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THE SCOTIA GROUNDWATER DISCHARGE COMPLEX, MURRAY BASIN, SE AUSTRALIA

BY

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RECORD 1995/43

AGSO
AUSTRALIAN
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ORGANISATION

RECORD 1995/43

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

The Scotia Groundwater Discharge Complex, Murray Basin, SE Australia

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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Minister for Resources and Energy: Senator the Hon. W.R. Parer
Secretary: Paul Barratt

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Neil Williams

ISSN: 1039-0073
ISBN: 0 642 24964 4

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ACKNOWLEDGMENTS

This study has developed from the inception by Campbell Brown before his untimely death. It was with the framework of his physiographic descriptions, initial logging and sampling that the direction and tenor of this work was established.

The following colleagues are thanked for their assistance and contribution to the study. Bill Keeley persevered with cutting the cores throughout the logging process. X-ray diffraction analyses were provided by Julie Kamprad. The proposed stratigraphic models have developed out of fruitful discussions with Bob Wasson and Ross Brodie.

Field investigations were carried out with perseverance, skill and enthusiasm by the members of the AGSO (EGG) Technical Resources Group. Special thanks are due to Peter Ryan and Bill Keeley for their contribution to developing the special drilling techniques necessary for salt lakes and to John Spring for fieldwork and detailed checks of the survey data and laboratory analyses. Others who have a major contribution to the fieldwork include Tim Ransley, Mark Glover and Mark Le Dieu. Members of the ESU Group at AGSO manufactured special equipment for the project at short notice and collaborated in its field testing. Diagrams for this record were prepared to highly professional standards by the members of the cartography section, AGSO.

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1. SUMMARY

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. Vertically-moving brines which reach the regional aquifer 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 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.

Application of this concept to natural systems such as Lake Tyrrell requires some knowledge of the geological evolution as well as the present-day lithostratigraphy of the area. A preliminary examination of the situation at Lake Tyrrell suggests that present-day conditions are not obviously conducive to brine reflux. 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 Scotia, in the Murray Mallee, N.S.W has been carried out. This discharge complex is sited beyond the northern limit of the Blanchetown Clay and is therefore likely to have a high sand content and high permeability which, as indicated by the numerical models, should favour advective reflux. Both 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. The stratigraphic and hydrodynamic history of groundwater discharge complex is accessible through information on the lithostratigraphy of the lacustrine sediments, and from the distribution and geochemistry of saline waters retained from previous hydrodynamic regimes.

The discharge complex occurs in a setting of uncleared Mallee woodland. It is about $30km^2$ in area and lies within undulating terrain covered in a Woorinen Formation (Pleistocene) dune field. It has a characteristic suite of landforms - salt lakes, salinas (playas), transverse dunes, gypsum plains and terraces. Within the discharge complex there are two north-south trending chains of interconnected active lakes which almost surround a central island of older lacustrine lake deposits and lunettes.

The Scotia Discharge Complex is located on the southeastern faulted margin of the Flinders Range - Scopes Range High. The complex lies on the upthrown side and within a flexural irregularity of the southwest-northeast trending Hamley Fault, where it overlies a partly eroded domed or anticlinal structure. Movement on the Hamley fault appears to have upwarped the Parilla Sand which regionally dips gently to the south. With the Parilla Sand upwarped to the surface this site has been an active discharge area since the uplift and subsequent erosional exposure.

The regional stratigraphic framework in the Scotia area shows that the upper Renmark Group aquifer is overlain and sealed by Geera Clay Equivalent which is generally covered by Parilla Sand. In the discharge complex, the Yamba Formation covers a deflation surface on both Geera Clay and Parilla Sand. Dunes of the Woorinen Formation overlie the Parilla Sand regionally, but are not present over the discharge complex.

The Geera Clay Equivalent forms a mud and clay aquitard which is about 10m thick in the centre of the complex and thins northward off structure to approximately 5m. Block-faulted control with a general northward plunge in the Geera - Parilla contact is most likely, producing a gently northward-plunging anticline or subtle dome structure. This structure is variably weathered, and the areas of thicker weathering may correspond to the extent of an initial discharge area (the Proto-lake), which is believed to have been in the centre of the complex.

The Parilla Sand surface expression in the discharge complex is mainly as indurated cross-stratified sets of limonitic sandstone which outcrops as a prominent dark brown-limonitic sandstone terrace. Subsurface distribution of Parilla Sand within the discharge complex at the northern margin ranges from <1m to 7m thick and thickens slightly to 11 metres off the discharge complex to the north. In the presumed area of the Proto-lake where the Parilla Sand was partly removed by deflation, the remaining Parilla Sand is deeper and overlain by a relatively thick (approx. 2.5m) lacustrine sequence.

The Yamba Formation in this complex is a heterogeneous but sand-dominant unit, comprising lacustrine sand, interbedded sand and clay, and clay deposits, and associated sand and/or clay-pellet lunette deposits. The extent of the lacustrine component is largely untested but believed to coincide with the broadest extent of the lake complex, with the lunette component extending eastwards from the lakes by 4 to 6.5 km.

A lithostratigraphic model of the evolution of the Scotia Discharge Complex invokes continued episodic activity through time of the Hamley Fault and associated structures. The anticlinal or domed structure continued developing during and after Parilla deposition, and subsequent groundwater discharge from the Parilla would have commenced directly over the crest. With the ensuing deflation, this central area of Geera Clay weathered preferentially. A regional structure running northwest-southeast across Scotia was downfaulted on its northern side, leaving the central area to develop a deeper weathering profile in the Geera Clay. This structural discontinuity probably increased the upflow of groundwater producing in this area the deepest erosion or deflation of the Geera Clay and the thickest lacustrine sequence in the complex.

The lithostratigraphic model implies that the Proto-Scotia Lake was at a higher elevation, with remnants of its deflation/lacustrine events still preserved as the highest topographic features within the central complex. The Parilla Sand was subsequently eroded/deflated away from a broader (wider concentric area) to lower levels. Subsequent lacustrine deposits indicate deeper deflation to the northwest. This trend is also implied from the surface topography of the outer lakes at present and indicates a pattern of deflationary evolution of the complex.

If provenance is considered for a deflation playa developing on a rising domal structure, then the sediment sources could only be local except for aeolian sand transported in the Woorinen dunefield system. Other sand and clay could only be derived from the Geera Clay and Parilla Sand locally. No fluvial sources could be anticipated. The repeated erosion and reburial of the Geera core would contribute little clay and even less with accumulation of the Yamba sequence. This model is compatible with an observed increasing predominance of sands in the lacustrine deposits.

The hydrodynamic setting of the Scotia Discharge Complex is one of lateral gradients towards the complex from the adjacent regional Parilla Sand aquifer to the north, and upwards vertical gradients from the underlying Renmark Group aquifer across the intervening Geera Clay aquitard to the Yamba Formation/Parilla Sand deposits. The magnitude of the lateral gradients is strongly dependent on location within the complex, indicating a variety of local hydrodynamic conditions.

There is a wide range of hydrodynamic regimes in the active lakes, resulting mainly from differences in the magnitude and anisotropy of sediment permeability, the presence of paleo-drainage channels which provide local rainfall-enhanced groundwater input, and from minor topographic variations within the lake systems which favour surface runoff of rainwater from some lakes and accumulation of surface brines in others. In this context, two of the more important hydrodynamic controls are: (1) the thickness and distribution of the lacustrine clay and sand layers in the Yamba/Parilla Sand deposits; and (2) whether the uppermost layer, which can host near-surface brines, is sand or clay.

The sand or clay nature of the surface layer is a major control on the way in which surface and near-surface brines form in the lakes In lakes with moderately thick (1 to 2m) surface clay layers the surficial clays dry by capillary evaporation and crack during the dry (summer) season. Efflorescences form on the clay surface and are partly removed by deflation, but those formed in the cracks persist till they are redissolved by winter rainfall and returned to the clay porewater as the cracks close. In some of the sand-surfaced (1 to 2m thick) lakes during the wet season brines saturate the topmost sand layer and are present as shallow surface ponds. The brines form from efflorescences deposited at the lake margins which are partly redissolved by rainfall and washed into topographically lower areas of the lake during spring/early summer. The brines in the sand layer persist through summer because the capillary zone associated with sands is narrow, which restricts evaporation. These surficial sands provide a continuous source of brine and probably a vertically downwards hydraulic gradient for downwards diffusion or advection of salt.

Beneath the uppermost sand or clay layers in the active lakes, three different hydrodynamic situations are evident. (1) Major salinity and other geochemical discontinuities occur at the sand-clay boundaries, which is consistent with a situation in which lateral movement of groundwater through sand layers overshadows advection and/or diffusion processes through, or from, the adjacent clay layers. This situation occurs in some of the clay-surfaced lakes where the discontinuity is evident as a salinity minimum immediately beneath the clay. (2) Minor discontinuities but a pronounced change in the slope of the salinity - depth profile occur at the sand-clay boundaries, which indicates that salt movement between adjacent sand-clay layers is significant but its influence is limited to near the interfaces. (3) There is a relatively smooth curve of decreasing salinity with depth, which suggests that vertically downwards advective or diffusive processes are dominant. In one lake this situation occurs over a sedimentary section about 4 to 5m in thickness and extends through several sand-clay alternations. In this section the overall ratio of the sand to clay is slightly more than 2:1, which is indicative of a relatively high vertical permeability and therefore consistent with the theoretical predictions.

Hydrodynamic processes at the margins of the discharge complex are influenced to a significant extent by the local topography. The more usual type of interaction occurs where the aeolian Woorinen Dunes and the reworked sands at the base of the dunes form a continuous and steep slope to a relatively narrow active lake margin. Under these circumstances the shallow groundwater at the lake margin, which is the source of most of the groundwater input to the lake, consists of regional Parilla Sand groundwater and a small overlying local rainfall-influenced lower-salinity lense. This lense is sourced by rainfall/runoff moving down the duneface. A different type of interaction occurs where the active lake is set some distance from the maximum (former) extent of the discharge complex. Under these circumstances the active lake margin may be separated from the Woorinen dunes by a wide gently-sloping area of Parilla Sand with a thin overlying layer of reworked Woorinen sand. This allows the development of an extensive low salinity lense. As a result, the source groundwater for the active lake is a mixture of rainfall recharge from this lense and a brine from a previous phase of lacustrine evolution.

The Yamba formation/Parilla Sand sediments of the Scotia Discharge Complex contain highly saline groundwaters which have been emplaced in at least two major phases. (1) Phase I, the earlier of the two phases, resulted in the formation over much of the discharge complex of a brine whose salinity (about 125,000 mg/L) is about three times that of the local regional groundwater (40,000 mg/L). (2) Phase II is a composite phase which extends from the end of Phase I up to and including the presently active hydrodynamic regimes. During this phase the Phase I paleo-brine was overprinted with groundwaters of higher or lower salinity. This Phase II overprinting is usually dominated by presently-active hydrodynamic regimes but at some locations the overprinting hydrodynamic regime has changed as the lake permeability has altered through ongoing deposition and reworking of the lake sediments.

The overprinting Phase II groundwaters range in salinity from about 60,000 to >250,000 mg/L. The lower-salinity waters are usually associated with the marginal sites and are combinations of regional groundwater and local rainfall recharge or Phase I brine and local rainfall recharge. The higher salinity Phase II waters are generally associated with mid-lake environments containing near-surface brines. Complex Phase II salinity patterns involving salinity minima occur at lateral flow-dominated sites. These sites are likely to have been subject to more than one type of hydrodynamic regime during Phase II.

There are three potential sources of water to the discharge complex - regional Parilla Sand groundwater, local rainfall, and groundwater from the underlying Renmark Group. Renmark Group groundwater can be eliminated as a major source on the basis of Cl-36 data.

The regional Parilla Sand groundwater and local rainfall undergo major chemical changes after they enter the discharge complex. These changes result from two main types of process: (1) intra-discharge complex processes such as dilution, evaporation, precipitation, water-sediment reactions and mixing; and (2) export processes which transfer groundwater and/or precipitated salts to the underlying aquitard and aquifers by diffusion and/or advection, or to the surrounding landscape by aeolian deflation. These processes have produced several different groundwater types which can be recognised on the basis of their Cl/Br ratios: (1) evaporated and diluted (by rainfall recharge) regional Parilla Sand groundwater (Cl/Br 330); (2) evaporated and diluted Phase I paleo-brine (Cl/Br 1020); and (3) groundwater brine formed by re-solution of evaporites such as NaCl, Na_2SO_4 and $MgSO_4$ salts in partly evaporated rainfall (Cl/Br > 4000). These groundwaters are the end-members of two and three-component mixtures and these mixtures are the main type of surface and groundwater in the discharge complex.

The major types of discharge complex groundwater and their mixtures all have Cl/Br ratios equal to or higher than that of the source water. i.e. residual low Cl/Br bitterns which should remain after halite precipitation from the regional groundwater have not been detected. This apparent imbalance could arise by: (1) incorporation of Br into the discharge complex sediments; (2) loss of bromide from the discharge complex by volatilisation (e.g. after conversion to bromoform by cyanobacteria or bromine radicals by UV-light); and/or (3) removal of Br from the discharge complex by selective aeolian deflation of Br-rich evaporites.

The latter process could occur at the lake margins as part of the annual summer aeolian deflation of evaporite-rich sediment. At other times evaporation from the top of the capillary zone and formation of surficial evaporites alternates with periods when rainfall redissolves the evaporites and they are transported in runoff from the lake margins to the topographically lower areas of the lake. In winter and spring the periods of evaporation are frequently interrupted by rainfall and, as a result, the earlier-formed salts in the evaporation sequence (gypsum to epsomite) would be selectively precipitated, redissolved and transported, and accumulate preferentially in the topographically lower parts of the lake. This would result in concentration of the residual salts, which would be rich in Br, in the porewaters of the uppermost sediments. As conditions become hotter and drier during summer, and the water table drops, the uppermost sediments would dry out and, with their Br-rich salts be deflated from the discharge complex.

Deflation of K salts could also occur by the above process, because they are predicted to be amongst the last to be precipitated. K concentrations within the discharge complex are invariably lower than predicted by geochemical modelling of the evaporation path of the regional groundwater. However, in view of the known ability of K to interact with sedimentary minerals, it is difficult to tell whether K is being lost by deflation or incorporated into the lacustrine clays.

The major ion composition (Ca, Na, Mg, SO_4) of the discharge complex surface and groundwaters has been strongly influenced by re-solution and transport of evaporites. As a result, the waters range in composition from an almost unaltered evaporated or diluted regional groundwater to a water consisting of local rainfall containing redissolved NaCl and $MgSO_4$ salts. Intermediate situations involve evaporated or rainfall-diluted regional groundwater to which salts have been added and/or precipitated.

Most groundwaters contain excess Mg and SO_4 over the predicted values (based on Cl concentrations), which is consistent with the re-solution of Mg-rich evaporation products such as epsomite ($MgSO_4.7H_2O$) and bloedite ($MgNa_2(SO_4)_2.4H_2O$). These Mg and SO_4-rich waters are concentrated in the topographically lower areas of the lakes, which points to a transport mechanism involving precipitation at the lake margins and dissolution and transport to the lower areas by local rainfall. Na concentrations can be lower or higher than predicted. The lower values could result from the precipitation of glauberite ($CaNa_2(SO_4)_2$) in response to the increased SO_4 concentrations induced by the dissolution of the Mg and SO_4-containing minerals. The higher values could result from dissolution of glauberite and bloedite. Limited spatial data indicate that higher Na concentrations are also concentrated in the central, topographically lower areas of the lake, although the trend is not well-defined.

