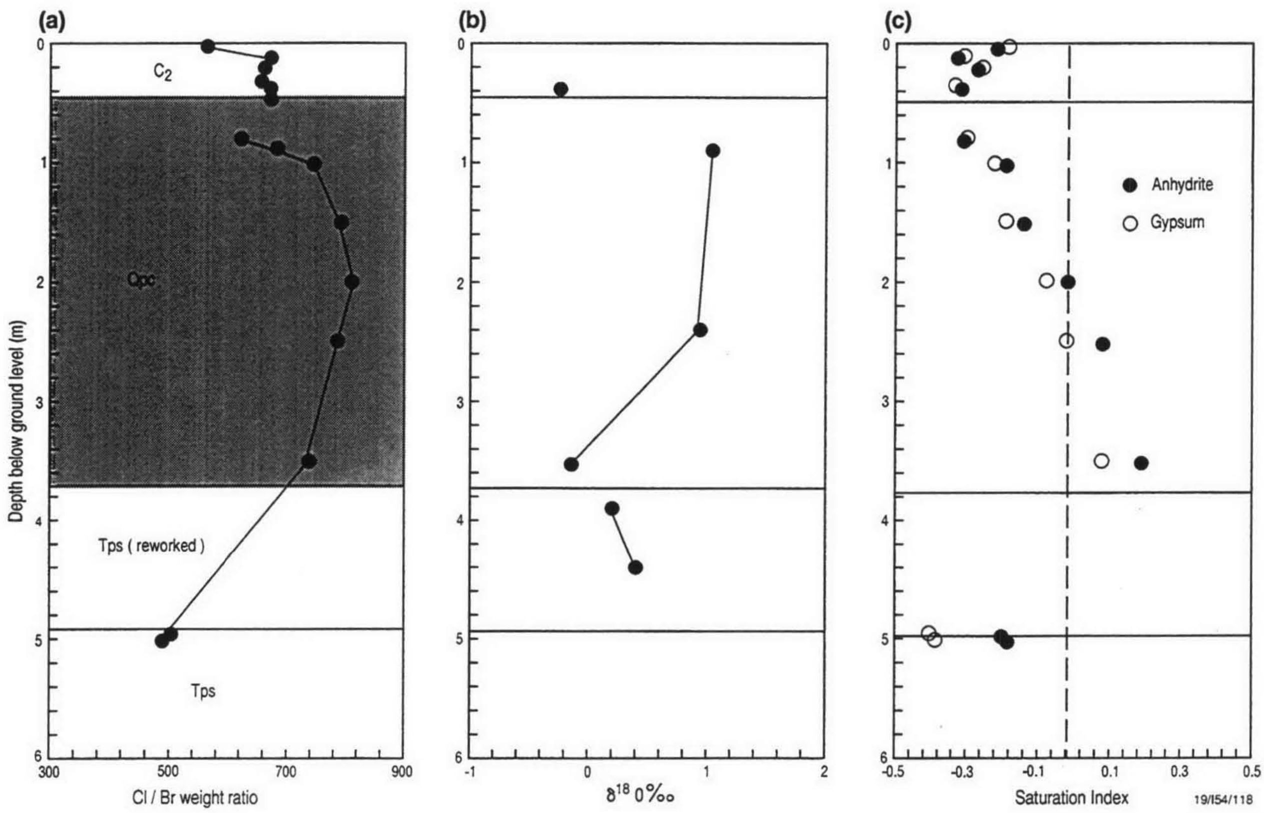


Figure 22. Changes in Cl/Br, $\delta^{18}O$, and saturation indicies with respect to gypsum or anhydrite at site NSL 11.

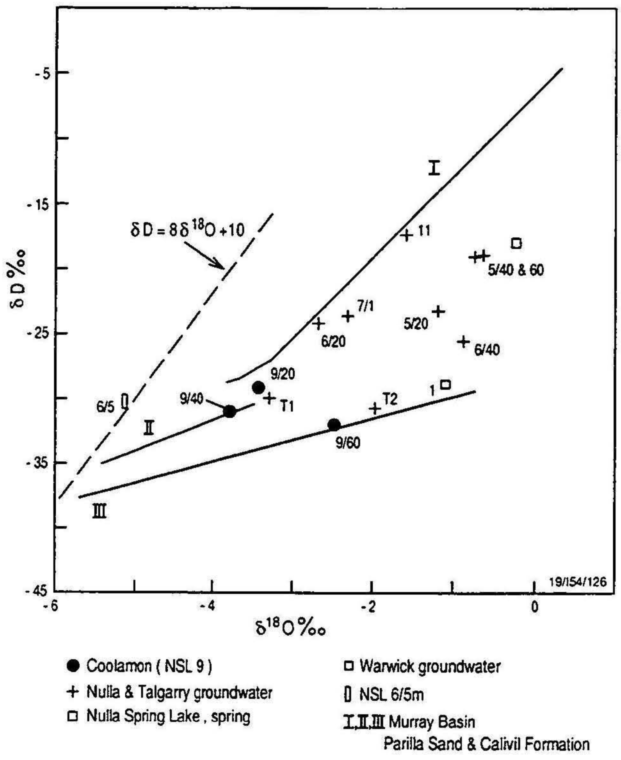


Figure 23. Relationship of the δD and $\delta^{18}O$ data for the Coolamon-Nulla Discharge Complex-Talgarry section to that for the Murray Basin Parilla Sand and Calivil Formation (J. R. Kellett, unpublished results).

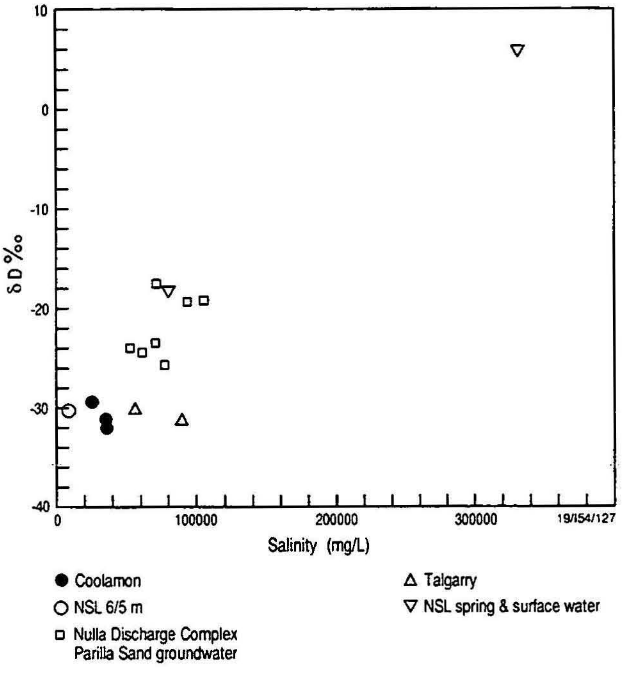


Figure 24. Relationship of δD to salinity for Coolamon-Nulla Discharge Complex-Talgarry groundwaters. There is a general trend of increasing ∂D with increasing salinity, but the data scatter considerably.

$^{36}Cl/Cl$ and $^{87}Sr/^{86}Sr$

The $^{36}Cl/Cl$ and $^{87}Sr/^{86}Sr$ ratios (Figure **25**) are consistent with the δD and $\delta^{18}O$ data in that they indicate a situation in which there are two or more types of water with different isotopic ratios are involved in the discharge complex.

A graph of $^{36}Cl/Cl$ against 1/Cl (Figure **26**) shows that there are two brines of similar salinity (100 to 125,000 mg/L) but considerably different ^{36}Cl values beneath the discharge complex.

The $^{36}Cl/Cl$ ratio of the Nulla Spring Lake surface water (about 20) is low compared to all of the groundwaters except that of the deeper brine at Talgarry. Possibly, the Talgarry brine was a more influential source of groundwater in the past.

The $^{87}Sr/^{86}Sr$ ratios range from values significantly above that of present-day seawater (e.g. at Coolamon, NSL 9/20m) to values significantly below (Talgarry 2; NSL 6/60m). The lower values could reflect the upwards movement of Sr in salt from underlying, older sequences at some stage in the evolutionary history of the aquifer system.

Tritium

The tritium contents (Table **3(d)**) of a surface water sample from the lake and the low salinity water from beneath the lunette fringe are high (4 to 5 TU) and consistent with a predominantly modern rainfall input. There is a significant tritium content in the upper Parilla Sand aquifer at Coolamon (NSL 9/20m; 1.0 to 1.6 TU), which is consistent with the lower salinity of these waters (28,000 mg/L) compared to those deeper in the aquifer at this site (36,000 mg/L). Other values are either below the detection limits or sufficiently close to be ascribed to possible minor contamination by drilling fluids.

Carbonate Hydrochemistry

The regional Parilla Sand groundwaters at Coolamon and Talgarry have moderate to high alkalinities (5.4 to 9.2 meq/L; Table **3(a)**) and pCO_2 values which are considerably above atmospheric (Table **3(e)**). They are close to saturation with respect to magnesite and to a lesser extent calcite. This indicates that the Nulla Discharge Complex is, potentially, the site of present-day carbonate deposition from the incoming regional Parilla Sand groundwater.

The ^{14}C- content of the upper Parilla Sand sample at Coolamon (NSL 9/20m; about 50% modern carbon) is higher than those of in the lower Parilla Sand at Coolamon (NSL 9/60m; about 30%) and a brine beneath the discharge complex (NSL 6/60m; about 30%). The upper Parilla Sand sample at the lake margin (NSL 7/1) has an intermediate value (about 34%), which is consistent mixing of upper and lower Parilla Sand waters.