The brines in the Yamba Formation/Parilla Sand sediments of the discharge complex have created a downwards salinity gradient through the Geera Clay aquitard to the underlying Renmark Group aquifer. The low permeability of the clay has meant that downward diffusion of salt is probably faster than upwards porous flow induced by the hydraulic gradient. This downwards-moving salt from the discharge zone has moved porewater salts from the underlying Geera Clay and then from the Yamba Formation/Parilla Sand into the Renmark Group. As a result, the salinity in the underlying Renmark Group aquifer has increased and the chemistry of the waters is that of a combination of Yamba Formation/Parilla Sand, Geera Clay and Renmark Group waters.

Correlation of the lithostratigraphic and hydrodynamic evolution of the discharge complex is possible to some extent. The first identifiable episode of brine formation (Phase I) is assumed to post-date the Proto-lake and coincide with a period when the lake had expanded to its maximum size. Springs and ironstone precipitation were active on the peripheral sandy margins, and discharge and evaporation in this large homogeneous system produced the first phase of lacustrine brine of uniform salinity across the complex.

Phase II groundwater activity spanned the three subsequent major phases of stratigraphic evolution. During these stratigraphic phases the larger peripheral lake contracted to its present size and deflated down to near the top of the Parilla at the margins. Deflation of the surrounding region continued and Woorinen dune systems developed over the Parilla Sand landscape. Parilla Sand partly deflated towards the lake periphery of the salina complex, lowering lake floor levels on the northern and (?)southern sides of the complex. Aeolian pelleted clay and lacustrine clay continued to be accumulate in the complex. Deflation again became active. Lunette deposits alternated with thin lacustrine clays. Collectively clay deposits accumulated. At any stage, the lake floor was either a clay or a sand. During these phases of stratigraphic evolution Phase II hydrodynamics was initially dominated by vertical flow, involving both downwards-moving recharge by local rainfall or surficial brines, and upwards-moving evaporation-driven flow. As clay layers accumulated there was a gradual change from vertical to a combination of vertical and lateral flow. The resultant spatially complex array of chemically different groundwaters from the Phase I and Phase II hydrodynamic regimes is preserved beneath some of the active lakes.

The attributes of the Scotia-type discharge complexes as disposal basins for saline groundwater are limited. The most favourable feature of this type of complex is the potential for advective reflux of the brines formed by evaporation. This advection would occur in the naturally-occurring advective sites, and in other sites of high vertical permeability where the increased downwards hydraulic head from the disposal water would change the dominant process from the naturally-occurring diffusion in the clay layers and lateral flow in the sands to overall downwards advection. However, the increased storage capacity for disposal water generated by these reflux processes would be limited because the underlying Parilla Sand sequence is unusually thin and it already contains natural brines. A major concern would be the potential for lateral flow of disposal water into the adjacent regional Parilla Sand aquifer. The regional hydraulic head about 1 km to the north would be equal to that in the discharge complex if an additional hydraulic head of up to 2m was produced by the disposal water. Because the surrounding aquifer is not hydraulically isolated from the complex, the disposal water could leak laterally relatively rapidly to the point where the disposal water-induced and regional hydraulic heads are equal.

The Scotia Discharge Complex differs considerably from the highly permeable "pure sand" environment envisaged by the advective reflux models. Firstly, the presence of the Geera Clay at shallow depths has modified the predominantly sandy environment provided by the Parilla Sand and Woorinen Formation sediment sources by restricting the thickness of the overlying Yamba Formation/Parilla Sand sequence and by providing a sediment source for clay layers in the predominantly sandy sediments. In the latter case the permeability is highly anisotropic and the much lower vertical permeability inhibits advective reflux to various degrees. Secondly, the mechanism by which the brines form at the surface of the active lakes at Scotia is different from the simple groundwater evaporation model. Because there are no active springs in the discharge complex, local rainfall is a significant component of the brines and it plays a major part in the transport and redistribution of salts within the active lakes.

Despite these differences, the Scotia investigation has provided some support for the theoretical contention that high permeability favours advective reflux. The presence of the Phase I brine throughout the discharge complex implies a early widespread brine reflux phase and the gradually increasing salinity with depth in one active lake suggests that vertically downwards brine movement occurs under sandy conditions.

2. GENERAL OBJECTIVES AND METHODOLOGY

2.1 General Objectives

This investigation of the Scotia Discharge Complex was undertaken as 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 developing lithostratigraphic criteria which will help predict the hydrodynamics of existing and potentially new basins on natural groundwater discharge sites.

2.2 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 Scotia Discharge Complex were known to have a high sand content and potentially high permeability. In contrast, Nulla Spring Lake within the Nulla Discharge Complex has a substrate of potentially low-permeability Blanchetown Clay.

2.3 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.

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

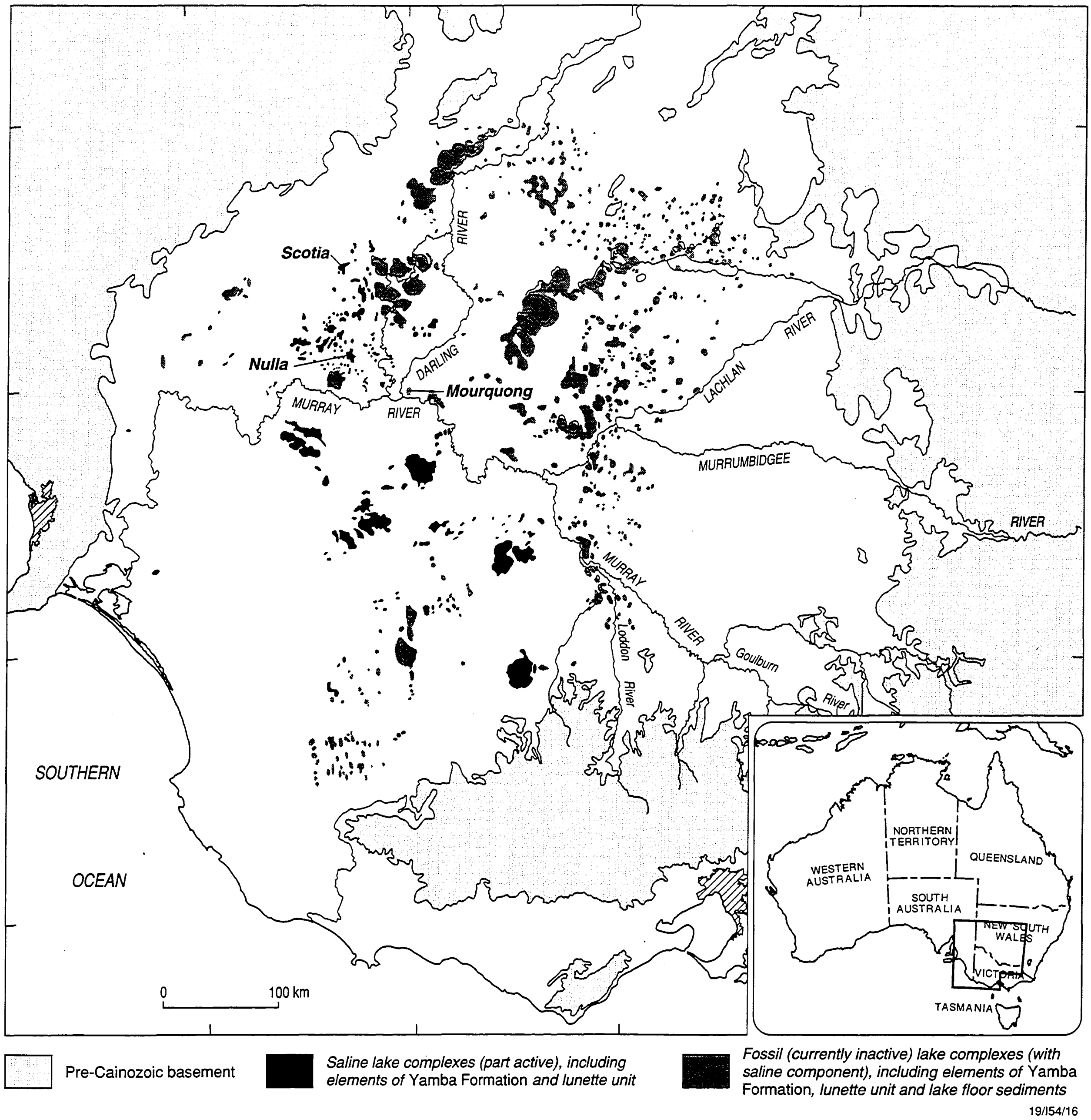


Fig. 1 Location of the Scotia Discharge Complex

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.

3. SCOTIA DISCHARGE COMPLEX

INTRODUCTION

Natural groundwater discharge complexes in the Murray Basin are commonly used for the disposal of saline groundwater from salt interception schemes (Hostetler and Radke, 1995). 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 (Wooding et al., 1996) 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. The hydraulic heads are currently directed upwards from the brine in the Parilla Sand aquifer to the lake (Macumber, 1991), 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 (J. M. Bowler; pers. comm.); 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 Scotia, in the Murray Mallee, N.S.W has been carried out. This discharge complex is sited beyond the northern limit of the Blanchetown Clay and is therefore likely to have a high sand content and high permeability which, as indicated by the numerical models, should favour advective reflux.

LOCATION and PHYSIOGRAPHIC SETTING

The Scotia Groundwater Discharge Complex is located in the Mallee region of western New South Wales (Figure **1**). This is a semi-arid region, with an annual rainfall of 270-320 mm. The region generally lacks surface drainage, except for the Murray River, the Darling River and its Anabranch; these three rivers flow through and define the boundaries of the region. Distinctive features of the Mallee region physiography include vegetated regional dunefields of Pleistocene age, with a relief of about 50 m, and groundwater-discharge complexes (Brown and Stephenson,1991). The term "mallee" refers to the characteristic natural vegetation of multi-stemmed eucalypts.

The Scotia Discharge Complex occurs in a setting of uncleared Mallee woodland. The complex covers about 30 km^2 and lies within undulating terrain covered in a Woorinen Formation (Pleistocene) dune field. Scotia is broadly similar to other groundwater discharge complexes (Macumber, 1980) in the region (Figure **1**). It has a characteristic suite of landforms - salinas (playas), transverse dunes, gypsum plains and terraces. The salinas within the groundwater discharge complexes are topographically low points in the landscape (Figure **2**) and at Scotia have a bed elevation of 31 m above sea level. Within the discharge complex there are two north-south trending chains of interconnected active lakes (Figure **3**) which almost surround a central island (here termed "Scotia Middle Island") of older lacustrine lake deposits and lunettes. There are subtle variations in topography (Figure **3**) between the active lakes in the chains.

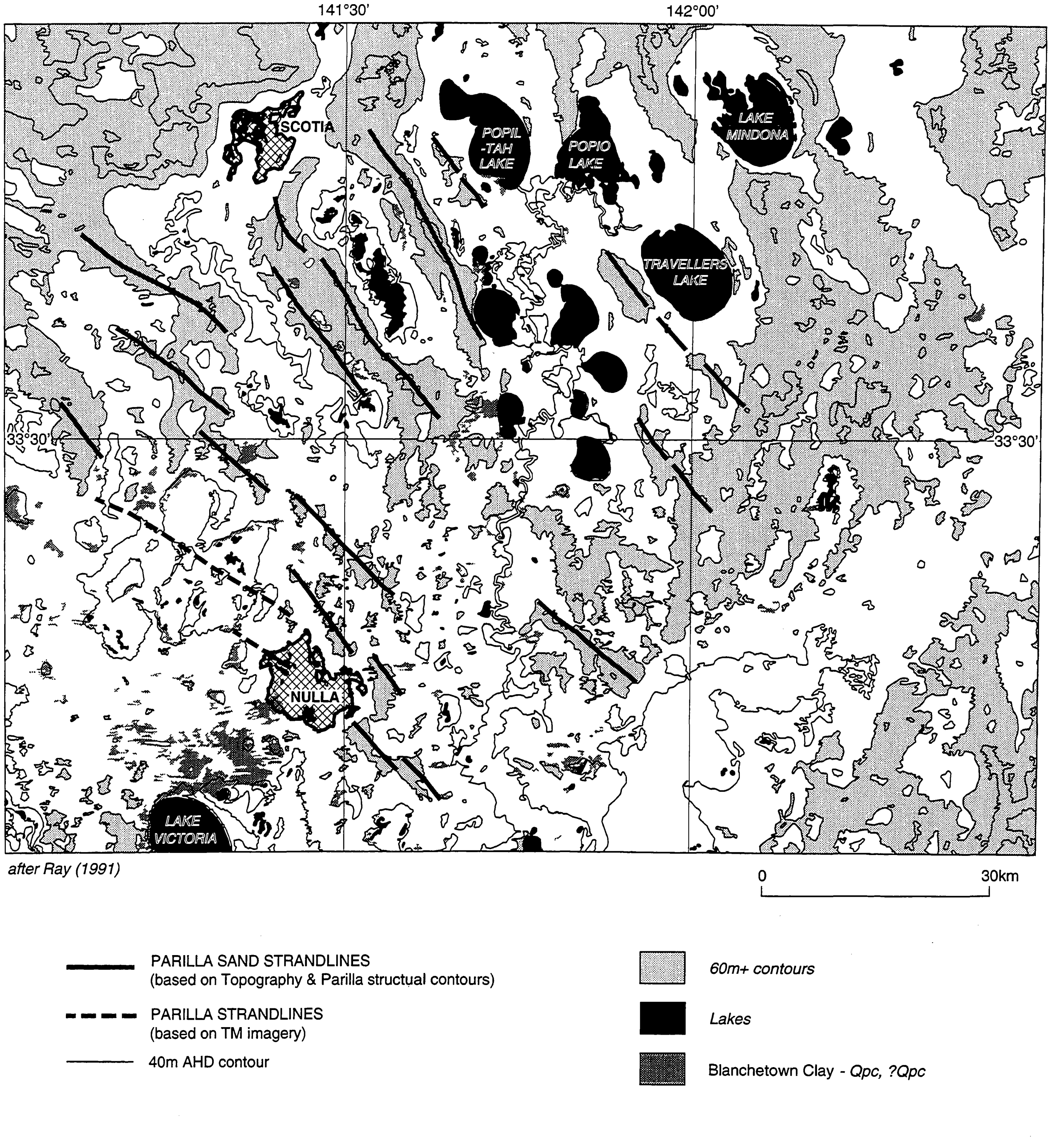


Fig 2 Relationship of Scotia Discharge Complex to former Parilla Sand strandlines