The ^{14}C- contents of the lower Parilla Sand groundwaters, which correspond to ages of about 7500 to 9400 years B. P., seem high because epigenetic organic matter in the aquifer should contain no ^{14}C. At Coolamon, the modern organic matter may be being introduced by

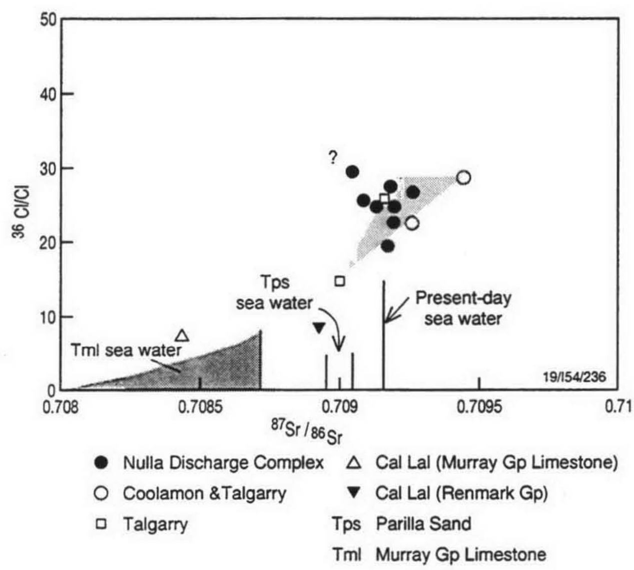


Figure 25. Relationship of $^{36}Cl/Cl$ to $^{87}Sr/^{86}Sr$ for the Coolamon-Nulla Discharge Complex-Talgarry section groundwater. Most of the waters associated with the discharge complex are intermediate in composition between those at Coolamon and Talgarry.

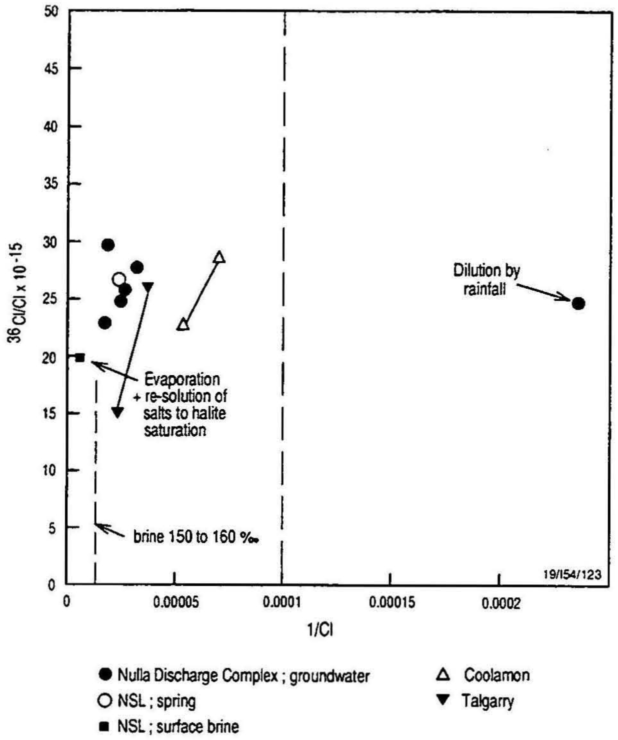


Figure 26. Relationship of $^{36}Cl/Cl$ to $1/Cl$ for the Coolamon-Nulla Discharge Complex-Talgarry section groundwater and surface water from Nulla Spring Lake.

rainfall recharging through the overlying dunes. The brine at NSL 6/60m has a relatively high ^{36}Cl value (30; Table 3(d)) which indicates that it is the product of a relatively recent reflux event. Possibly, the modern carbon was produced in the discharge complex and was transported with the reflux brine.

The $\delta^{13}C$ values of the carbonate in the groundwaters lie in the range -8.8 to -13.3‰ (Table 3(d)). That of the lake surface water is positive (2.8‰) and the value for the spring is intermediate between the surface and groundwaters, which is consistent with mixing of the two.

$\delta^{13}C$ values of carbonates which are lower than that of source organic matter for biogenic activity can arise by: (1) reaction of the biogenic CO_2 with aquifer carbonates of lower $\delta^{13}C$ values; and/or (2) evolution of isotopically lighter CO_2 from the groundwaters in the shallower parts of the aquifer. Reaction (1) seems the most likely process for the generation of the $\delta^{13}C$ values in the deeper parts of the Parilla Sand aquifer, which are close to 50% of typical organic matter values (e.g. -13.3‰ at NSL 9/60m; -10.1 at Talgarry 2; -11.7‰ at NSL 6/60m; and -10.8‰ at NSL 5/60m). However, there is little evidence of carbonate in this area of the Parilla Sand, and the brines may have interacted with the underlying Bookpurnong Beds. The effects of reaction (2) are evident in the shallower parts of the Parilla Sand aquifer, where the $\delta^{13}C$ values are slightly higher (-8.8‰ at NSL 9/20m; -9.6‰ at NSL/7; -9.5‰ at NSL/20m). The positive value in the surface water is consistent with extensive CO_2-evolution, although this is unlikely to be the sole cause.

Discussion

Geochemical Processes in Nulla Spring Lake

Under present-day conditions in Nulla Spring Lake, brines are forming predominantly in the topographically low areas from a combination of two sources: (1) incoming Parilla Sand groundwater which emerges as springs either directly in the brine-forming areas or in the nearby marginal areas, from where it can flow to the sites of brine formation as surface streams; and (2) saline water which forms at the margins as rainfall/runoff dissolves salt efflorescences formed by capillary evaporation of Parilla Sand groundwater, and then moves by surface flow to the topographically lower areas. Brines that formed predominantly from source (1) should have major-ion chemistries similar to those predicted from evaporation of the incoming Parilla Sand groundwater. In contrast, those formed from source (2) may be influenced by selective dissolution of the salts which form the efflorescences. Theoretically, evaporation to dryness of the incoming Parilla Sand groundwater at the margins should result in the transfer of the major-ion chemistry of the source Parilla Sand groundwater almost intact to the brines. In reality, a selection process operates at the lake margins as seasonal conditions change from regular washing/flooding during wet conditions to aeolian deflation of the surface sediment during extended periods of dryness. This selection process favours the incorporation of magnesium sulphate, sodium sulphate and sodium chloride minerals into the rainfall/dissolution brines.

Thus, depending on the balance between processes (1) and (2), brines formed in discharge complexes range in composition from solutions of magnesium sulphate plus sodium chloride to only slightly modified concentrated Parilla Sand source waters. These various chemical signatures are transferred to the underlying clays and the Parilla Sand aquifer with diffusing salt and refluxing brines.

Groundwater in the Lacustrine Clays

Beneath Nulla Spring Lake the salinity, Cl/Br and $\partial^{18}O$ data for the lacustrine clays are consistent with the presence of two groundwater brines. These two brines, and their geochemical characteristics, could have been generated during the following three phases in the hydrodynamic evolution of Nulla Spring Lake.

(1) During an arid phase Nulla Spring Lake deflated to its maximum depth in the Blanchetown Clay as the water table in the Parilla Sand decreased. Under these conditions, groundwater flow into the lake was low, evaporation was high and deflationary removal of salts and clay pellets was extensive. Under these conditions a highly evaporated, highly saline brine with a high Cl/Br ratio developed in the topographically low areas of the lake. Based on investigations of other discharge complexes, particularly that at Scotia (Ferguson et al. 1995), this brine could have formed mainly by dissolution of surface efflorescences by rainfall and their transport to the topographically lower areas of the lake. This brine then provided a source of salt for diffusion through the Blanchetown Clay to the underlying lower salinity groundwaters in the Parilla Sand.

(2) At the conclusion of the arid phase, rainfall/runoff and the flow rate of groundwater into the lake started to increase. Flooding of the lake became widespread and deflation was restricted to marginal areas of similar extent to those existing today. The surface waters were generally similar in chemistry to those of the source Parilla Sand groundwaters but they were modified by dilution by rainfall, concentration by evaporation and, to a limited extent, by evaporite precipitation, re-solution and transport involving the small proportion of the lake susceptible to drying and deflation. Under these conditions the groundwaters were highly evaporated and very saline (eg. 300,00 mg/L at NSL 11; 270,000 at NSL 1). Their Cl/Br ratios were higher than those of the source springs but lower than those from the previous more arid phase. A diffusion profile then became established between these waters and the underlying, slightly more saline waters in the Blanchetown Clay.

(3) As the wetter phase continued the C_2 sediments were deposited, gradually reducing the groundwater input to its present level. Salt built up the lake and the salinity of the surface waters increased to the present value (340,000 mg/L at NSL 11). Cl/Br ratios did not alter significantly, except seasonally when halite precipitated from the surface and near-surface brines during summer (Figure 16a). A diffusion or mixing profile became established between the slightly more saline surface waters and the underlying lower salinity waters.

The aeolian deflation processes which selectively deflate Br and other salts from the

Nulla Discharge Complex are relatively ineffective under present conditions. If the ratio of the seasonally deflated to the permanently moist area of the lake determines the effectiveness of the selective deflation process, then the small increase in the Cl/Br ratio in Nulla Spring Lake can be attributed to the proportionately small area of deflation at the lake margins. By similar reasoning the higher Cl/Br ratios and higher salinity in the lacustrine clay beneath NSL 11 indicates previous, drier lake conditions during which the deflation area was larger.