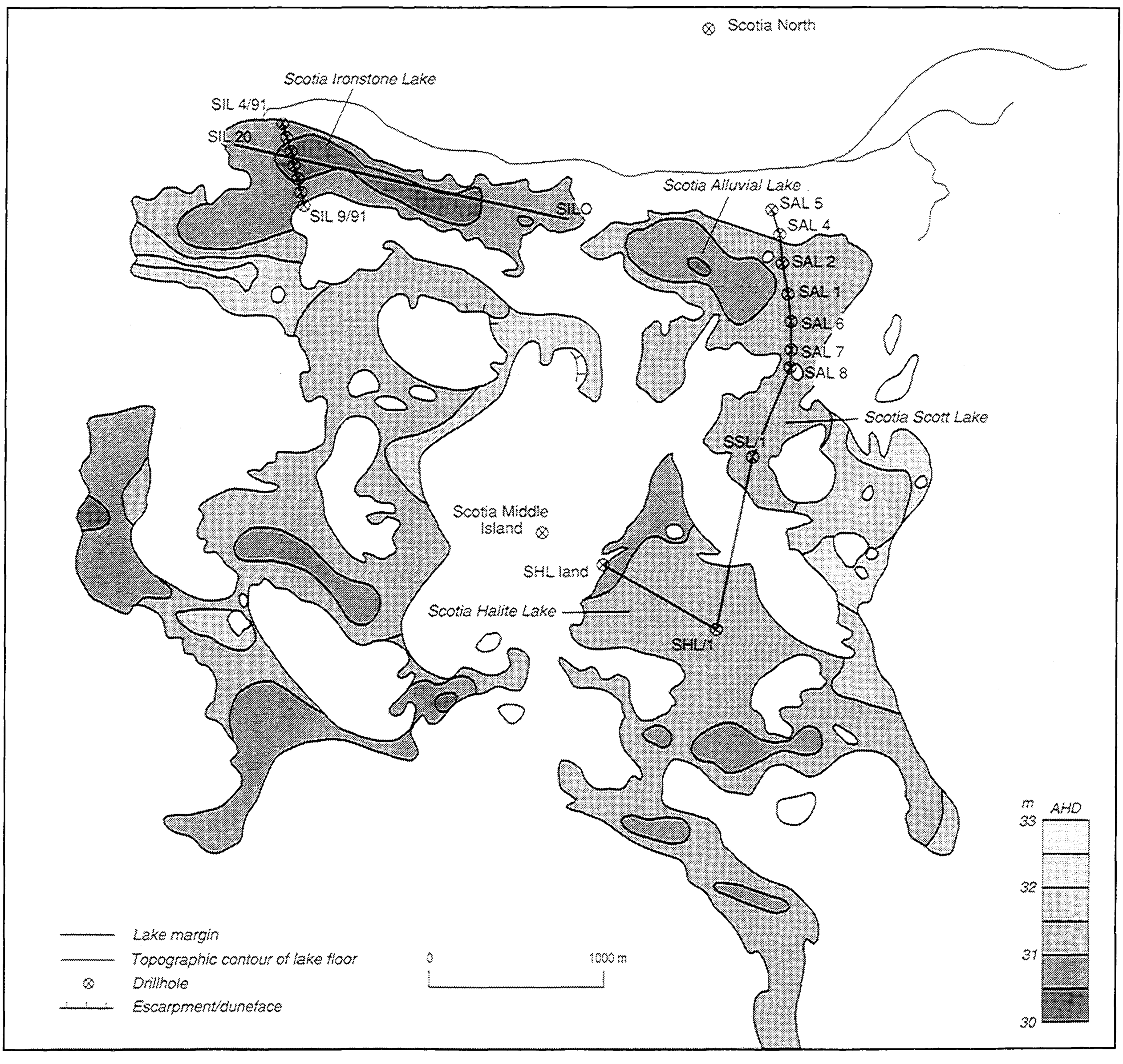


Fig. 3 Lake floor topography and location of transects.

METHODS

Drilling was undertaken in 1990 and 1991 along the transects shown in Figure **3**. 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 two 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. Shallow groundwater samples were obtained by hand augering to depths about 0.4 m below the water table.

The drill-hole and core-hole transects (Figure **3**) were designed to provide data both for the discharge complex and its adjacent regional setting to the north, and for individual, possibly hydrodynamically different active lakes along the transect. The north-south (N-S) transect connects the two deep holes at Scotia Middle Island (SMI) and Scotia North (SN) and includes the active lakes Scotia Halite Lake (SHL), Scotia Scott Lake (SSL) and Scotia Alluvial Lake (SAL). The west-south (W-S) transect includes the N-S section from SMI to SAL 1, which is close to the centre of the lake, and then diverts westwards to include sites in Scotia Ironstone Lake (SIL). Shallow groundwater samples were taken along two transects at SIL (Figure **4**).

The drillholes were cased as piezometers, and subsequently levelled relative to the Australian Height Datum (AHD), except for the SIL sites whose elevations are approximate.

Salinity and geochemistry was measured on porewater squeezed from the base of each core section. The sections were then split for lithostratigraphic examination. Groundwater samples from the deep drill-holes at Scotia North and Scotia Middle Island 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 are those developed by Lusczynski (1961) and Lusczynski and Swarenski (1966), as detailed in the Appendix.

Additional information on the methods is in the Appendix.

STRATIGRAPHY

3.1 Regional Structural and Stratigraphic setting

The Scotia Discharge Complex (Figure **5**) is located on the southeastern faulted margin of the Flinders Range - Scopes Range High. It overlies a domed or anticlinal structure which is eroded down to the Geera Clay Equivalent. The complex lies on the upthrown side and within a flexural irregularity of the southwest-northeast trending Hamley Fault (R.Brodie, pers. comm.,). This structure, a subtle dome or gently plunging anticline, attracted seismic

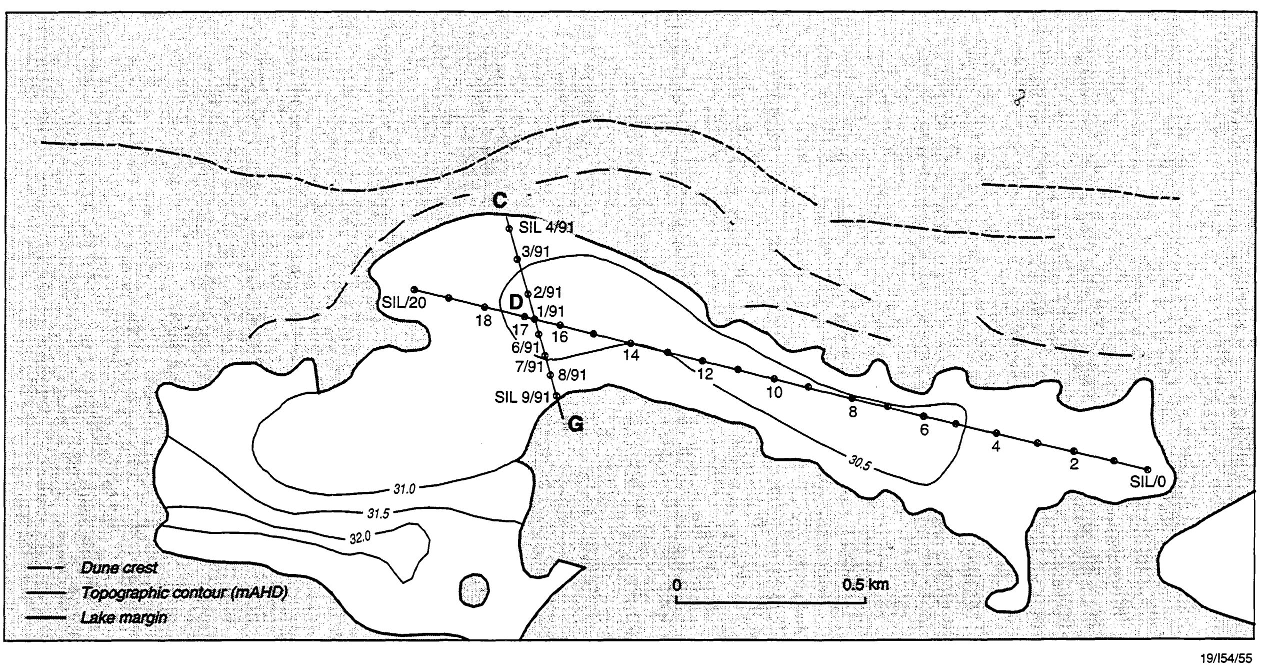


Fig. 4 Corehole (SIL 1/91 to 4/91) and shallow groundwater sampling sites (SIL 1/91 to 9/91 and SIL /0 to SIL/20) in Scotia Ironstone Lake.

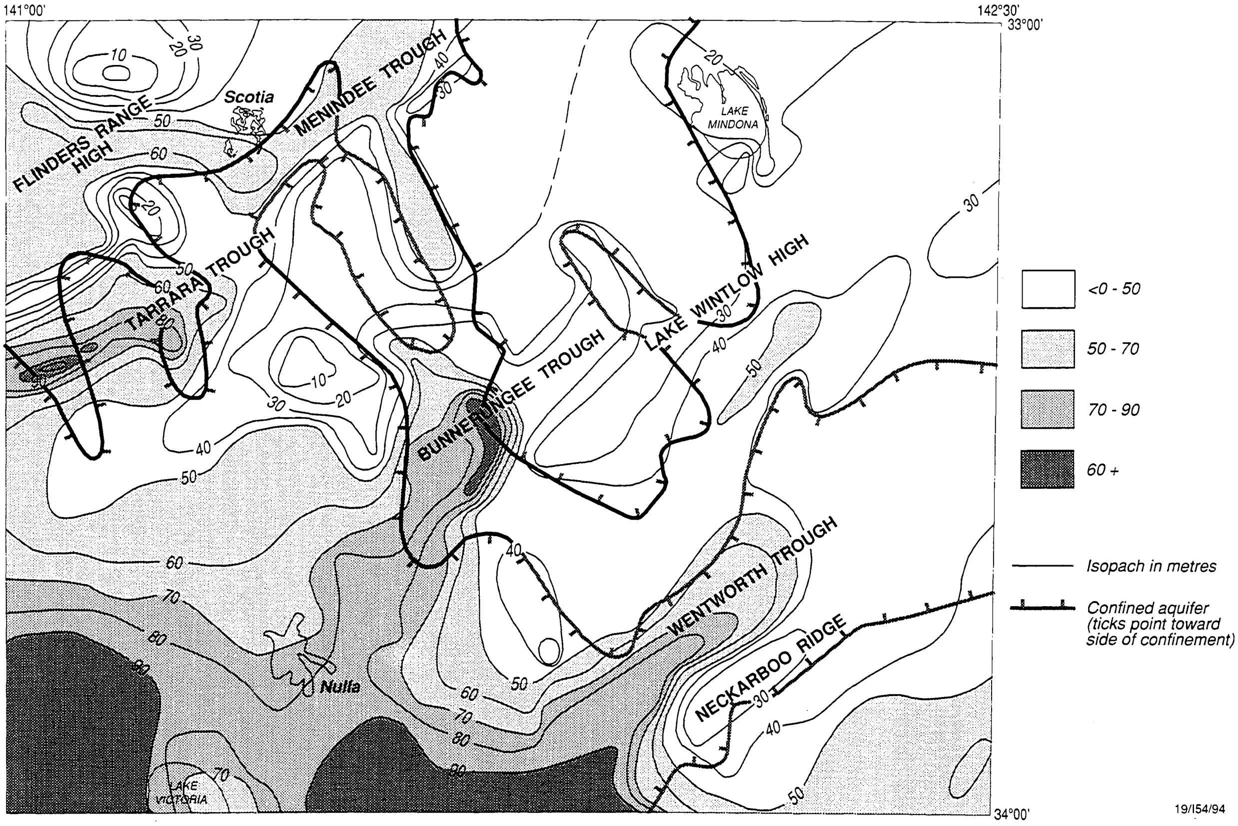


Fig. 5 Thickness of Parilla Sand and Bookpurnong Beds on the Anabranch 1:250 000 Sheet area. The extent of Parilla Sand confined by Blanchetown Clay indicates the extent of Lake Bungunnia.

exploration for a hydrocarbon trap and several stratigraphic holes were drilled by Claremont Petroleum N.L. (Gorter, 1986).

Hamley fault has an anomalous change of direction around the southern and southeastern margin of the Scotia Discharge Complex, most probably a deeper basement influence.

Movement on the Hamley fault appears to have upwarped the Parilla Sand which regionally dips gently to the south. The common recharge area for both the Parilla Sand and the Renmark aquifer (below the Geera Clay), lies to the north but these aquifers in the Scotia region are not known to be hydraulically linked (G.Jacobson pers. comm.). With the Parilla Sand upwarped to the surface, and consequently with its overlying aquiclude removed, this site has been an active discharge area since the uplift and subsequent erosional exposure.

Thematic Mapper imagery indicates two major lineament sets over Scotia Lakes (Figure 6). The origin of these lineaments is uncertain but both appear to have a structural origin in part. A northwest-southeast trending series of subparallel features may be an expression of former Parilla strandline trends. The regional strandline fabric on the Anabranch sheet is in this orientation (Figure 2). This lineament set aligns with the orientation of some islands and parts of shorelines within the Scotia Discharge Complex. The other lineament set trends west-southwest - east-northeast and is extensive regionally. One lineament of this set aligns with the northern shoreline of the complex and parallels a regionally evident feature 78 kilometres to the north, the northern faulted basin margin east of the state border. By inference, this lineament along the northern shoreline of Scotia Lakes may indicate some basement dislocation. Immediately to the south of the complex, the Hamley Fault is a component of this lineament and basement structural trend.

An additional lineament set with a northeast-southwest orientation is only evident on small-scale aerial photography, and like the northwest-southeast set, has expression within the Lake complex as linear sections of shorelines. Such expression within very recent physiographic features appears to indicate recent subtle flexure, fracture, or possibly rupture. Fracture and dislocation has probably influenced the variable depth of weathering of the Geera Clay through its influence on groundwater discharge, and deflation of the Parilla Sand exposing the aquitard.

3.2 Regional Stratigraphy

The regional stratigraphic framework in the Scotia area is shown in Figure 7. The upper Renmark aquifer is overlain and sealed by Geera Clay which is generally covered by Parilla Sand. Under the Scotia Discharge Complex, the Yamba Formation covers a deflation surface on both Geera Clay and Parilla Sand. Dunes of the Woorinen Formation overlie the Parilla Sand regionally, but are not present over the discharge complex.