Groundwater in the Parilla Sand

A classification of the various types of groundwater in the Parilla Sand which can be recognised from the available data is presented in Table **4**. The concept of a regional Parilla Sand groundwater is blurred in these discharge complex-influenced environments but the waters beneath the dunefield at Coolamon are probably the closest in terms of hydrodynamic setting and geochemistry. However, even these waters have $^{36}Cl/Cl$ ratios higher than the predicted present-day input ratio.

Three geochemically different brines have been identified in the lower Parilla Sand aquifer - the Talgarry reflux brine and two Nulla reflux brines. Although these brines occur near the base of the Parilla Sand, they have some geochemical signatures which are best explained as originating in the underlying Bookpurnong Beds. The Talgarry brine and one of the Nulla brines have $^{87}Sr/^{86}Sr$ ratios below that of modern seawater, indicating a possible contribution from older Sr in the underlying aquifer. Also, as pointed out previously, the $\partial^{13}C$ values of the brines are best explained by reaction of biogenic CO_2 with carbonate from the underlying aquifer.

The classification of the recognisable water types probably simplifies the actual situation. A plot of Ca against salinity (Figure **27**) and data on the saturation indices of the groundwaters with respect to gypsum and anhydrite (Figure **28**) show that mixing of the various types of groundwater has further complicated the picture. Significant is the large scatter of points for sites NSL 5 and 6 where the Nulla Reflux Brines occurs beneath the discharge complex. i.e. this is consistent with the presence of chemically different brines at these two sites. It appears, therefore that the simple picture of a reflux brine of uniform chemical composition in the Parilla Sand beneath the discharge complex is not correct. Further variability would be introduced by mixing with previous generations of brine and saline groundwaters in the aquifer.

The Nulla Diffusion-Influenced Groundwater (NDG) occurs at the top of the Parilla Sand beneath Nulla Spring Lake. This groundwater results from superimposition of salt from the present-day diffusional processes on the previous generations of saline water within the aquifer.

DISCUSSION

Geological Evolution

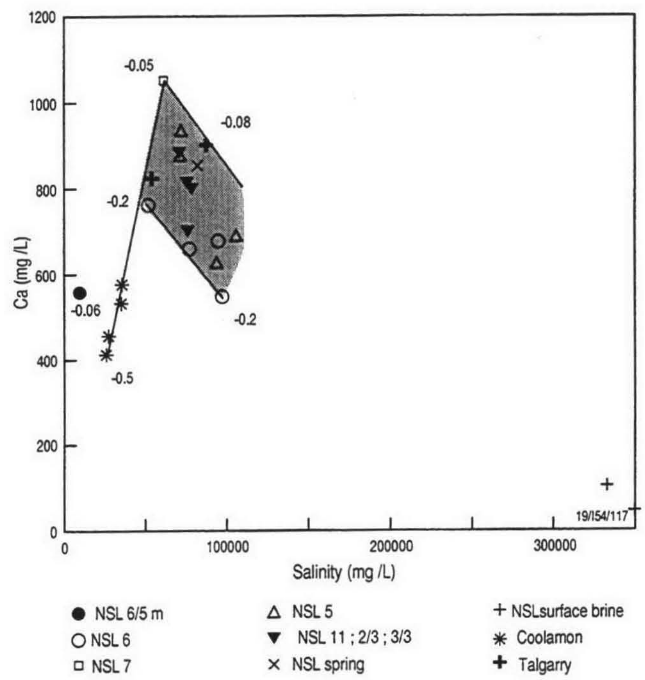


Figure 27. Graph of Ca against salinity for the Coolamon-Nulla Discharge Complex Talgarry groundwaters and surface waters. The numbers on the graph are saturation indices with respect to gypsum. An indication of the changes expected from evaporation of the Coolamon waters to gypsum saturation and beyond is obtained from the position on the graph of two of the almost saturated samples (Talgarry 2 and NSL 7). Most of the brines are mixtures.

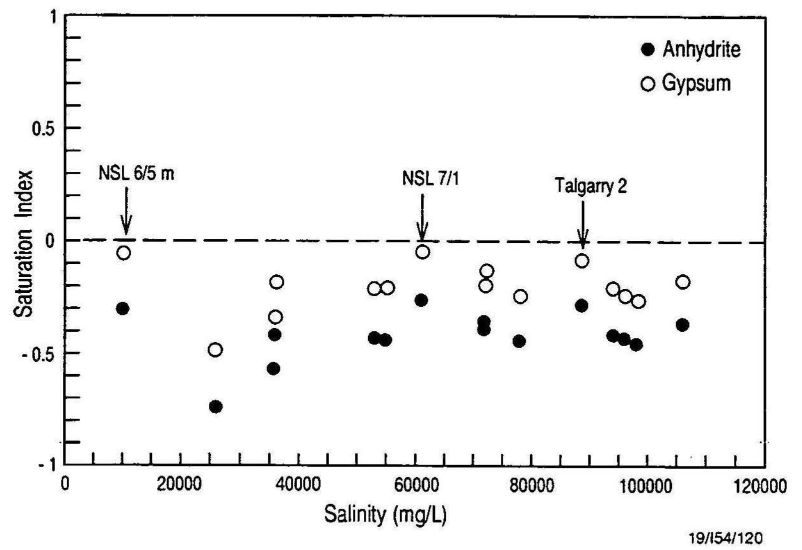


Figure 28. Saturation indicies with respect to gypsum and anhydrite of the Coolamon-Nulla Discharge Complex-Talgarry groundwaters. Only three samples are close to saturation. Two of them, (NSL 7/1 and NSL 6/5m) occur in or near the gypsiferous lacustrine clays of the discharge complex, but the other (Talgarry 2) has no obvious nearby source of gypsum.

Lake Bungunnia and the Blanchetown Clay

Bowler (1980) used magnetic reversal stratigraphy to establish that the oldest Blanchetown Clay was more than 2.4 Ma old and that the youngest sediments were less than 0.7 Ma old. At Nulla Spring Lake, two thermoluminescence dates obtained from just below the upper deflated surface of the unit were 840 ± 252 Ka and 800 ± 240 Ka. Other samples were saturated. The Blanchetown Clay is believed to have been accumulating within Lake Bungunnia throughout its 2 million year duration from the Late Pliocene. Zhisheng *et al.* (1986) interpret the onset of aeolian and saline gypsiferous deposits characteristic of aridity to follow soon after the Bruhnes-Matuyama boundary, about 500 Ka ago. Stephenson (1986) and Brown and Stephenson (1991) have demonstrated that in some lakes in the Western Murray Basin, there has been continuous deposition from Blanchetown Clay to modern lake deposits, even though Lake Bungunnia sedimentation along the northwestern margin has fluctuated and been interrupted by changes of lake level.

Conditions for the initiation of Nulla Discharge Complex

Nulla Discharge Complex, and associated discharge sites to the northwest, Warwick, New Bluff, etc, overlie a general depression in the upper surface of the Parilla Sand (15 to 20 m AHD) (Figure **29**). This coincides with the thicker Parilla sequence of the Bunnerungee Trough (Figure **30**) and a nearby area of unconfined Parilla Sand to the northeast of Nulla Discharge Complex which is a local area of recharge. From Scotia Lakes south, there is a discontinuous meandering string of depressions in the upper Parilla surface, suggesting a probable former drainage system that extended southwards to Lake Victoria. To the northeast of Nulla Discharge Complex the Parilla surface is higher (40m AHD) creating a locally steeper slope of this upper surface. Palaeostrandlines of the Parilla Sand (Figure **31**) are indicated by TM imagery, existing topographic expression, and structural contours of the top of the Parilla Sand. These suggest that the northern part of Nulla Discharge Complex is coincident with a Parilla strandline oriented west-northwest to east-southeast (Figure **3**).

With the demise of Lake Bungunnia, dewatering from the Parilla Sand would have been initiated where the Parilla was exposed at or near the surface, in conjunction with steeper hydraulic gradients within the aquifer. Additional to these factors, the Parilla Sand could be expected to change sorting characteristics and hence a reduction in permeability towards the south and southwest. Parilla thickness is strongly controlled by underlying pre-Tertiary structure to the north of the Nulla Discharge Complex, whereas to the southwest, where the Central Western Depocentre was active during its deposition (Figure **30**), Parilla Sand is thicker, laterally more homogeneous and lower in permeability, Consequently, the additional concurrence of a decreasing permeability gradient with the strandline feature and upper surface slope, collectively would have strongly localized surface discharge of Parilla waters in the north of the Nulla Discharge Complex.