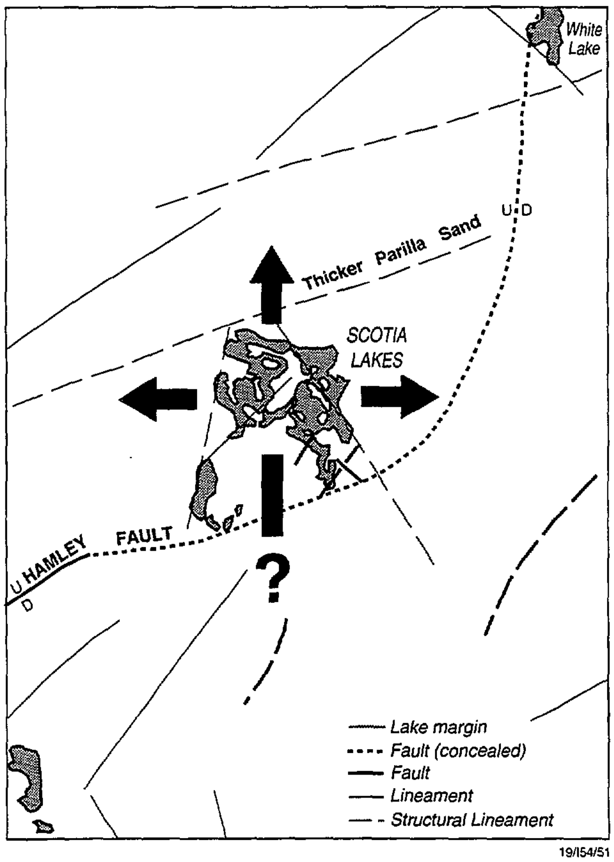


Fig. 6 Tectonic setting of the Scotia Discharge Complex

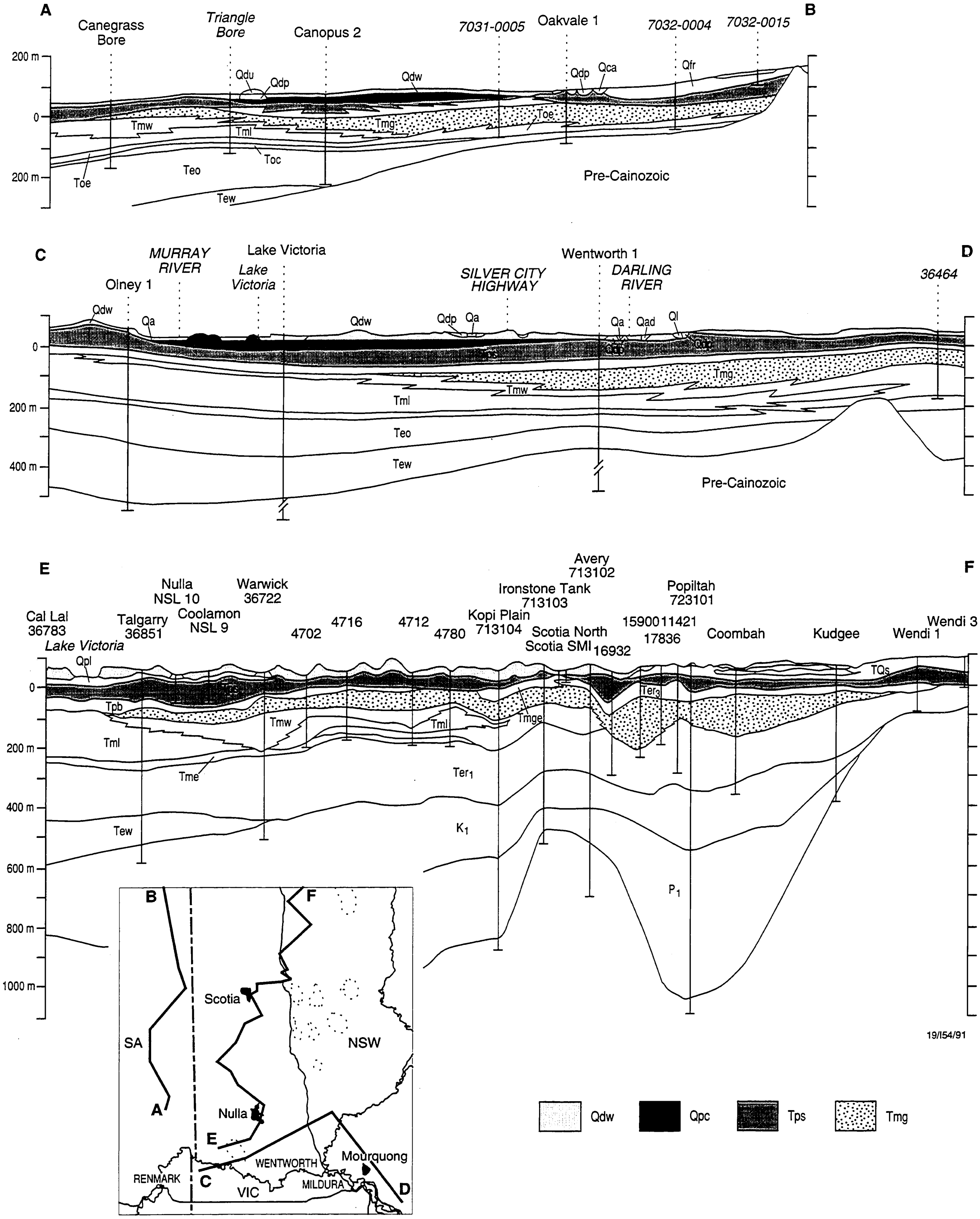


Fig. 7 Regional stratigraphic framework in the Scotia area.

3.2.1 Geera Clay Aquitard

The Scotia Discharge Complex is underlain (Figure **7**) by a mud and clay aquitard which is 10.1 m thick in the centre of the complex (Scotia Middle Island) and thins northward off structure to approximately 5.5m in Scotia North. Below Scotia Middle Island, there is a prominent weathering profile with root tubules replaced by massive siderite at 13.6m depth (18.9m AHD). This unit comprises an upper 3 metres of brownish black clay with pyritized plant remains and numerous thin flaser-like very fine silty sand interlaminations. Below this is 5.3m of plastic black clay with pyritized plant impressions, carbonaceous wood fragments, and fine pyritic bioturbation, interbedded with bituminous sands with *Callianassid* type bioturbation. A 0.3m band of reddish weathered siderite marks a hiatus with prolific subvertical root tubules. Underlying are brown black sandy muds and clayey sands.

The palynological and dinoflaggelate assemblages in this unit indicate a late Early-late Middle Miocene *T. bellus* zone age (Michael Macphail, pers. comm. 1992). This age determination is based primarily on one dinoflagellate species and negative palynologic evidence. However this age, in conjunction with a distinctive lithology and associated bioturbation structures, strongly indicates a correlative of Geera Clay as described in Piangil West No.2 (Radke, 1987).

The highest elevation of unweathered Geera Clay is in SHL1 where the upper weathered zone is thinner than below Middle Island and at Scott Lake. In the deeper SSL 1 (TD 20.75m AHD) to the north, the top of the Geera Clay is much deeper and was not intersected. In all other holes, Middle Island, Alluvial Lake, and in Ironstone Lake the upper surface is weathered, shallowest and thinnest in Ironstone Lake, slightly deeper but with a 2m weathering profile under Middle Island, and deeper, dipping northwards in Alluvial Lake where the weathered profile is about 1.5m thick in SAL 8, 7, and 6, but thins markedly northwards to SAL 5 (<0.4m). Further north, cuttings information from Scotia North is equivocal. The apparent concurrence of interpreted structure and the variable depth and weathering of Geera Clay probably indicate block-faulted control with a general northward plunge in the Geera - Parilla contact, as indicated by the regional seismic survey.

Assuming an upper surface to the aquitard which has not been significantly differentially eroded and a consistent northerly dip, the Geera Clay would be expected to cropout in the lake floor of the southwestern most discharge area adjacent to the Hamley Fault, as well as in the south-southeast discharge area. This model is untested and a gently northward-plunging anticline or subtle dome structure is more likely (Figure **6**). However, subtle flexure or rupture has probably influenced the variable weathering of this structure. The thickness of the weathering on the Geera Clay may be a direct result of the aerial extent of the initial discharge area believed to have been in the centre of the complex (Figure **8**).

3.2.2 Parilla Sand

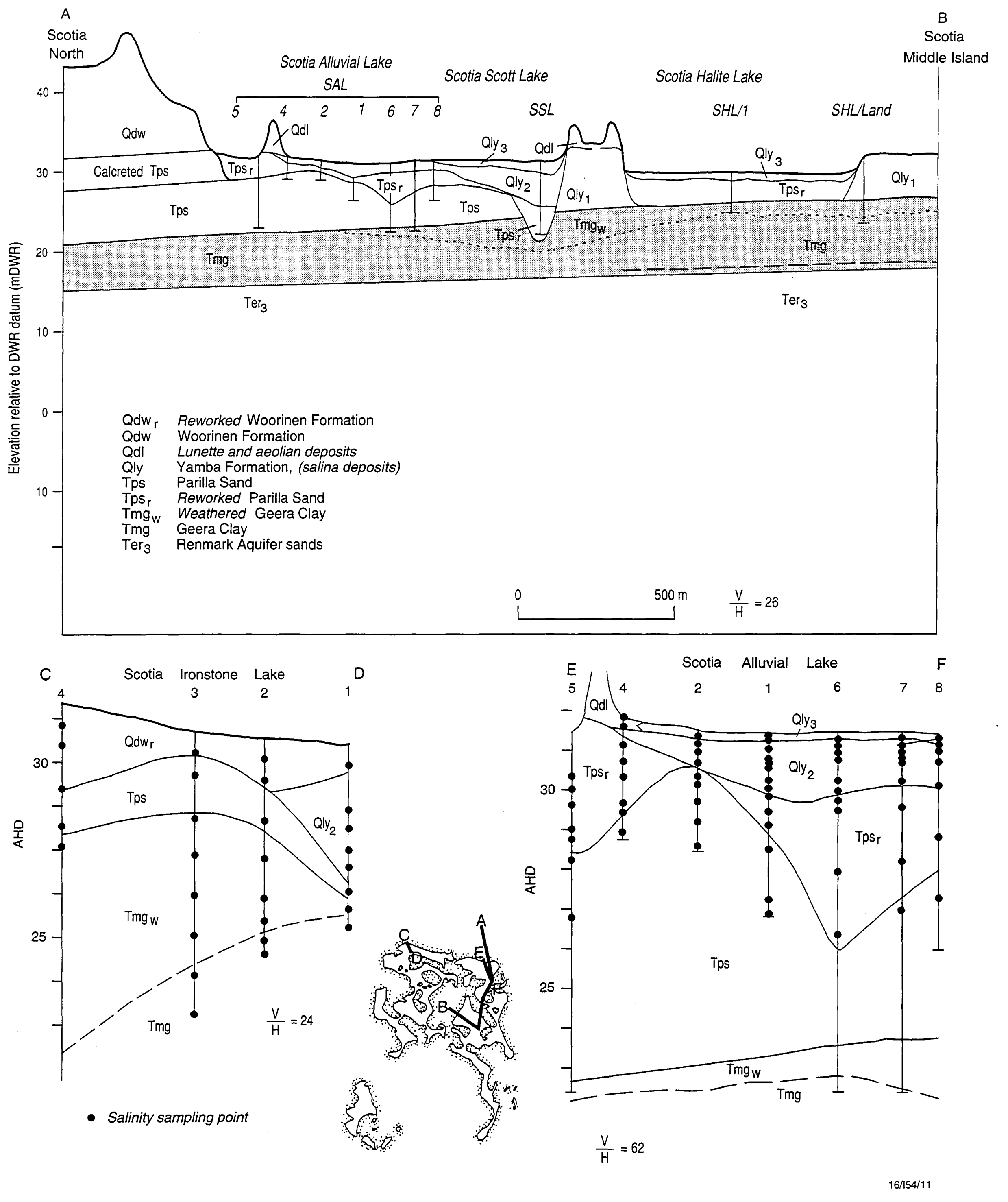


Fig. 8 Stratigraphic cross-section of the Scotia Discharge Complex from Scotia North to Scotia Middle Island.

At the Scotia Discharge Complex, the Parilla Sand has two distinctive lithologies: an unconsolidated uniform medium quartz sand, and an unconsolidated bimodal, granular to fine and medium quartz sand. Both sand types have variable, trace, but ubiquitous occurrence of the opaque minerals, ilmenite, rutile, and tourmaline. The surface expression is as indurated cross-stratified sets of limonitic sandstone seen to outcrop at the western end of Ironstone Lake where it forms a prominent dark brown-limonitic sandstone terrace which is covered in Woorinen dunes and plain to the west and north. Other ferruginous outcrops down the western margin of the complex are also interpreted as Parilla Sand. A northwest trend of inliers of ferruginous Parilla sandstone, away from the central part of the north end of the lake, are most likely a result of fault uplift (Figure **9**). Subsurface distribution of Parilla Sand within the lake complex appears to be limited to the northern margin under Ironstone Lake (thinnest, <1m thick) and Alluvial Lake (approx. 7m) and thickening slightly to 11 metres in Scotia North. On the basis of ferruginous sandstone outcropping along the lake margin at the foot of Woorinen dunes, to the west and possibly southwest, the Parilla Sand may also have subsurface remnants around the western and southwestern margins of the complex. Scott Lake (SSL 1) is problematic as there appears to be alternation of Parilla Sand or derivative, and lacustrine clay lenses. Here the Parilla Sand is deeper, and overlain by a thicker lacustrine sequence (approx. 2.5m thick).

This distribution may indicate the limited extent of the Protolake (see Figure **10**), where the Parilla Sand was removed by deflation, exposing the underlying Geera Clay.

3.2.3 Woorinen Formation

The Woorinen Formation is present only in the surrounds to the Scotia Discharge Complex which lies within flat to slightly undulate terrain covered in a well-established dune field. These dunes form a steep westerly margin to the lakes, with individual dunes terminating as small promontories on the western shoreline of the western lakes. On the eastern side, they have a similar orientation and fabric beyond earlier lacustrine and lunette features of the Complex. To the south, a higher dune-covered area, separates lakes in the southwestern and southeastern limit. Dunes in this area have modified orientations on the steeper northern and southern slopes where they tend to be contour-parallel around the slope rather than directly downslope.

The formation is approximately 11m thick where it was intersected in Scotia North. It comprises unconsolidated light brown (5YR 5/6) to reddish brown (10R 4/6?) well-sorted quartz sand with increasing white patches and calcrete induration at its base. The contact with the underlying Parilla Sand is equivocal with the absence of core. White calcrete induration is pronounced at Scotia Lake at the groundwater level and the upper surface of the Parilla Sand is at approximately this level.

3.2.4 Yamba Formation

The Yamba Formation in this complex is a heterogeneous but sand-dominant unit,

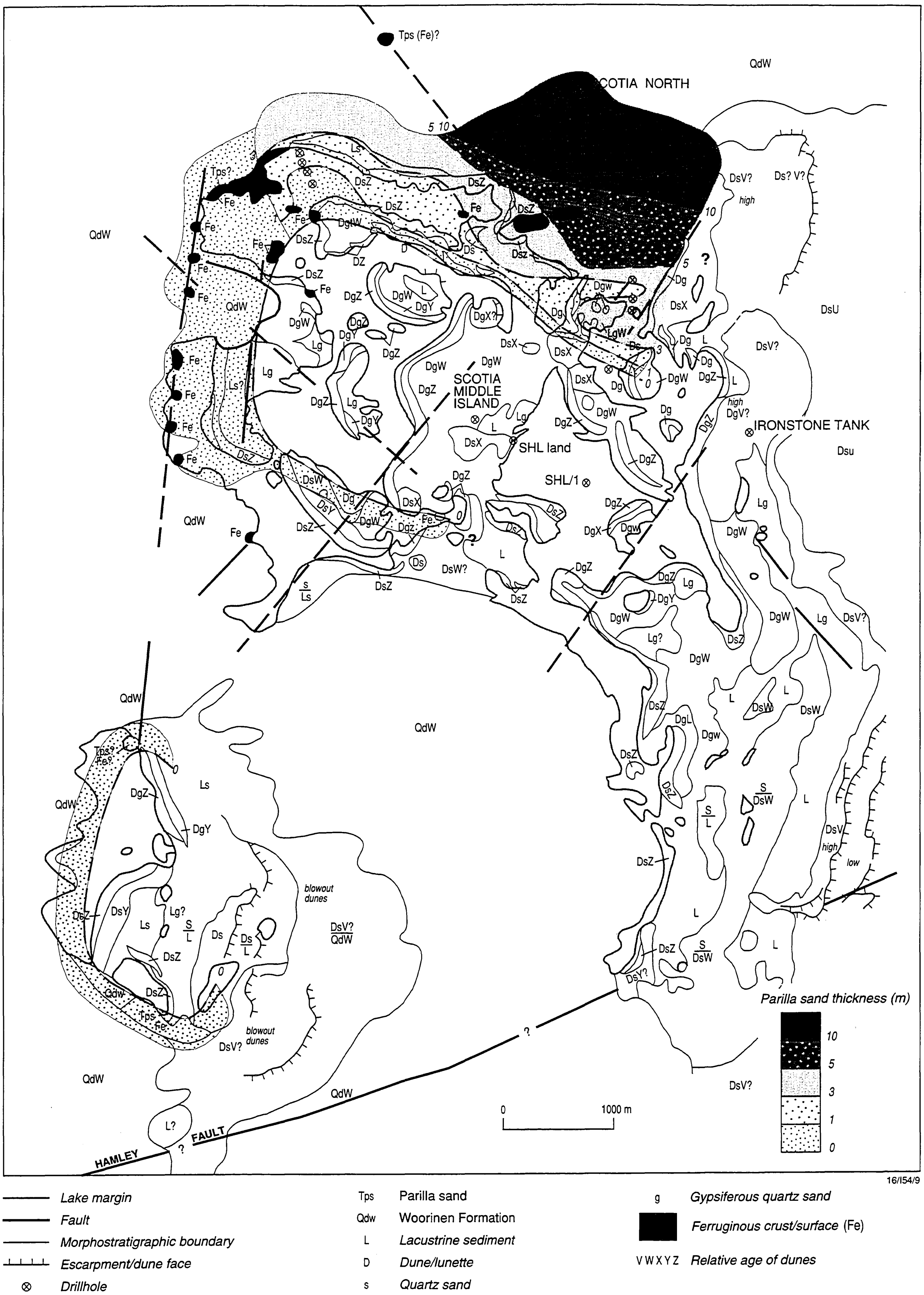


Fig 9 Ferruginous sandstone and Parilla Sand thickness.

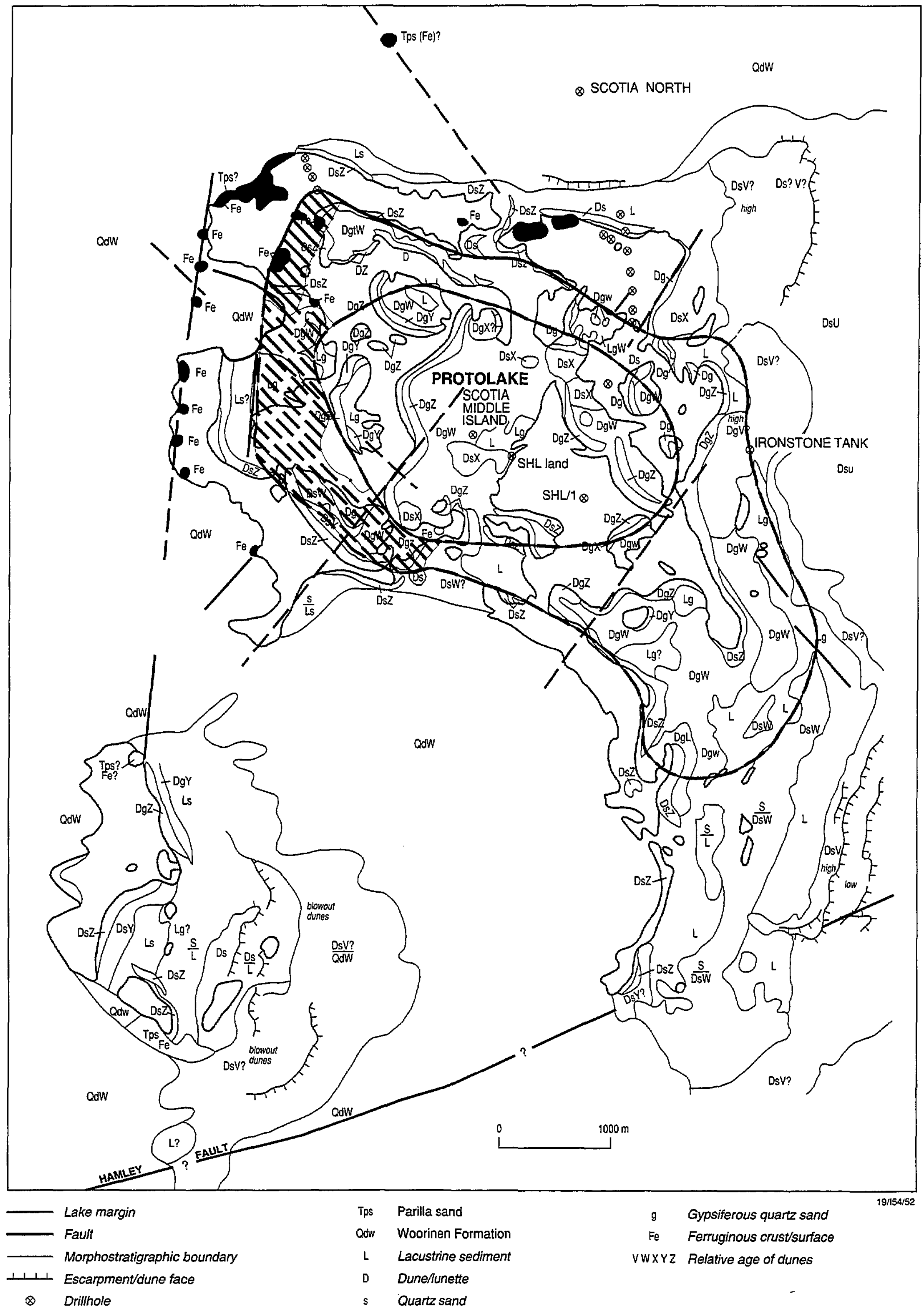


Fig. 10 Lithostratigraphic model showing initial groundwater discharge areas and Protolake.

comprising lacustrine sand, interbedded sand and clay, and clay deposits, and associated sand and/or clay-pellet lunette deposits. The extent of the lacustrine component is largely untested but believed to coincide with the broadest extent of the lake complex, with the lunette component extending eastwards from the lakes by 4 to 6.5 km. Lithofacies of this formation are described in the Lithostratigraphy section below.

3.3 Geomorphology

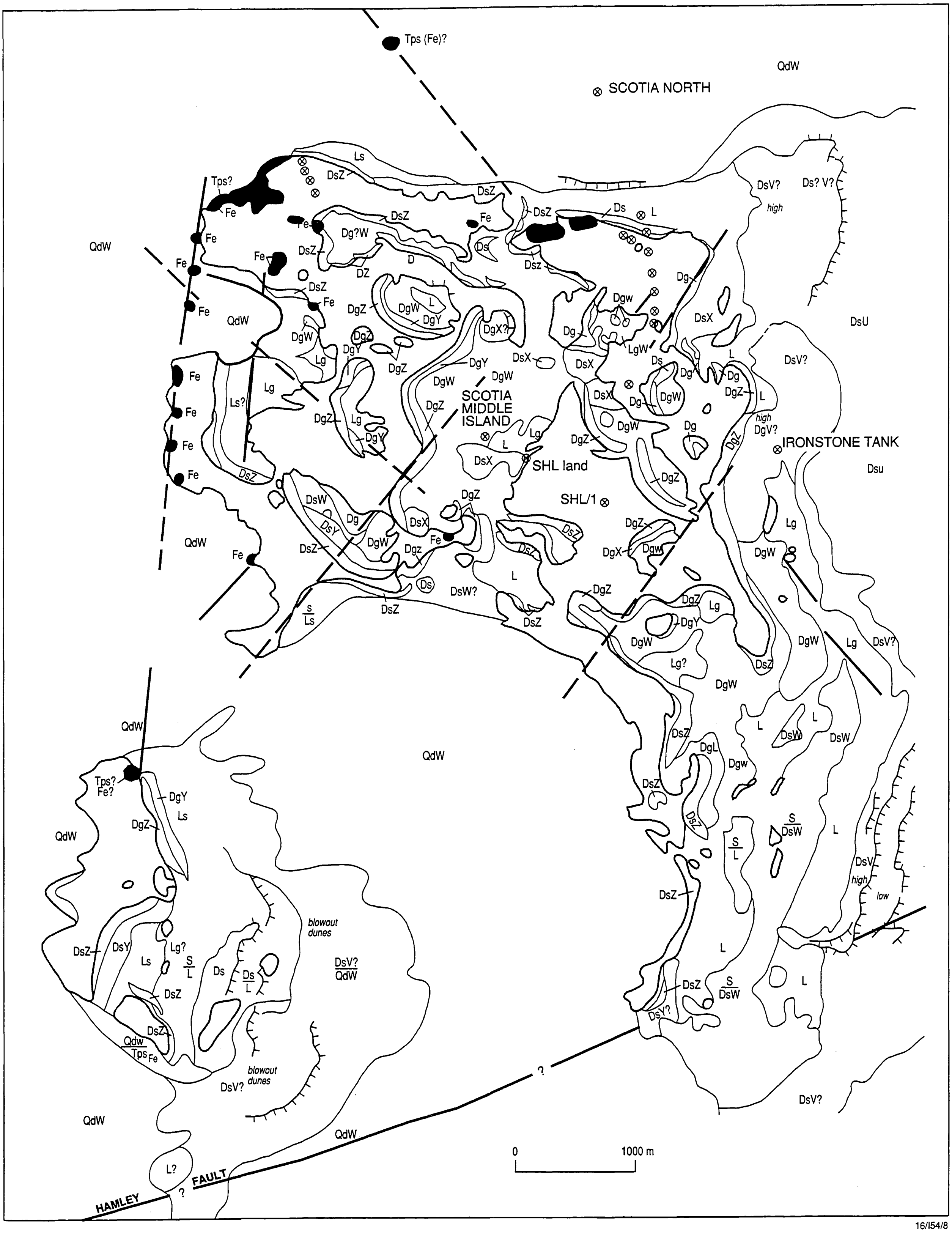
Scotia is situated within a dunefield of the Woorinen Formation. On the northern and southern margins of the main lake, lunettes and dunes within the deflated area of the discharge complex and adjacent to the lake, comprise quartz sand derived from the Woorinen dunefield. These areas signify active transport of sand around these margins of the complex to the eastern leeward lunettes and dunefield which show greater areal extent to the northeast and southeast of the main playas. These dunes do not appear cemented and accordingly, physiographic preservation diminishes or is actively modified in the crests of the older dunes further east.

In contrast, lunettes within the central area of the lake complex have a significant gypsum and clay content, sufficient to allow cementation and stabilisation of lunettes at various times, preserving more of the history of evolution of the complex. Some mobile quartz sand dunes (with minor gypsum) also occur on the central island and elsewhere and these appear to have migrated to these areas during drier periods, across the lake floor. Consequently, it seems that at Scotia, quartz sand is generally migrating continually across the complex. Where deflation of a lake basin occurs, a gypsum-enriched sand accumulates and, with suitable groundwater/rainfall overprint, may be anchored or at least the base is cemented and a relict of that position is preserved.

At present, the gypsum content of the lake sediments is minimal. In comparison with the relative abundance of gypsiferous lunette deposits, preservation is biased towards preservation of gypsum-rich events.

Evaluation of the physiographic character of the Scotia complex is based almost entirely on air photo interpretation of RC9 photography (Commonwealth of Australia, 4th November, 1987) and photogrammetric spot heights (produced by AUSLIG).

The average height of the main eastern lunette dunefields are in excess of 5 metres above the Woorinen dune surface. A smaller playa to the southwest of the main Scotia lakes has a very pronounced downwind dune swell over which the Woorinen fabric is not as pervasive as elsewhere. The islands of the main lake are interpreted to be a complex pattern of playa and lunette deposits (Figure **11**), and have elevations generally between 32 and 36 mAHD. Within this area, localised higher points reach up to 40 metres. These form a discontinuous ellipsoidal ring, 4km E-W by 2.5km N-S, which is concentric within the general perimeter of the complex. With the underlying Geera Clay probably domed in this area, this ring is interpreted as a remnant perimeter (hardpan?) of the proto-Scotia lake (Figure **10**).



Lake margin
Fault
Morphostratigraphic boundary
Escarpment/dune face
⊗ Drillhole

Tps Parilla sand
Qdw Woorinen Formation
L *Lacustrine sediment*
D *Dune/lunette*
s *Quartz sand*

g *Gypsiferous quartz sand*
Fe *Ferruginous crust/surface*
VWXYZ *Relative age of dunes*

Fig. 11 Morphostratigraphic units.

Elevations of the lake floor topography (Figure **10**) reveal a possible WNW-ESE trend of highest surfaces (>31.5m). Although two of the three areas adjoin eastern shores and may also indicate a sediment-accumulation trend, they do coincide with the proposed Protolake area and probably also indicate the higher underlying structure of the Geera aquitard.

The Scotia islands comprise a complex mosaic of lacustrine, and lunettes deposits that are interpreted as either dominantly quartz sand, or gypsiferous (Figure **11**). This latter distinction has been made on the criteria dune morphology and colour, as well as erosional form of the older deposits. Quartz sand-dominant dunes appear to have more distinct crests or blowouts, a higher reflectance and lighter in aerial imagery, and vegetation cover is darker, discrete trees? which may be more widely spaced. Gypsiferous lunettes have a greyer appearance, more rounded morphology or apparent karst-like erosional features, and vegetation appears to be grasses and low shrubs. The character of the lacustrine sediments is difficult to differentiate with any certainty. Gypsiferous deposits are generally distributed centrally with sand-dominant deposits around the periphery of the complex, especially in narrower belts to north and south. The leeward dune complex is interpreted to be predominantly quartz sand-dominant, especially eastwards in the higher dunes (Figure **11**).

Adjoining lunette deposits appear to young westwards. At least five, probably six, lunette events are recognised on the basis of general character and local physiographic characteristics. Unit D(dune) g (gypsiferous) W has the most distinctive character of numerous small `U' shaped lunettes, generally facing the west. At the time of its development, rejuvenation of the complex was by the development of numerous small scattered springs around which deflation occurred and extremely arcuate lunettes developed almost entirely surrounding the central, almost insignificant playa. This pattern is widespread within the complex and it may be unique to a specific period of dune development.

On the downwind eastern side of the lakes, the dunes rise significantly in elevation. Remobilisation appears to be ongoing at the northern and southern ends. This, and the lake floor topography (Figure **3**), have probably developed from more active deflation on the northern and southern sides of the lake, on either side of the main gypsiferous deposits (Figure **11**). The isolated lake to the southwest appears to be also active in deflation.

Island shorelines of the main Scotia lakes have many linear segments or alignments with other shores (Figure **3**) which may reflect fracture or slight structural movement on a pre-existing structural fabric.