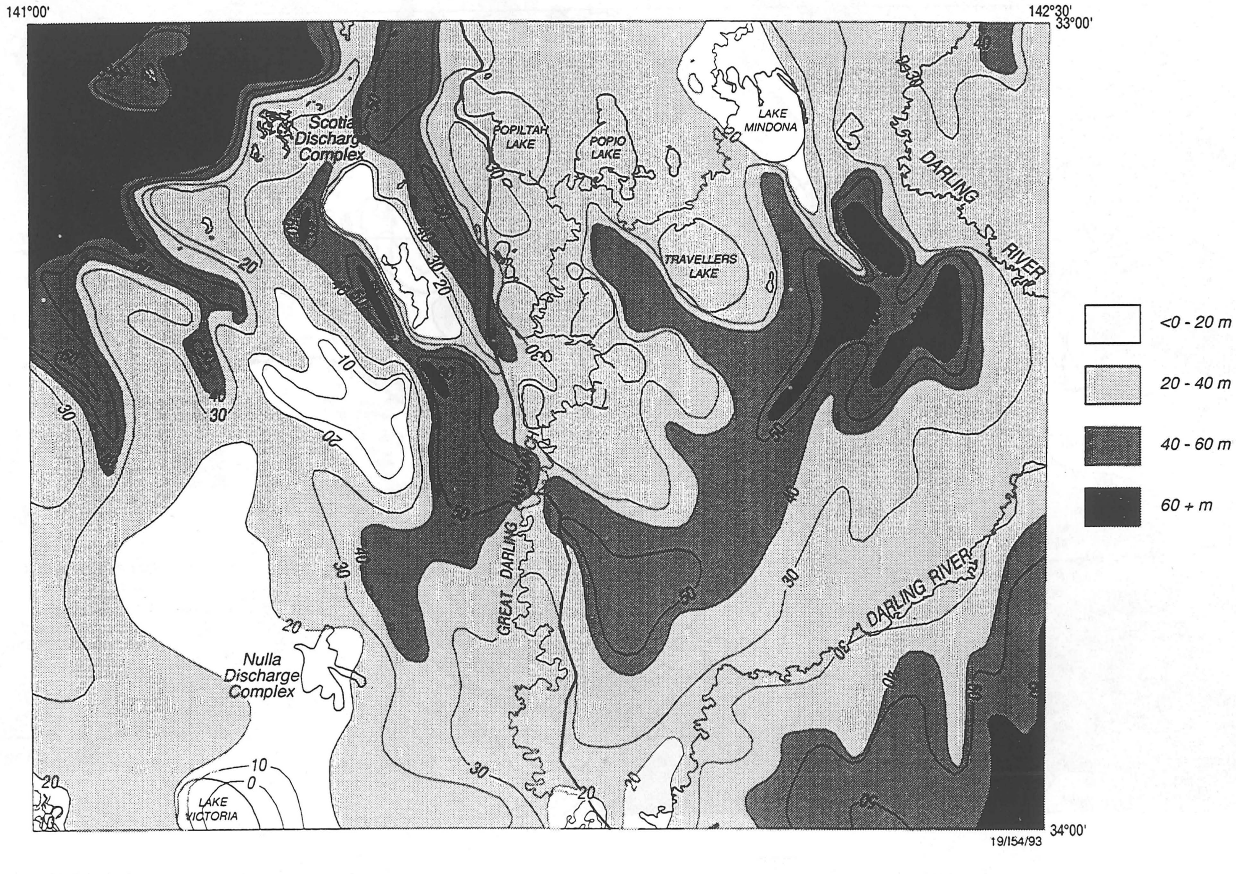


Figure 29. The upper surface of the Parilla Sand. Structure contours are in metres AHD (from Brodie, 1992).

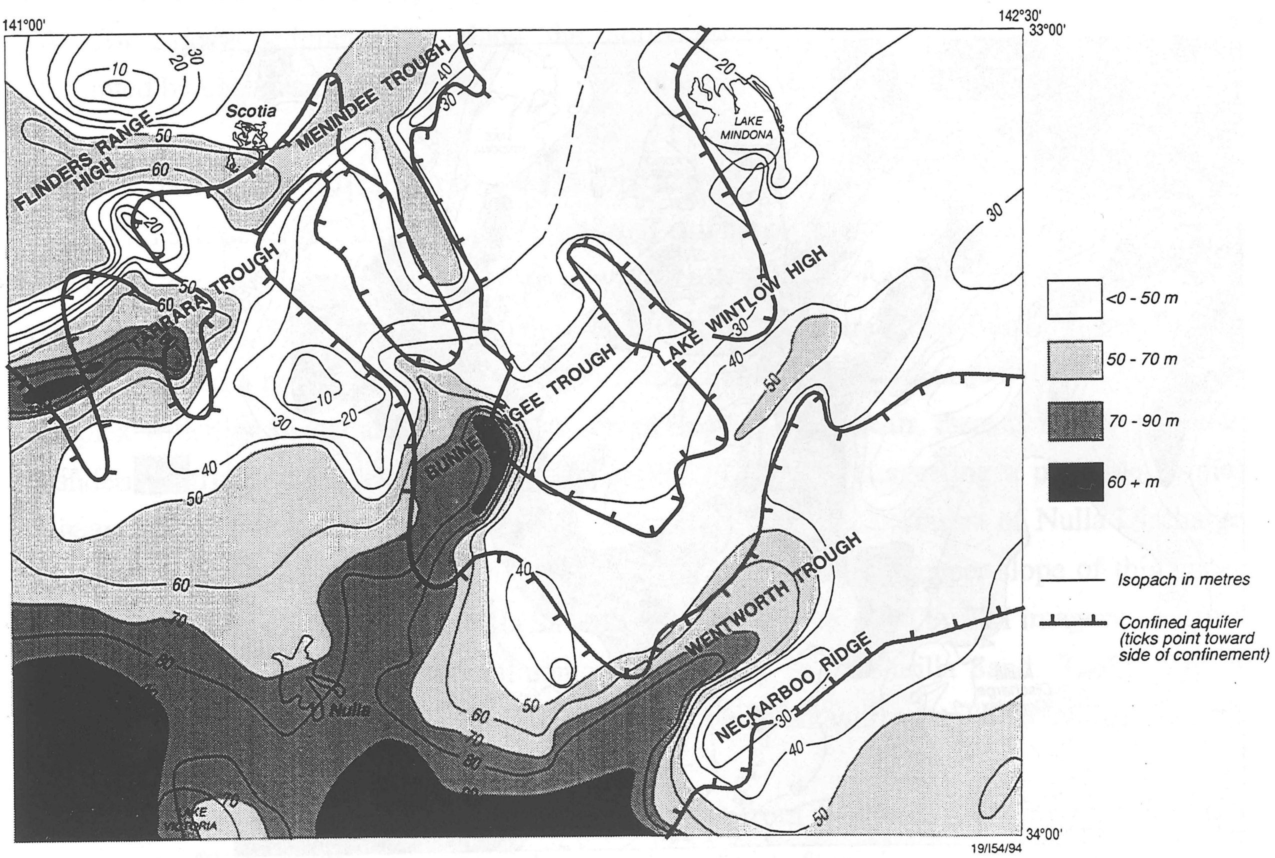


Figure 30. Thickness of Parilla Sand and Bookpurnong Beds on the Anabranch 1:250 000 Sheet area. The extent of Parilla Sand confined by Blanchetown Clay indicates the extent of Lake Bungunnia.

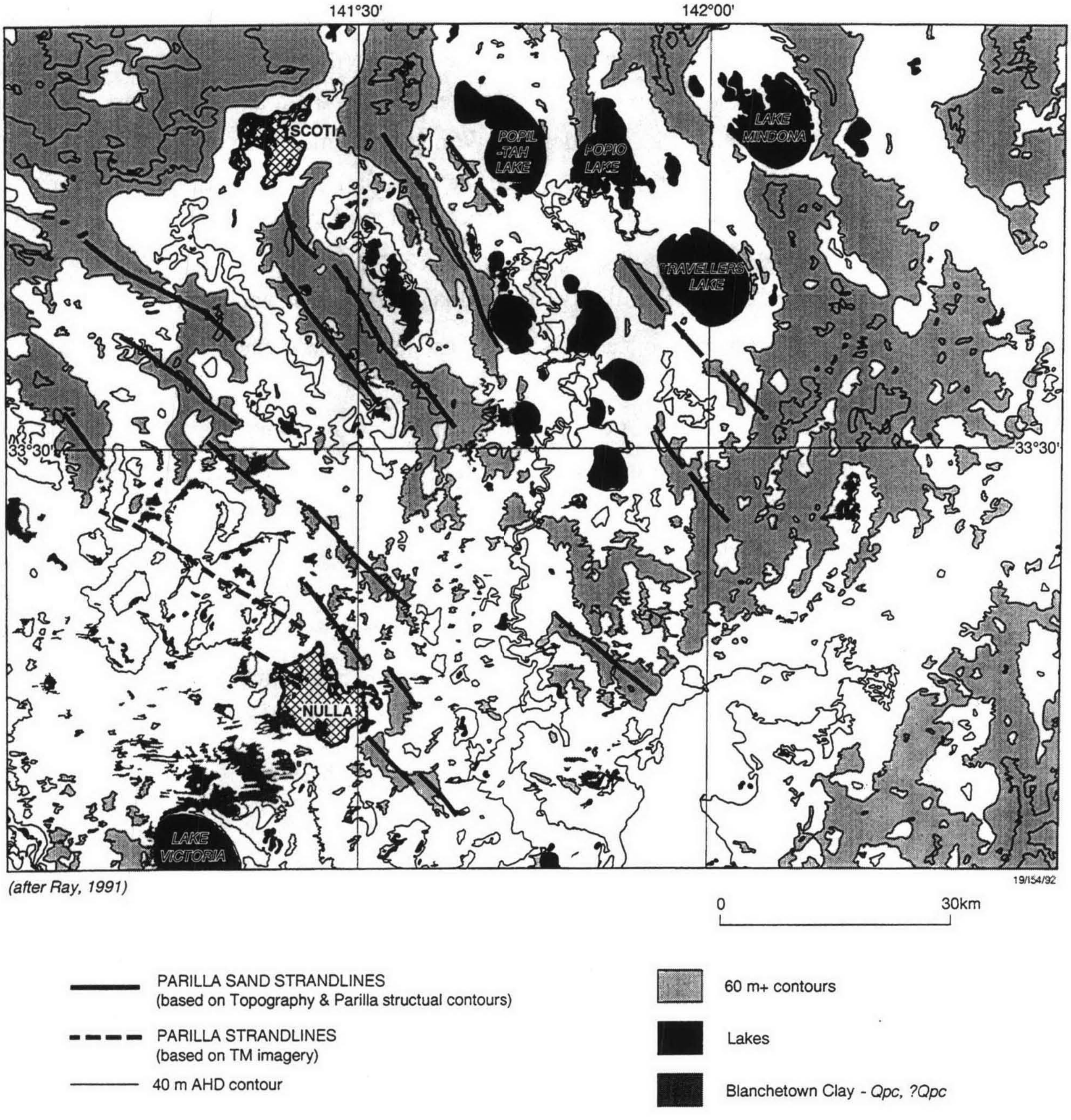


Figure 31. Topography and distribution of Blanchetown Clay on the Anabranch 1:250 000 Sheet area.