3.4 Lithostratigraphy

Sequences within the discharge complex are subdivided and described as lithostratigraphic units, even though there is known overlap with formal units already discussed in the regional stratigraphy. Documentation of lithostratigraphic units is based on the detailed core logs of Appendix 1 of Radke (1992), and lithological summaries in Figures **12** and **13** which include additional auger hole information (J. Ferguson, pers. comm., 1992). The spatial

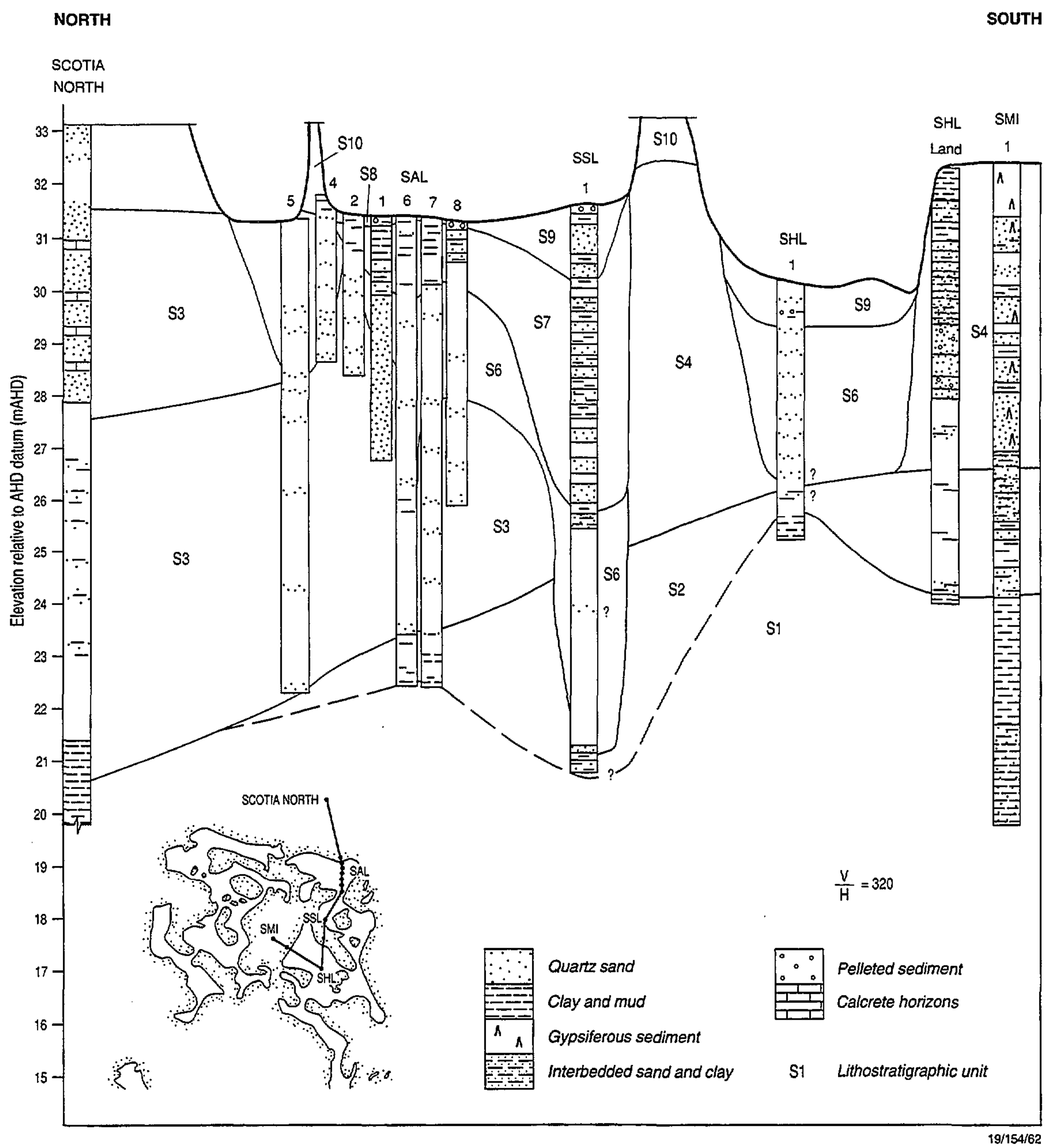


Fig. 12 Lithostratigraphy, north-south.

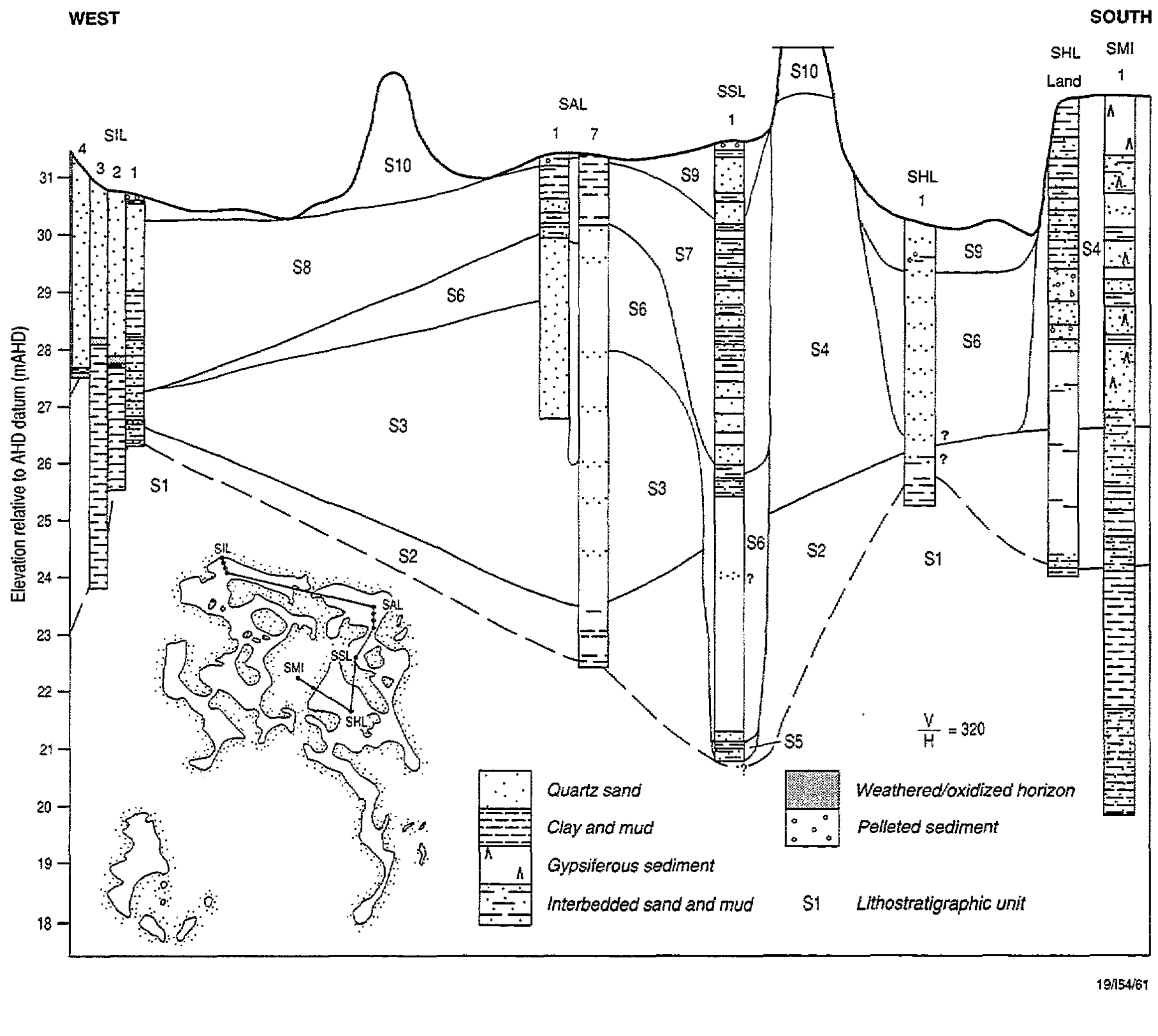


Fig. 13 Lithostratigraphy, west-south.

and stratigraphic relationships of these units are illustrated in the lithostratigraphic model of Figures **8** and **11** which include consideration of topography, structure and physiographic information.

The lacustrine sequence has a very limited range of sediment types, of which the sands are commonly reworked and may have no distinguishing features from their original source except for their stratigraphic position. As a consequence, and without any diagnostic intervals for correlation between lake areas, this model must be taken as a preliminary interpretation.

3.4.1 Unit S1

Location in lake complex: Underlies the entire complex. There is no outcrop. The lithofacies is shallowest under Halite Lake and Middle Island (25.5 to 24m AHD top of unit) and at the northwestern end of Ironstone Lake (26.3m AHD top of unit). To the northeast, the top of the unit is intersected progressively deeper to 20.4m AHD in Scotia North.

Geometry and thickness: This is a tabular unit, 9 metres thick under Middle Island, thinning to 6 metres at Scotia North.

Description: Generally a distinctive brownish-black (5YR 2/1) fissile to compact clay. At the base it is brownish black (5YR 3/1) clay and sand gradational? with the underlying unit of uniform sands. This basal lithology is overlain by a structureless dark orange brown (5YR 3/6) clayey sand grading up to brownish black (5YR 2/1) sandy mud with a strong hydrogen sulphide odour. Sand is about 20% in a black clay matrix. The sand is fine to coarse subrounded quartz, with black diturpenoid? coating.

Overlying dark grey noduled mudstone has a bituminous odour and jarositic efflorescence. Subvertical root tubules in this mudstone are infilled by porous rust-coloured very coarse quartz sand. The upper part of this zone which is 0.26 m thick is indurated with pale red (10R 6/2) siderite. This marks a distinctive weathered erosional surface. Overlying this distinctive band is brownish-black (5YR 2/1) fissile clay containing plant impressions, bioturbation tubules filled with framboidal pyrite, and random agglutinated foraminifera. The clay develops sulphur?-jarositic efflorescence with exposure. Upwards are present thin flasers of pinkish grey (5YR 7/1) very fine to silty sand with rust-coloured bases. The uppermost 30cm of the unit has increasing sand content of this flasered clay which oxidises to light grey (N7).

Stratigraphic relationships: Interdigitating ?lower contact, upper gradational transition with Unit S2.

Depositional Environment: Marginal marine, paralic lacustrine to estuarine conditions.

Discussion: This unit is identified as the Geera Clay equivalent on the basis of its microflora and distinctive lithologies. Macphail (pers.comm. 1992) ascribes an age of late Early to late Middle Miocene *T. bellus* zone.

3.4.2 Unit S2

Location in lake complex: Directly overlies Unit S1, but is present only under the Scotia salina.

It is present in almost all drillholes.

Geometry and thickness: A tabular body of variable thickness from 0.4 metres in SIL 2, to 2.5 metres under Middle Island.

Description: Characteristically it has variable clayey lithologies with oxidised colours. Centrally it comprises a blotchy to laminated sediment of uniform pinkish-grey (5YR7/1) very-fine sand laminae in a medium light grey (N6) clay which becomes increasingly soft and puggy upwards. Towards the periphery of the complex, the unit is a pale to moderate yellowish brown (10YR6/2-4) quartz silty mud with minor thin interbeds of moderate yellowish-brown (10YR5/4) silty to very fine quartz sand.

Stratigraphic relationships: Overlies Unit S1 with gradational contact, and is overlain by Unit S3 on the northern side of the complex, and Units S4 and S6 in the central area.

Depositional Environment: Presumed the same as Unit S1.

Discussion: Unit S2 is interpreted as oxidised and weathered Geera Clay equivalent, capping its source under the Scotia Discharge Complex. This oxidation and weathering thickens towards the central area presumably because of the central structurally-domed host where it was first exposed for a more prolonged period.

3.4.3 Unit S3

Location in lake complex: Unit S3 overlies Unit S2 on the northern side of the complex. It is absent from the central area and its distribution to the south is not known.

Geometry and thickness: Regionally it appears to be tabular and approximately 11 metres thick in Scotia North. It thins progressively to 4 metres thick at the northern end of Scotia Scott Lake, and thins westwards under Scotia Ironstone Lake to less than 1 metre.

Description: Unit S3 has a distinctive range of colours, greyish orange, light grey, and dusky yellow to dark yellowish brown. Under Alluvial Lake, the sequence comprises a lower 0.6m bimodal and porous horizon of greyish orange (10YR7/4) and minor light grey (N7) coarse to fine quartz sand. Coarse quartz is well-rounded, the medium to fine to very fine quartz being equant and variably angular. Sand particles are clay coated.

A middle horizon of about 2 metres thickness comprises a greyish orange (10YR7/4) fine to very fine quartz sand, very porous, with distinctive silt-sized dark heavy minerals (<0.5%). The quartz is generally variably angular and clear.

The upper 0.3 metres is broadly colour-banded dusky yellow (5Y7/4) to greyish orange (10YR7/4) and light grey (N7). The sand is bimodal with well-rounded very coarse sand in a fine quartz sand matrix that is more angular with ubiquitous traces of silt-sized heavy minerals are ubiquitous.

In Scotia North, offstructure and to the north of the Complex, the unit is 11 metres thick. On the north-eastern margin of Scotia Alluvial Lake, the upper 4 metres of the unit has an indurated white stratified to uniform calcrete overprint.

Stratigraphic relationships: Unit S3 overlies Unit S2, weathered Geera Clay equivalent, with disconformity.

It is overlain with unconformity by Unit S6.

Depositional Environment: Considered to be coastal beach deposits with its well-sorted character and relative abundance of heavy minerals, presumed ilmenite, with minor tourmaline.

Discussion: This sand unit is the Parilla Sand.

3.4.4 Unit S4

Location in lake complex: S4 has only been intersected at Middle Island in SHL Land and Scotia Middle Island. By physiographic analogy, it may also occur in the high islands to the east and north of Middle Island, especially the peninsula separating Halite and Scott Lakes.

Geometry and thickness: Probably tabular, it has an exposed upper surface and is in excess of 6.5 metres thick.

Description: Comprises a sandier lower sequence, grading up to dominant clay and muds.

Basal unconsolidated sands are light brown speckled (5YR6/4 to 5YR5/6), very fine to fine quartz sand with minor opaques (ilmenite), and red-brown clayey pellets that are variably compacted. Locally the sands are cross-stratified and calcareous.

The plastic muds range in colour from lower light to moderate brown (5YR5/4 - 6/6), mottled greyish orange (10YR7/4), and grade upwards to strongly-mottled light olive grey (5Y6/2) and light brown (5YR 6/6). Mottling increases with the displacive gypsum overprint in the upper section.

Stratigraphic relationships: Overlies weathered Geera Clay with disconformity, and is overlain by recent quartz sand and gypsiferous lunette material of Unit S9.

Depositional Environment: Conditions were of alternating aeolian and lacustrine activity. Vegetation established on the lake surface during drying phases. The preserved sequence comprises thin sand/clay cycles from 50 to 120 centimetres thick.

Discussion: The upper metre of section has a coarsely crystalline displacive gypsum overprint and most earlier structures in the sediment has been obliterated. Where this overprint has not completely destroyed original features, traces of rootlets can be recognised in two thin upper intervals, and faint original lamination is recognised in scattered parts of the section.