Nulla Discharge Complex and the Chronology of the Yamba Sequence

Preliminary thermoluminescence dating of the Yamba Formation is available and chronological control is based on 10 dates with 30% error margins. This dating program has focussed on the deflation events manifested in the lunette stratigraphy. Lacustrine deposits in the complex are thin and largely incomplete.

The A_1 deflation phase commenced in the early to middle Pleistocene, some time before ca. 260 Ka ago. The main Woorinen sand mobilization was over a protracted period.

The Woorinen Formation reflects arid to semi-arid climates since 500 Ka ago (Zhisheng *et al.*, 1986) and Wasson (pers. comm., 1992) considers the Woorinen Formation to be older than 250 Ka. Significant accumulation of Woorinen dunes occurred at Nulla Discharge Complex at about 250 Ka ago. This aeolian period continued and overlapped with the early part of the B_1 deflation phase which, as presently defined, extends from ca. 170 to ca. 23 Ka BP.

The C_1 deflation which created the present Nulla Spring Lake appears to have been initiated in the mid-Holocene at about 6 Ka BP with the last significant deflation in this episode at 1 Ka BP.

Palaeoclimates in the last 150 Ka can be inferred from a continuous record of ∂D and $\partial^{18}O$ values in the Vostok ice cores (Lorius, 1985; Jouzel *et al.*, 1987). Figure **32** shows the wet interglacials and arid glacial patterns in this period and an additional extrapolation of climate for the Murray Basin in the period 500 to 150 Ka BP.

Evolution of Nulla Discharge Complex

The evolutionary history of the Nulla Discharge Complex is summarized in Figure **33**, and as discussed in the chronology of the Yamba deposits, this history is documented in these periods.

Early to mid Pleistocene before 260 Ka

<u>A_1 deflation phase</u>

The deflation of exposed Parilla dunes of a Parilla strandline in the northern part of the playa commences with increasing aridity. A large dunefield develops east of area with initial and widespread accumulation of Parilla-derived sand.

Groundwater discharge from the strandline develops a playa on Blanchetown Clay and deflation of the Blanchetown Clay commences. Mixed sand and clay-pellet lunettes develops on the eastern margin (A_1).

Lakes persist intermittently at this strandline discharge site through to the present

Gypsiferous playa sediments accumulate at about 28m AHD.

Mid to late Pleistocene ca. 250 Ka

The main Woorinen sand mobilization commences and longitudinal dunes develop, migrating across area and dry playa. During intermittent climatic fluctuations and resultant higher watertable, playa deflation is reactivated and the longitudinal dunes are lost from the

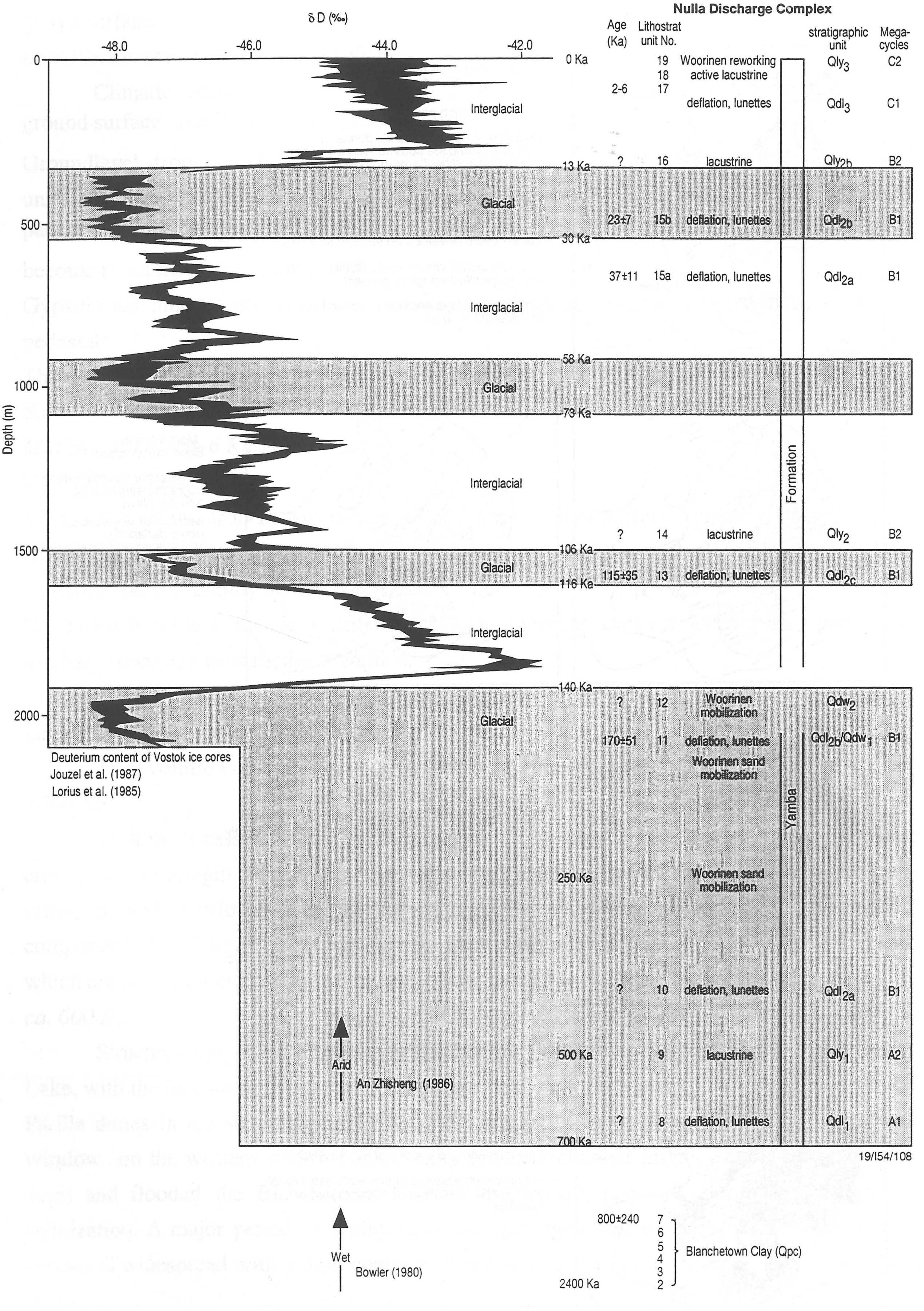


Figure 32. Wet interglacials and arid glacial patterns during the last 150 Ka and an additional extrapolation of climate for the Murray Basin in the period 500 to 150 Ka BP.

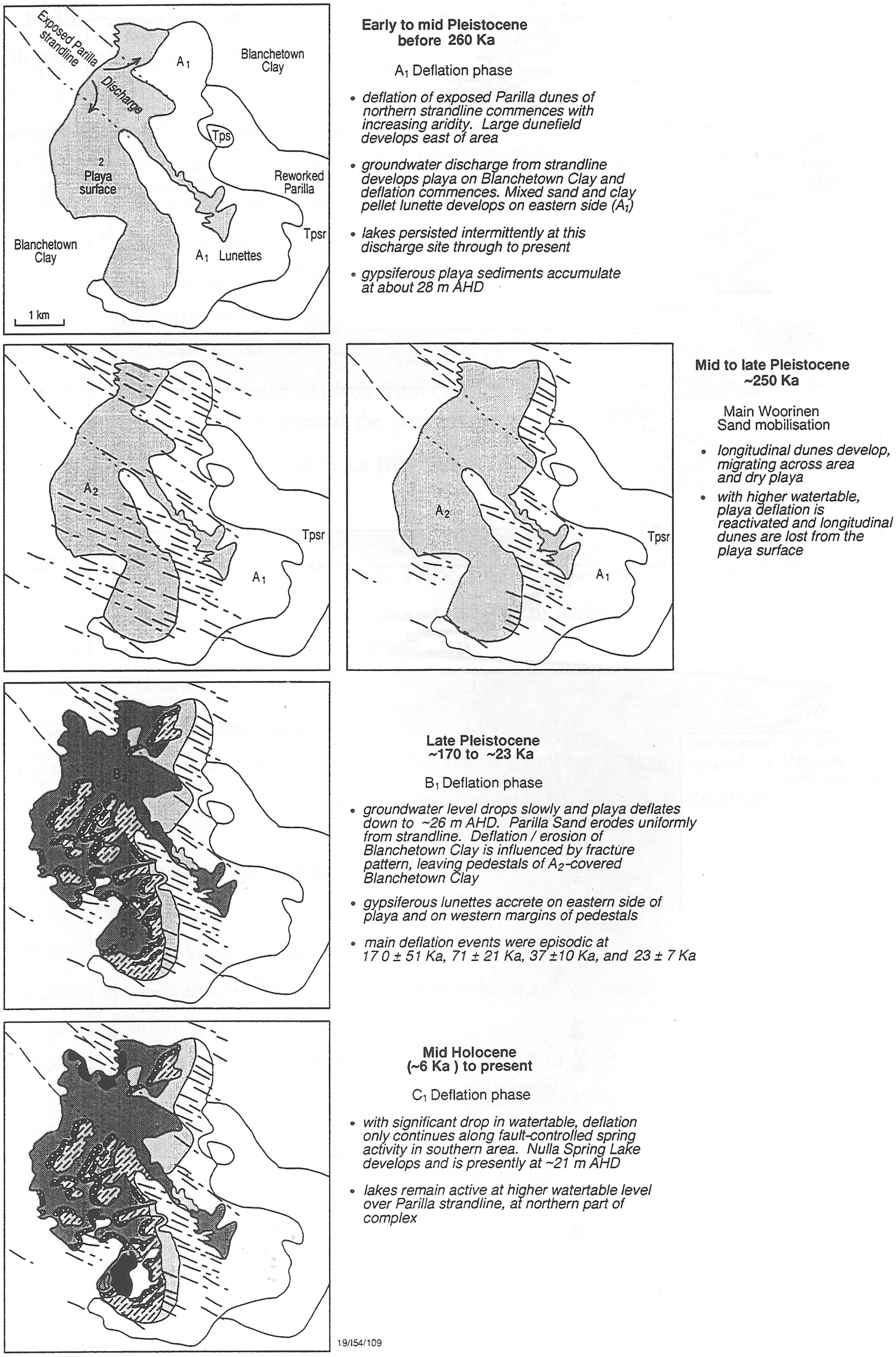


Figure 33. Evolutionary history of the Nulla Discharge Complex.

playa surface.

Late Pleistocene ca. 170 to ca. 23 Ka

Climatic conditions are suitable for a higher watertable with capillary zone reaching the ground surface. The B_1 Deflation phase is initiated.

Groundlevel drops slowly and playa deflates down to ca. 26m AHD. Parilla Sand erodes uniformly from strandline. Deflation / erosion of Blanchetown Clay is influenced by the fracture pattern in the Blanchetown Clay and remnant pedestals of A_2-covered Blanchetown Clay become prominent on this lower surface.

Gypsiferous lunettes accrete on eastern side of playa and on the western margins of the pedestals.

The main deflation events were episodic at 170 ± 51 Ka, 71 ± 21 Ka, 37 ±10 Ka, and 23 ± 7 Ka.

Mid Holocene (ca. 6 Ka) to present

C_1 deflation phase

With a significant drop in watertable and/or a sealed playa surface, deflation only continues along fracture or fault-controlled spring activity in the southern area. Nulla Spring Lake develops and is presently at ca. 21 m AHD.

Where the watertable always remained high lakes remained active at the northern part of the discharge complex over Parilla strandline.

Lithostratigraphic Evolution of Nulla Spring Lake

The evolution of Nulla Spring lake is outlined in Figure **34**.

>700 Ka

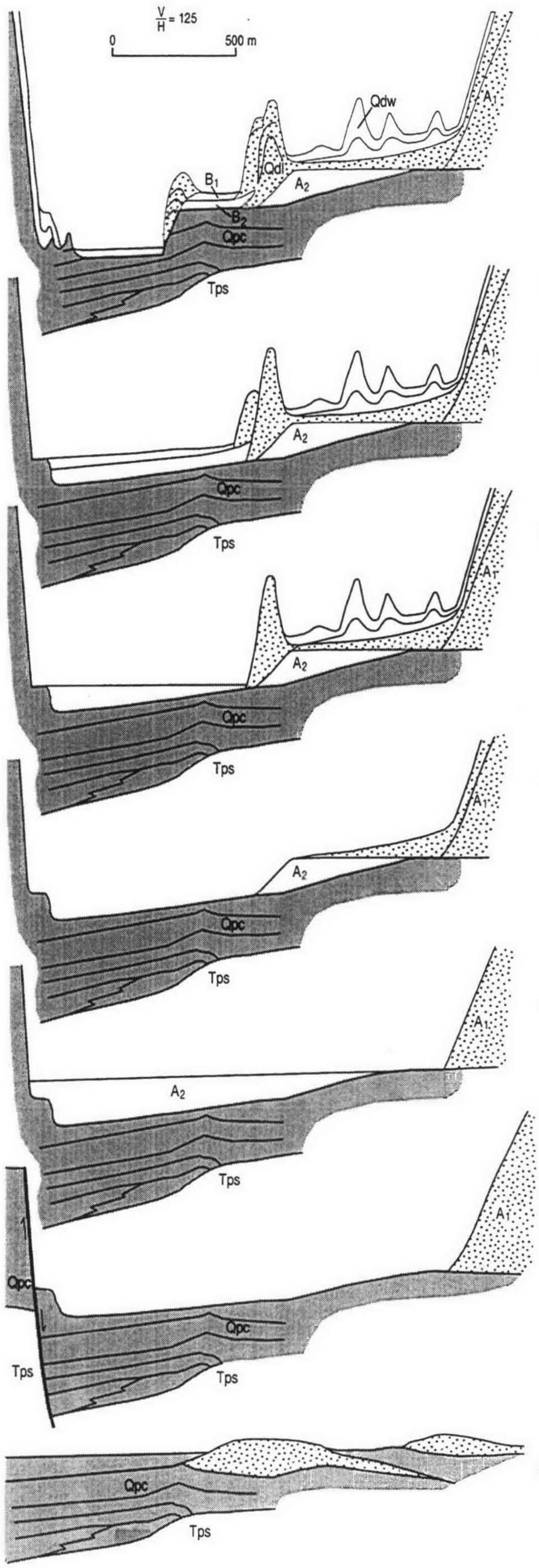
With the recession of Lake Bungunnia, and dropping of lake level below Parilla dune crests, the lake margin became increasingly complex and marginal areas became isolated, slowly salinized, and developed into playas where gypsum became an increasingly significant component of the lake sediments. Deflation of these playas produced gypsiferous pelletal sands which are now predominant in the upper Blanchetown Clay at Nulla Discharge Complex.

ca. 600 Ka

Structural movement probably recurred at this time on the western side of Nulla Spring Lake, with the lake area downthrown to the east. In the northern part of the complex, saturated Parilla dunes in the strandline across the northern sector, as well as this probable structural window on the western side of Nulla Spring Lake, discharged groundwater from the Parilla Sand and flooded the Blanchetown surface, maintaining playa development with gradual salinization. A major period of aridity develops and significant deflation of the Blanchetown surface is widespread with a high complex of dunes and lunettes along the eastern side of this playa.

ca. 500 Ka

Lacustrine deposits with predominant gypsiferous sediment accumulated(A_2 lacustrine



0 - 6 Ka

- *at least three deflation events incise depression on western side of B terrace*
- *gypcrete hardpan distribution within B terrace influences incision. Separate small lake develops beyond western extent of gypcrete occurrence and Nulla Spring Lake*
- *very thin accumulation of gypsiferous saline lacustrine deposits*

~13 Ka

- *second aeolian - lacustrine accumulation across B terrace*

40 - 23 Ka

- *last deflation events of the B megacycle add gypsiferous lunettes to B lunette complex*
- *landform stabilizes for long period and gypcrete hardpan develops below playa surface*

115 - 70 Ka

- *major deflation events with lunettes accumulating on eroded edge of A2 terrace*
- *additional Woorinen remobilization*
- *lacustrine accumulation over playa surface*

300 - 140 Ka

- *major Woorinen deflation and dune mobilization*
- *deflation of A2 surface and some Blanchetown Clay*
- *low relief and blanketing accumulation on pre-existing A1 dunes*

~500 Ka

- *A2 lacustrine event, deposits of unknown thickness*

~600 Ka

- *structural movement on west side of Nulla Spring Lake, upthrown to west*
- *saturated Parilla dunes in strandline across northern sector of complex, as well as this probable structural window allow discharge from Parilla, flooding Blanchetown surface, and allowing playa development*
- *major A1 deflation dunes develop*

>700 Ka

- *Lake Bungunnia recedes with local salinization of remnant isolated lakes*
- *gypsiferous lacustrine and pelletal lunette sediments comprise uppermost Blanchetown Clay*

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Figure 34. Lithostratigraphic evolution of Nulla Spring Lake.

event). The extent of this accumulation is unknown but presumed extensive.

300 - 140 Ka

Aridity became significantly prolonged and regional deflation and mobilisation initiated Woorinen dune development. Dunes developed across the playa but with a subsequent climatic change and rising watertable, deflation of the playa was reactivated and the Woorinen dunes were erased from the playa. Low relief blanketing Woorinen sand covered the pre-existing lunette dune field on the eastern side.