3.4.5 Unit S5

Location in lake complex: Only recognised in the bottom of SSL/1.

Geometry and thickness: Probably a lens in a structural depression? and in excess of 50cm thick.

Description: At the base, semi-indurated millimetre-sized lumps of siltstone occur in moderate yellowish brown (10YR5/4) unconsolidated sands, comprising coarse to fine to very fine quartz sand with about 5% limonitic clay matrix. This is overlain by plastic sandy clay of moderate greyish red (5R5/2), which grades up into faintly-laminated moderate yellowish brown (10YR5/4), and clayey sand (very fine to fine quartz) which is very finely laminated in porosity, matrix content, and colour variations from moderate reddish brown (10R4/6) to light grey (N7) colours.

Stratigraphic relationships: It is unknown if Unit S5 directly overlies Geera Clay or Unit S4. It is overlain by Unit S6.

Depositional Environment: Lunette and lacustrine conditions similar to S4? prevailed, with basal clasts being derived from the Geera Clay.

Discussion: Scotia Scott Lake 1 has an atypical section compared to other lake basins and is interpreted to be a narrow structurally controlled depression on the basis of its deeper section and different facies.

3.4.6 Unit S6

Location in lake complex: Unit S6 is widespread, present in lower SSL 1, SAL 1, 6, 7, 8, and SHL 1.

Geometry and thickness: The unit infills and blankets a variable substrate of irregular topography. Up to 4.5 metres thick.

Description: Light olive grey to dusky yellow (5Y6/1 - 5Y6/3) sand, with light grey (N7) and dark yellowish orange (10YR5/6) colour variations. The sand is uniformly unconsolidated with high interparticle porosity, is commonly calcareous and locally gypsiferous; and comprises very fine to predominantly fine quartz sand, with variably angular and clear quartz, and a ubiquitous trace of silt-sized opaques (<0.5% ilmenite, goethite?).

The sand may appear oxidised with reddish clay cutans imparting a greasy appearance.

Stratigraphic relationships: Unconformably overlies the Geera Clay and Parilla Sand, and is conformably? overlain by Unit S5.

Depositional Environment: Predominant lacustrine deposition of aeolian? transported sand suggests very little exposure to clay source units.

Discussion: S6 is considered to be reworked Parilla Sand. Although difficult to differentiate from Parilla Sand, its position over laminated clays suggests accumulation after a clayey lacustrine deposit was established.

3.4.7 Unit S7

Location in lake complex: Unit S7 is only recognised in Scott Lake 1.

Geometry and thickness: It is a probable tabular body in this lake, about 3 metres thick and wedging out on the margins.

Description: The unit comprises a repeated alternation of sands, laminated muds and clays. Bands of sand, 10 -15cm thick, are light brownish grey (5YR7/1) locally mottled to moderate yellowish brown (10YR5/4). The granular to coarse rounded quartz sand is locally goethitic-stained. Interbedded plastic clays are distinctly laminated with sand, mud, and silt. The clays are yellowish grey (5Y7/2) to dark greyish orange (10YR6/4) and pale red purple (5RP6/1), and have wavy and sometimes lensoidal sandy laminae. Porosity accordingly alternates from significant interparticle porosity to being nonexistent.

Stratigraphic relationships: Unit S7 overlies S6, and is overlain by recent pelletal sediment which is probably forming in situ.

Depositional Environment: Mixed and alternating conditions are indicated ranging from quiet lacustrine to possible periodic aeolian transport of sand into the lacustrine environment.

Discussion: Unit S7 is considered similar to Unit S4, if not the same sequence.

3.4.8 Unit S8

Location in lake complex: S8 is present across Alluvial Lake and in the central part of Ironstone Lake.

Geometry and thickness: The unit is almost tabular, and interpreted as thinning from the western end of Ironstone Lake (metres thick), to a 1.5 metre sequence in Alluvial Lake.

Description: Characteristic is the repeated alternation of sand and clay. Plastic clays tend to be uniform, light olive grey (5Y6/1 - 6/2) and dark greyish orange (10YR6/4 to 10YR7/2), silty, and have a possible pelletal texture in Alluvial Lake. The clays have very thin laminae to lenses of sand which varies with bed size. The thicker beds, >10 centimetres, are semi-unconsolidated and porous, yellowish grey (5Y8/1), commonly cross-stratified and comprise bimodal, coarse to very coarse rounded, and very fine sand, traces of mafics, and goethitic cement.

Thinner sand laminae in the clays are greyish orange (10YR7/4), pale brown (5YR7/4), or moderate red (5R5/6).

Stratigraphic relationships: Unit S8 overlies Unit S6 in Alluvial and Ironstone Lakes, and also Parilla Sand at the western end of Ironstone Lake. It is overlain in part by recent lunette accumulation.

Depositional Environment: Alternating quiet lacustrine and drier conditions prevailed, with pelletization of the lake surface clay and aeolian sand input during the more arid conditions.

Discussion: In Ironstone Lake, the sequence is predominantly sand with thin clay laminar interbeds. Further East in Alluvial Lake, the sequence becomes predominantly clayey but with distinctive thin bands and laminae of sand, most prevalent in the lower section.

This unit may equate with the top of Unit S7. It is probably the deposit that followed the last deflation period, prior to any active deflation that is observed today.

3.4.9 Unit S9

Location in lake complex: S9 forms a surface veneer over Halite, Scott, and the southern part of Alluvial Lake. It also may form lunettes on the western end of Ironstone Lake and on the northern margin of Alluvial Lake, as well as a lunette veneer over the older high peninsula between Alluvial and Halite Lakes.

Geometry and thickness: Generally it is a stratiform tabular body up to 2m thick over the lake surfaces, but wedges out northwards across Alluvial Lake. The unit forms lenses of various proportions as lunettes.

Description: The uppermost sediment is a loose friable moderate brown (5YR4/4) grapestone, gypseous and calcareous to dolomitic. It comprises irregular granule to coarse sand-sized pellet aggregates of clay, sand, gypsum and dolomite mud. The quartz sand component is predominantly fine to coarse, and variably angular to rounded. Clay content is approximately 25%.

The grapestone grades down through pelletal sand to light olive grey (5Y6/2), pale orange to pale yellowish orange (10YR7/2-6), and medium-light to light grey (N6-7) dolomitic muddy sand which is commonly bimodal, ranging from coarse quartz sand to quartz silt variably sorted in a packstone texture. Muscovite silt may be present.

Stratigraphic relationships: This surficial unit overlies Units S4, S6, S7, and S8.

Depositional Environment: The lake surface has been under repeated inundation and evaporitic desiccation, with some aeolian deflation of the resultant pelleted material.

Discussion: This is a surficial facies, active in formation and apparently deflating at present. The degree of significance of the present deflation is unknown.

3.4.10 Unit S10

Location in lake complex: This unit forms the active lunettes of the Complex.

Geometry and thickness: Lunettes form asymmetric lens-shaped deposits on the eastern and north or south sides of lakes within the complex.

Description: These units have not been drilled but erosional scours in the sides of the lunettes reveal lox-angle parallel to cross-cutting stratification of light brown to greyish orange-pink pelleted sands. These sands are subcompact away from the lake surface and have superimposed erosional surfaces.

Stratigraphic relationships: Unit S10 overlies most units, Units S4, S7, and S8, and is a correlative of similar lithologies across the lake as Unit S9.

Depositional Environment: Present-day processes indicate the lunettes are accumulating and eroding with wind deflation of the lake surface.

Discussion: These deposits are actively accumulating and eroding.

3.4.11 Correlation and distribution of lithostratigraphic units

The intercepted sequence at Scotia, described in the informal units above, is interpreted below. Deposits that accumulated within the Scotia Discharge Complex are the lithostratigraphic units S4 to S10.

Units S5 and S6 have been combined and categorised as reworked Parilla Sand. Apart from the initial and underlying thin clays of Unit S5, Unit 6 is lithologically almost indistinguishable from Parilla Sand.

Three ascribed phases of accretion of Yamba Formation, with major erosion and redeposition are identified but without the control of dating, the correlation of these events with those of Nulla Discharge Complex are arbitrary.

S1 Geera Clay
S2 weathered and oxidised Geera Clay
S3 Parilla Sand
S4 Yamba Formation (phase 1)
S5 reworked Parilla Sand
S6 reworked Parilla Sand
S7 Yamba Formation (phase 2)
S8 Yamba Formation (phase 2)
S9 Yamba Formation (phase 3)
S10 Yamba Formation equivalent - lunette (phase 3)

This interpreted stratigraphy is shown in Figures **14** and **15**.

The Geera Clay (S1, S2) is seen to have highest elevation along an axis from Middle Island to the western end of Ironstone Lake and descends northeast towards Scotia North. The unit has its thickest upper weathering/oxidation at the highest elevations, and possibly below Scott Lake.

The earliest lithofacies of the Yamba Formation, S4 (Qly_1), is centrally located on the higher central area of Geera Clay, and has the highest clay and gypsum content with repeated alternations of compacted pelletal lunette material. This lithofacies is deflated in places back to the underlying Geera Clay, and on the northern side in Scott Lake, it has an apparent sudden termination against a deep erosional depression. Several narrow erosional depressions into the Parilla Sand (S3) to the north in Alluvial Lake are interpreted collectively as a probable former drainage system which extended from the north-northeast of the complex, to along the eastern side of the central higher deposits, and southwards. The deepest part of this surface in Scott Lake coincides with a prominent lineament which may imply structural influence.

The filling and smoothing of this irregular surface is by very thin and apparently discontinuous clay lenses of lithofacies S5 which is present basal to and within the overlying sands of lithofacies S6. These sands are indistinguishable with the Parilla Sand and are considered to be a local reworking of the Parilla Sand host sequence. Overlying lacustrine clays and intercalations of sand (S7,S8 - Qly_2) cover these reworked Parilla sediments and over an erosional surface, probably deflational, which generally follows the underlying surface. S7 and S8 form significant lacustrine deposits under Alluvial, Scott and Ironstone Lakes.

Surficial deposits in Alluvial, Scott and Halite Lake, S9 (Qly_3), blanket the most recent significant deflational surface. This lithofacies is absent in Ironstone Lake which has a veneer of remobilised quartz sand from the Woorinen dunes. This sand forms a significant proportion of the sandy clay-pelleted sediment in the active lunettes, S10, and the present surficial pelleted lake sediments (S9) to the east.

3.5 Diagenetic Features

Diagenetic alteration and cementation in the Yamba sequence is relatively minor. The

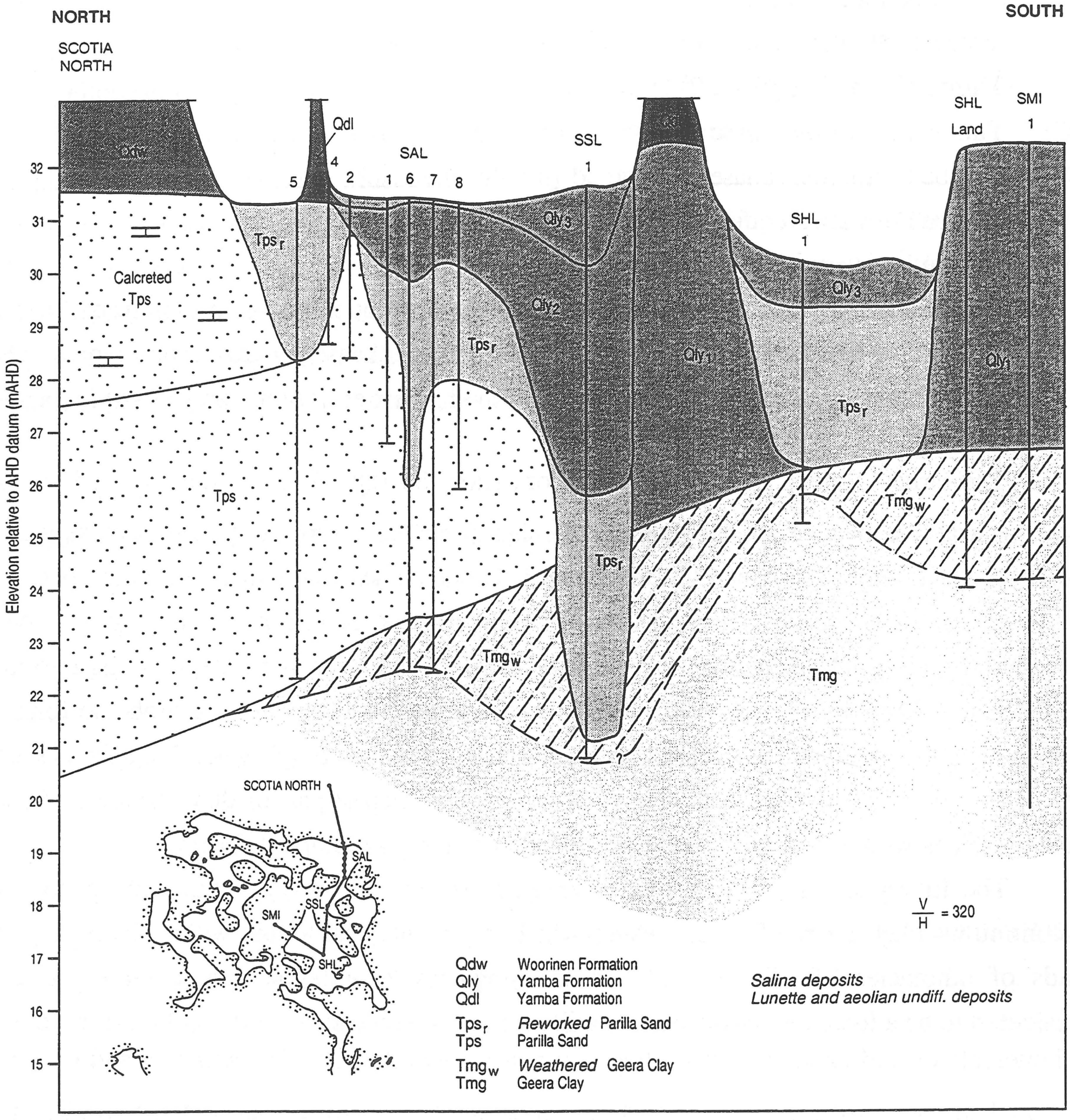


Fig. 14 Stratigraphy, north-south section.