115 - 70 Ka

Saline conditions on the playa accumulated gypsum. A major deflation period relocated these gypsiferous sediments as lunettes on the eastern eroded edge of the A_2 terrace. The playa level was lowered by 2 metres in this period. During intermittent periods of much lower water table, Woorinen dunes were remobilized and accumulated as intermittent deposits within the lunette sequence.

A thin pelleted-gypsiferous lacustrine deposit accumulated.

40 - 23 Ka

Another arid period but with relatively high groundwater table reactivates deflation of the playa surface and another phase of lunette accretion commences, generally along the same shoreline. This landform stabilizes and meteoric dissolution of gypsiferous lunettes allows gypcrete development at the watertable surface. The shallow gypcrete layer helps reduce further deflation of this surface.

ca. 13 Ka

A change to wetter climatic patterns allows subsequent lacustrine material to be stabilized with only minor aeolian winnowing of some surface gypsum. This forms another capping on the B_1 lunettes.

0 - 6 Ka

With the gradual nett accumulation of lacustrine sediment, groundwater discharge was reduced by this selfsealing process. Only at Nulla Spring Lake, where continued subtle differential movement was occurring could groundwater escape along these structural conduits as springs. Playa conditions here continued intermittently and at least three deflation events lowered this playa to four metres below the B playa level. The existing hard gypcrete surface resisted the deflation in patches but significant deflation occurred further west and a satellite lake developed adjacent to the spring-fed area (Nulla Spring Lake). Nett accretion of gypsiferous clay is minor (<1 metre) in the lake, compared to the drop in level from the B surface.

Hydrodynamics

The existence of linear salinity-depth profiles beneath Nulla Spring Lake is consistent with salt entering the underlying aquifer by diffusion through the underlying clays, as predicted by theoretical models.

The brine in the Parilla Sand aquifer underlying Nulla Spring Lake is not a product of the present-day hydraulic regime in the lake. Most likely, brine reflux occurred elsewhere in the discharge complex, where the underlying Blanchetown Clay sequence was thin or absent. Several episodes of brine reflux probably occurred when the climate was sufficiently wet for the lakes to cover most of the discharge complex but dry enough for brines to form.

Figure **15** shows one of several possible sets of groundwater flow directions for the Parilla Sand brine which can be drawn on the basis of the limited data. The flow pattern is probably a result of the superimposition of the effects of the current hydrodynamic regime in Nulla Spring Lake on brines which formed in lakes further north in the discharge complex. Nonetheless, the flow pattern has several elements similar to those predicted for a lake where advective reflux of brine is occurring. These elements are: (1) lateral and upwards movement of water from the upper part of the aquifer into the lake; (2) outwards lateral flow of brine along the base of the aquifer into the surrounding regional groundwater; (3) indications of a circulation pattern within the brine pool which facilitates the entrainment of brine in the shallow regional groundwater which discharges into the lake.

Although there are measurable hydraulic gradients associated with the brine in the Parilla Sand beneath the discharge complex, the flow rates resulting from these gradients are comparable the rate at which salt would move by diffusion (Andrew Tucker, pers. comm.). Also, the linear decrease in salinity with depth in the Parilla Sand at NSL 6 is consistent with upwards diffusion of salt from the brines to the lower-salinity shallow groundwaters. In the present hydrodynamic phase of the discharge complex the rate of movement of the brine or its salt is very slow and either advection of diffusion may be rate determining.

CONCLUSIONS

- Nulla Discharge Complex is a broad shallow deflation depression that lies within Blanchetown Clay except at its northern extremity where Parilla Sand dunes may be unconfined. Lakes are present within the complex only at this northern margin adjacent to probable Parilla Sand exposure, and in the south, Nulla Spring Lake.
- Nulla Discharge Complex began to develop with the final recession of Lake Bungunnia, and evolved through the Pleistocene and Holocene. Three morphostratigraphic cycles are differentiated. The A cycle (oldest) is recognised in the easternmost and highest lunettes which are considered to be 500-700ka. The B cycle produced the widespread playa surface of the discharge complex and adjoining eastern lunettes. It commenced during the Woorinen sand mobilisation, and spanned a period of ~250 to ?13 ka. The Holocene C cycle is recognized in the Nulla Spring Lake depression and adjoining lunette deposits which date from 6 to 2ka.
- Nulla Spring Lake is totally enclosed by Blanchetown Clay, an aquitard whose hydraulic conductivity is probably $\leq 1 \times 10^{-4}$ m/day. The aquitard is about 3 metres thick below the lake
- Groundwater enters the lake by numerous small springs via fracture-based flow paths from the underlying and adjacent Parilla Sand. Higher permeability carbonate-rich horizons in the Blanchetown Clay also interconnect various fracture paths.
- Lateral heads in the lacustrine clay within the discharge complex show a "drawdown" effect of groundwater evaporation from Nulla Spring Lake which extends for a distance of less than 300m from the lake margin. This indicates that the lake plays only a minor role in "protecting" the surrounding area from rising saline groundwater levels.
- The discharge of groundwater through the Blanchetown Clay into the Nulla Spring Lake is not sufficiently rapid to cause any observable "drawdown" of the groundwater heads at the top of the underlying Parilla Sand aquifer.
- Vertical gradients from the top of the Parilla Sand to the lacustrine clays in the discharge complex are directed upwards. The upwards gradients increase in magnitude towards Nulla

Spring Lake where they correspond to an artesian head of at least 1m above the lake surface.

- This high artesian head in the lake is related to the low permeability of the surrounding Blanchetown Clay sediments, which allows the development of large vertical heads without large volumes of groundwater being discharged into the lake. In this sense, Nulla Spring Lake has been unable to respond normally to increases in the Parilla Sand groundwater levels and as such, is a hydrological relict or "fossil" feature.
- Lateral gradients and vertical gradients in the Parilla Sand beneath the discharge complex indicate a complex circulation pattern involving inwards flow from Coolamon and Talgarry at shallow depths, and slightly outwards flow near the base of the aquifer. Lateral flow rates are in the range 0.7 x 10^{-4} to 13 x 10^{-4} m/day, vertical gradients are in the range <1 to 32 m/km.
- In Nulla Spring Lake, salinity against depth profiles (for areas of the lacustrine clays directly influenced by the emerging springs) have a pronounced salinity minimum near the top of the Blanchetown Clay and beneath the thin overlying lacustrine sequence (C_2). Away from the springs, the salinity decreases linearly with depth, which is consistent with downwards diffusion of salt through the impermeable lacustrine sequences into the top of the Parilla Sand aquifer.
- For sites where more detailed information is available, the data is better described by different diffusion profiles in the C_2 and Blanchetown Clay sequences. The two salinity imprints result from the superimposition of the hydrodynamic regime associated with the deposition of the C_2 sequence on that associated with the preceding deflation event.
- In the gypsum hardpan on older lake terraces to the the east of Nulla Spring Lake, the salinity profile is consistent with a net upwards-movement of water from the underlying Parilla Sand through the clay. The higher salinity water produced near the top of the capillary zone does not reflux against this gradient and salt formed at the surface is continuously removed by deflation.
- In the Parilla Sand aquifer beneath the southern area of the Nulla Discharge Complex there is a brine which is unlikely to be a product of current conditions in the lake, and could be the southern fringe of a large brine pond centered to the north. It is speculated that there is a northernmost area of the discharge complex where the Blanchetown Clay is missing and that brine reflux occurred in this area.
- Nulla Spring Lake brines are forming predominantly from a combination of two sources: (1) incoming Parilla Sand groundwater which emerges as springs either directly in the brine-forming areas or in the nearby marginal areas, from where it can flow to the sites of brine formation as surface streams; and (2) saline water which forms at the margins as rainfall/runoff dissolves salt efflorescences formed by capillary evaporation of Parilla Sand groundwater, and then moves by surface flow to the topographically lower areas.
- A geochemical differentiation process operates at the lake margins as seasonal conditions

change from regular washing/flooding during wet conditions to aeolian deflation of the surface sediment during extended periods of dryness. This favours the incorporation of magnesium sulphate, sodium sulphate and sodium chloride minerals into the rainfall/dissolution brines.

- Three geochemically different brines have been identified in the lower Parilla Sand aquifer; a Talgarry reflux brine, and two Nulla reflux brines. Although these brines occur near the base of the Parilla Sand, they have some geochemical signatures which are best explained as originating in the underlying Bookpurnong Beds.
- The present-day hydrodynamics of Nulla Spring Lake involve diffusion through the underlying clays, as predicted by theoretical models. In contrast, the underlying brine in the Parilla Sand aquifer probably results from several episodes of brine reflux which occurred when the climate was sufficiently wet for the lakes to cover most of the discharge complex, but dry enough for brines to form.
- The flow pattern of brines in the Parilla Sand is probably a result of the superimposition of the effects of the current hydrodynamic regime in Nulla Spring Lake on the palaeo-brines Nonetheless, the flow pattern has several features similar to those predicted for a lake where advective reflux of brine is occurring. These features are: (1) lateral and upwards movement of water from the upper part of the aquifer into the lake; (2) outwards lateral flow of brine along the base of the aquifer into the surrounding regional groundwater; (3) indications of a circulation pattern within the brine pool which facilitates the entrainment of brine in the shallow regional groundwater that subsequently discharges into the lake.

APPENDIX

Methods

Drilling Techniques and Sediment Storage

The following procedures were designed to sample lacustrine clays and sandy clays in playas and salt lakes. The drilling equipment was readily dismantled and transported between sites with vehicle access to the lake shore, and then either hand carried or ferried by hovercraft. Lake surface conditions which ranged from dry, through muddy, to surface water less than 0.5 m deep have been successfully drilled. Existing techniques would have to be modified to cope with greater water depths.

The drilling method employed is a variation of the penetrometer technique in which steel tubes (5 cm diameter; 0.5 m long) are hammered into the sediments to 0.4 m depth using a drop hammer. The hammer is operated by a motorised hoist and mounted on an aluminium tripod derrick. The tripod accommodates lifting tools in 3m sections.

In lakes where surface conditions were wet or muddy a 20 cm diameter PVC tube was used to protect the drill-hole from influx of surface water. A steel tube was then hammered into the lake sediments, the uppermost wet, unconsolidated sediment removed, and the core tube extracted. A lightweight portable auger was then used to enlarge the core hole to 10 cm diameter The next steel tube attached to a drill rod was inserted and hammered down a further 0.4 m. This alternating hammering and augering procedure was repeated to the limits of the ability of the equipment to retrieve the cores, or until changes in the nature of the sediment made the technique inappropriate.

Holes up to 11 m and typically 6 m deep were cored by this method. The degree of success is a function of the clay content of the sediments. In the Murray Basin, the Blanchetown Clay and younger lacustrine clays were readily cored, and there was some success with the clayey sands which occur at the transition from the top of the Parilla Sand to the lacustrine clays. Water-saturated aeolian-derived sands, such as those which occur interspersed with lacustrine sediments above the Blanchetown in the Mourquong evaporation basin, rapidly refilled the core-hole. These sand layers could not be cored unless they were less than about 0.5m thick.

Cores were sealed and transported in the steel core tubes. Prolonged storage in these tubes caused significant damage to the sediments and later cores were dealt with by the following procedures. Clay sediments were extruded either on site or in the laboratory using a specially designed hydraulic extruder. Cores containing sandy sediments could not be extruded and the tubes were cut lengthwise. The cores were extruded onto lengthwise-cut 8 cm PVC tubing and split. Each section was then sealed into an evacuated plastic sleeve to provide medium-term preservation against dehydration.

Porewater Extraction and Analyses

To minimise the possibility of contamination by 'float', sediment samples for porewater analyses were obtained from the bottom 0.1m of each 0.5m tube. Salinity was determined by optical refractometry using a portion of small volume of porewater (typically ≤ 1 ml total) extracted from the sediments using a Manheim press or, occasionally for sandy sediments, by centrifugation.

Surface water samples were filtered through a disposable 0.45μ filter, and an aliquot (usually 10 ml) pipetted into a separate container for determination of alkalinity. A portion of the sample for determination of cations was preserved by addition of a small quantity of concentrated nitric acid.

Analyses of cations was by ICP and analysis of anions was by ion chromatography.

Installation of Piezometers

Piezometers used for water sampling and the determination of standing water levels in shallow holes were 8 cm - diameter PVC tubing, slotted over 1m in length. Where possible, the piezometers were cemented into place. This type of piezometer was effective when installed in the clayey sands at the Parilla Sand - Blanchetown Clay transition zone, or in the shallow, bedded clays and sands typical of the Yamba Formation at Mourquong.

Piezometer Measurements

The standing water level and then a two or three point salinity profile down the water column in the piezometer was usually measured and averaged if necessary. The density of the water in the piezometers was calculated from the salinity assuming a temperature of 20°C.

Response of piezometers set in the Blanchetown Clay can be very slow so a measurements at different times were made for each piezometer till the water level reached a constant or fluctuating level. This situation ,which is an indication that the water in the piezometer had reached its equilibrium level, had not been reached for some piezometers at the time of preparation of this report (see below).

Calculation of Hydraulic Heads

Lateral and vertical hydraulic heads and gradients were determined separately using the concepts (Figure 35) developed by Lusczynski (1961) and Lusczynski and Swarenski (1966). This concept implies that lateral gradients can be determined from freshwater heads in piezometers screened to the same depth relative to a datum, and that vertical gradients can be obtained from environmental water heads measured along a vertical.

Application of the Lusczynski and Swarenski (1966) concepts to the hydrodynamics of groundwater discharge complexes has been described by Macumber (1991). The lateral heads are freshwater heads, calculated from the equation:

$$\rho_f H_{if} = \rho_i H_{ip} - Z_i(\rho_i - \rho_f)$$

The vertical heads are environmental water heads, calculated from the equation:

$$\rho_f H_{in} = \rho_i H_{ip} - Z_i(\rho_i - \rho_a) - Z_r(\rho_a - \rho_f)$$

H_{if} is the freshwater head at the point 'i' in groundwater of variable density

H_{ip} is the pointwater head at 'i'

Z_i is the elevation of 'i', with measurements being positive upwards

ρ_i is the density of water at point 'i'

ρ_f is the density of fresh water

ρ_a is the average density of water between elevations Z_r and 'i'

H_{in} is the environmental water head at 'i'

Z_r is the elevation of the reference point from which the average density of water to 'i' is determined, and above which the water is fresh

In the calculations of H_{in}, for Scotia Z_r was taken as equal to the top of the zone of saturation. Because this measurement was not known at most locations, the SWL in the topmost piezometer was used instead. The value for the freshwater density was taken as 1.00 g/cm^3. Macumber (1991) has pointed out that, for the Lake Tyrrell brines, a change of the freshwater density from 1.03 to 1.00 g/cm^3 made less than 4 cm difference to the value of H_{in}.

The lateral and vertical velocities were calculated from the equations:

$$v_x = - K_x [\partial H_{if}/\partial x]$$
$$v_z = - Kz[\partial H_{in}/\partial z]$$

For this investigation, the horizontal gradients were determined from piezometers set as close as possible to a constant elevation, and the vertical gradients from nests of piezometers at different depths at the same location. Under field conditions, installation of the piezometers to constant depth was not always feasible and the freshwater head at the designated depth was approximated by interpolation or extrapolation assuming a linear change in pressure with depth between piezometers. Interpolations and extrapolations were made using measurements of the actual groundwater pressure (P_{actual}) in piezometer nests. Care was taken to use piezometers in the same aquifer (e.g. the Parilla Sand) or the same aquitard (e.g. the Blanchetown Clay) for determine the vertical pressure gradients for use in interpolation. These interpolated or extrapolated pressures were then converted to freshwater heads. For locations where only one piezometer had been installed, it was assumed that $P_{actual} = 0$ at a depth equal to the SWL in the piezometer, and the interpolations and extrapolations made on this basis.

Logging

Core preparation

Core was stored under dark coldroom conditions in air-evacuated sealed plastic tubes. Where possible core was extruded from the steel core tubes using a hydraulic press, into PVC half tubes and cut with a putty knife. If the sediment was predominantly sand, or the core old and the internal steel partly corroded, the core tube and sediment was cut with a power jigsaw and the core manually transferred to PVC half tubes. The homogenised cut surface was cleaned by a variety of methods dependant on the sediment type, stiffness, induration, or desiccation; cutting or scraping with a putty knife, or brushing with a soft bristle brush.

Documentation

Where possible core was photographed immediately in colour. Methodical observation of the sediment, observation of sedimentary structures, and measurement of clastic sediment particle size used a Wild M5 field stereomicroscope with calibrated graticule. Particle-size assessment usually involved disaggregation of a small fraction in a watch glass using distilled water and dilute HCl where necessary. The mineralogical composition was assessed visually at this stage. Where clay composition or an unidentified component required identification, X-ray diffraction samples were taken. Colour assessment was always made of wet surfaces, by comparison with colour tiles of the Rock Colour Chart, and recorded using the Munsell system.

Information was recorded on graphic log and notations as described by Radke (1992). Porosity type and qualitative abundance was assessed visually.

The scale of logging was generally at 1:2 Scotia fully cored holes.

In the deeper, 60 metre stratigraphic holes, coring was only undertaken in the uppermost 5 metres, and cuttings taken in each subsequent metre to the bottom of the hole. These holes were logged at 1:200 scale.

Logging Reduction

With the detailed logging at 1:2, it was necessary to reduce these logs for generalisations to be made on the lithostratigraphy. The condensing process was based on a 25 cm interval in which all information was reduced to one statement per category and recorded at 1:33. Lithologies in this reduction were recorded in histogram format, and the reliability of each increment qualified by a core-recovery assessment.

Core Sampling

Where minerals could not be identified, XRD samples were taken, either as a segment of core for clays and fine-grained carbonates, or individual particles hand-picked in the case of trace components.

Petrographic samples were taken of characteristic sediments, or unusual structures.

Imagery interpretation

TM interpretation

A regional assessment of geomorphological features, specifically other discharge zones, their lunette fields, and Parilla strandlines, as well as any structural elements, were interpreted from Thematic Mapper Imagery. Several manipulations of the rectified raw data were undertaken by Phil Bierwirth to remove instrument and atmospheric artefacts from the data. Principal components analysis and unmixing techniques were applied to attempt to delineate the geomorphological, structural, as well as mineral components of the discharge complex sediments.

These techniques were applied in conjunction with and using recent geological mapping of the Anabranch sheet by Rae (unpublished) as a control.

Airphoto Interpretation

Photogeological interpretation of the Scotia Discharge Complex was based on detailed air photo interpretation. Imagery used was black and white 1:27 200 scale photography flown on the 29/9/89 by the Australian Survey and Land Information Group. Morphostratigraphic interpretation and elucidation of processes at Nulla and Scotia were aided by detailed contouring of topography, based on spot height data by AUSLIG.

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