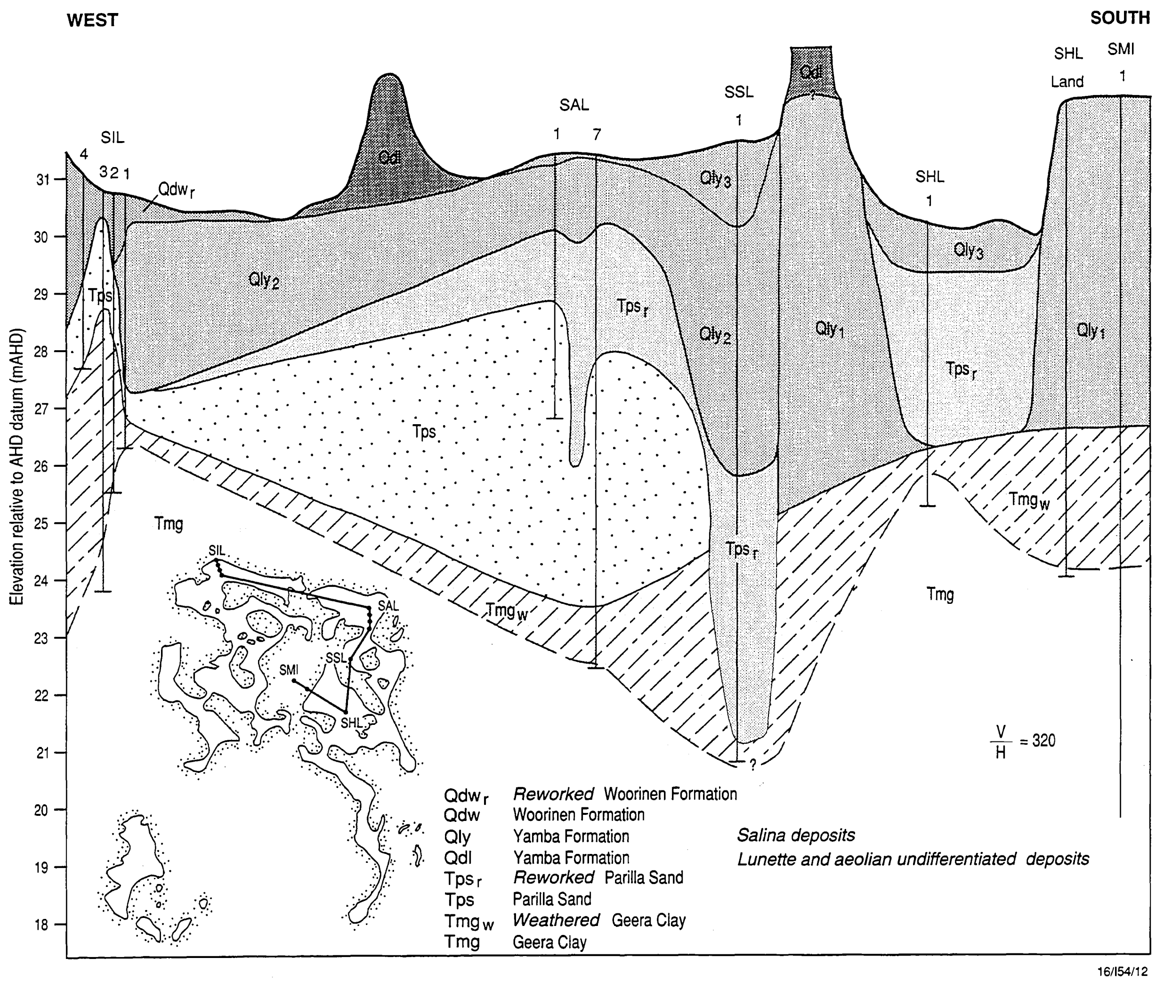


Fig. 15 Stratigraphy, west-south section.

most evident alteration is in the central area where incised pedestals of earliest Yamba Formation have a gypsum hardpan nearsurface.

3.5.1 Carbonate

Carbonate is rare in the sediments of the complex. It is present in the Parilla Sand sequence just north of the lake as a calcrete overprint (trace of calcisiltite) throughout the approximate 4 metres thickness, the upper limit lying at or near to the present lake level. In the lacustrine sequence, calcite has a scattered distribution as a trace of micrite in the matrix of the sands, but is more continuous downhole in SSL 1. Only in the SHL Land hole is calcite present as an indurated band (Figure **5**). Probable dolomite is present in upper SSL 1, SAL 8, and in Scotia Middle Island as traces of dolomicrite in the matrix.

Discussion: Present groundwaters do not indicate a potential for precipitating carbonate. Most probably, an earlier horizon of Parilla Sand with a calcrete overprint has been reworked and this is the probable source.

3.5.2 Sulphate

Gypsum has variable distribution in the sequence (Figures **5** and **6**), abundant in Unit S4 at Middle Island where haloturbation has almost obliterated original textures, and S5 at the western end of Ironstone lake and in the top of SAL 8, Alluvial Lake. Elsewhere only trace amounts are found.

Unit S4 In this unit, intersected in cores in Middle Island, the gypsum overprint is dominant. Late diagenetic horizontal millimetre-sized to centimetre-sized displacive hemispheroidal crystals. Locally the gypsum may be replacive. Remnant textures of primary small clastic gypsum are preserved at random within this unit.

Unit S8 The latest lacustrine unit also contains small (<1mm) crystals of primary hemispheroidal and prismatic clastic crystals and particles.

Jarosite is present as a pale yellow efflorescence of deeper Geera Clay (19 and 23.5m AHD in Scotia 1, Middle Island), and in the Parilla Sand at 22-23m AHD. The jarosite occurs in black to very dark muddy sands and muds.

3.5.3 Sesquioxides

Iron sesquioxides, predominantly goethite, are a characteristic of, and distinctive in the sequence of this complex and occur as stainings, crusts, concretions, and reworked clasts of the latter forms.

Concretions occur in the mixed lacustrine-lunette sediments of Units S4 in Middle Island, and S7 in Scotia Scott Lake 1.

Crusts and/or fragments are thin platy and well-indurated, usually less than a centimetre thick and are found in core in various orientations within unconsolidated sand or clay, probably disturbed in the drilling process. Crusts occur in Unit S7 of Scotia Scott Lake 1, and on the contact of Parilla Sand and weathered Geera Clay in Ironstone Lake. As a matrix cement, sesquioxides occur in Scotia Alluvial Lake 1, and Scott Lake 1. In Ironstone Lake, the muddy sands are highly ferruginized in most of the section but induration is only observed with a clay contact.

Sesquioxide precipitates are predominant in clay and mud sequences, within thin laminae or interbeds of sands and silts. The proportion of goethite precipitated as interparticular cement appears to be primarily porosity-dependant. Where, on micro and mesoscale, the porous sands and silts are not confined, there is little to no goethite precipitated with one exception. The upper contact with an impermeable clay or mud is the only site that could have significant goethitic precipitates. Here, on the microscale, the concentration of goethite appears proportional to the degree of occlusion of porespace by down-filtered clay.

Discussion: At a height of 2 to 3 metres above present lake level, ferruginous sandstones of the Parilla Sand are well-indurated and form extensive benches and a peninsula in the northwestern corner. This is attributed to the oxidation of groundwater discharges at an earlier phase of deflation, but post-protolake time, at a higher elevation than at present. Outcrop of ferruginous sand is found around the complex, predominantly on the western margins and aligning with interpreted structure (Figure **11**). It is apparent that earlier groundwater discharge was controlled by the domed? or anticlinal? structure of the Geera Clay, as well as local anomalies caused by fracture and faulting which tapped groundwater from the underlying Renmark aquifer. The exposed ironstone deposits and their reworked products scattered through Scotia sediments are thought to have formed by sudden pH and Eh changes at the sites of groundwater discharge.

Macumber (1991) documents extensive ferruginization of lake sediments and indurated ironstone at depth in Lake Tyrrell. There he observes that the ironstone is found extensively in the spring zone and the marginal flats of the western and southern shorelines. He attributes deposition in the spring zone to exposure of ferrous-rich springwaters to the atmosphere, and precipitation at the lake edge to mixing of acid springwaters with neutral lake water.

HYDROGEOLOGY and HYDRODYNAMICS

3.6 Permeability

Measurements of permeability in the Scotia Discharge Complex were not attempted. However, the lithostratigraphic data on grain-size (Figures **12** and **13**) are an indication of the relative permeability of the various lithostratigraphic units.

3.6.1 Discharge Complex and its Regional setting

The Scotia Discharge Complex (Figures **7** and **8**) is set in a shallow, unconfined aquifer (the Parilla Sand) which is separated from an underlying confined aquifer (the Renmark

Group) by an aquitard (the Geera Clay).

The permeability of the discharge complex has been strongly influenced by two factors.

(1) A major sediment province which has provided mainly sand from the Woorinen Formation and the Parilla Sand.

(2) A minor but significant clay sediment source from the Geera Clay in the middle of the discharge complex.

The clay occurs in the sandy lacustrine sediments of the Yamba Formation as layers of varying thickness (up to 1 to 2m). These clay layers have produced a strongly anisotropic environment in which lateral permeability probably exceeds vertical permeability by up to two to three orders of magnitude. Overall, however, the lacustrine sediments derived from these sources have a high sand component and they are considerably more permeable than lacustrine deposits elsewhere in the Murray Basin where the Blanchetown Clay is available as a clay source for lacustrine sedimentation (e.g the Nulla Discharge Complex; Figure **1**).

The central dome of Geera Clay beneath the discharge complex has restricted the overlying Parilla Sand and lacustrine Yamba Formation sediments to a relatively thin (about 5 to 10m) outwards-thickening, permeable, wedge-shaped body of interbedded sand and clay (Figures **12** and **13**). The progressive outwards expansion of the Scotia lakes with deflationary activity has removed the older outer margin of lacustrine deposits and, consequently, there are no permeability barriers between the preserved lacustrine sequence and the laterally-enclosing regional Parilla Sand aquifer.

3.6.2 Sub-environments of the Discharge Complex

Individual active lakes in the discharge complex show a range of permeability distributions, depending on the location and thickness of the clay layers. The permeability of the lake surface is one of the hydrodynamically more important of these features, and it is convenient to group the lakes into those which are sand-surfaced and those which are clay-surfaced.

(1) Sand-surfaced Lakes (Scotia Scott Lake ; Scotia Halite Lake; Scotia Ironstone Lake).

In these lakes the surficial sand layers are typically 0.5m thick. The sand layer may overlie relatively thin (< 0.5 m) alternating clay and sand layers, as occurs in Scotia Scott Lake (SSL; Figures **12** and **27**) and Scotia Halite Lake (SHL; Figures **12** and **27**). Alternatively, it may overlie a relatively thick layer of lacustrine clay (about 3 m) which is separated from the underlying Geera Clay by only a thin layer of Parilla Sand (e.g. Scotia Ironstone Lake; Figures **8**, **13** and**17**).

(2) Clay-surfaced Lakes

These lakes have surficial clay layers of significant thickness (about 1 m). Surficial clay occurs in Scotia Alluvial Lake (SAL; Figures **8**, **12** and **16**), where it overlies several metres of Parilla Sand and its reworked equivalent.

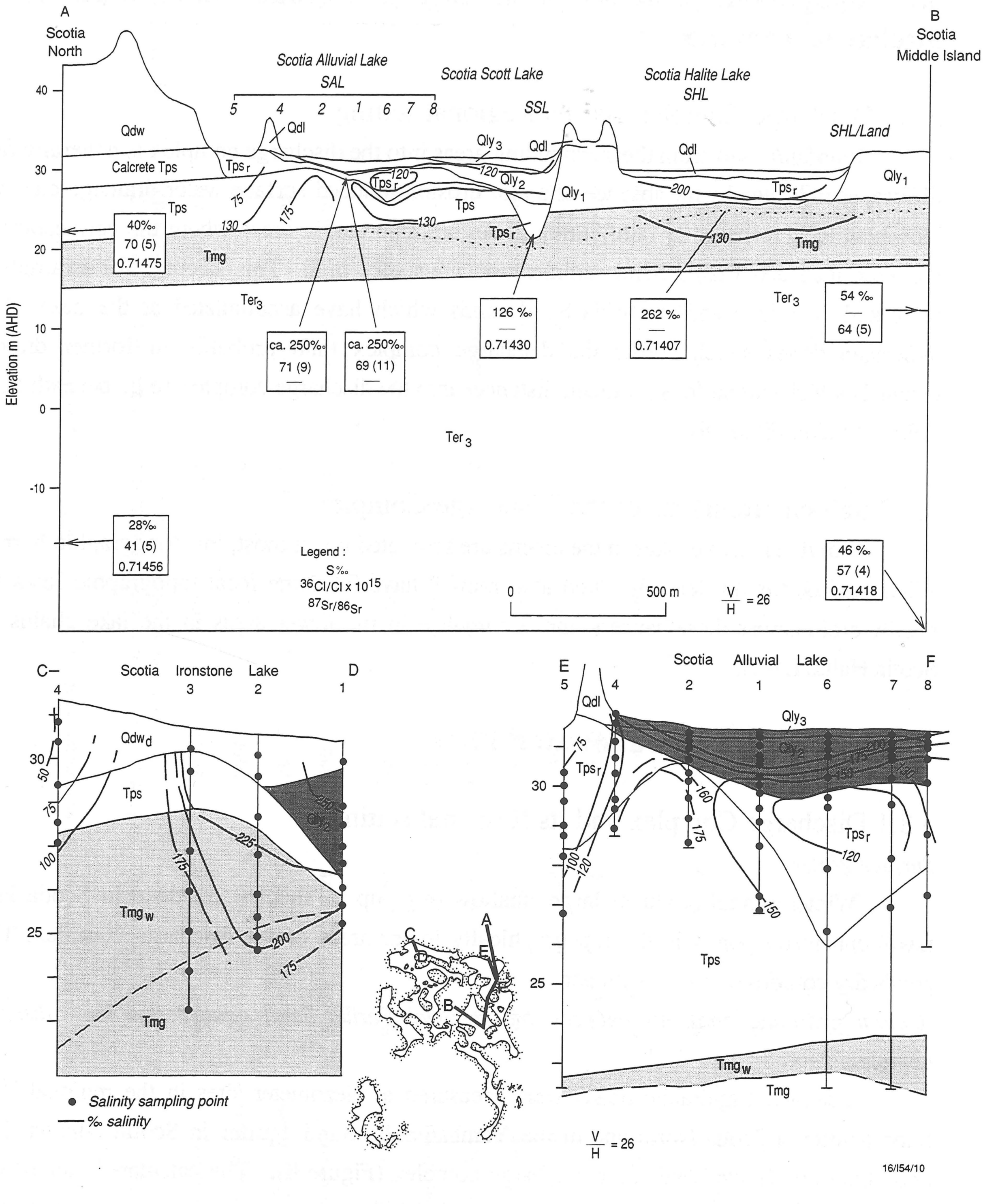


Fig. 16 Section A-B: iso-salinity contours, salinity, $^{36}Cl/Cl$ and $^{87}Sr/^{86}Sr$ ratios for groundwaters on the Scotia North-Scotia Middle Island section.

Section C-D: detailed isosalinity contours for sites SIL 1/91 to 4/91 at the northern margin of Scotia Ironstone Lake

Section E-F: detailed isosalinity contours for sites SAL 1 to 8 across Scotia Alluvial Lake.

3.7 Topographic controls on surface and groundwater input to the discharge complex

3.7.1 Discharge Complex and its Regional setting

Rainfall/runoff from the surrounding areas into the discharge complex is generally fairly diffuse, as indicated by the absence of major erosion-induced surface water drainage channels. However, local recharge by rainfall/runoff can be important in areas where the permeability of the Woorinen and Parilla Sand sediments is unusually high. This occurs, for example, in reworked Woorinen and/or Parilla Sand sands which have accumulated at the base of the Woorinen dunes which border the discharge complex (and probably in former drainage channels which extend for significant distances into the discharge complex (e.g. beneath Scotia Alluvial Lake; Figure **8**).

3.7.2 Sub-environments of the Discharge Complex

Individual active lakes in the chains are separated by, at most, low topographic barriers. When surface floodwaters generated after rainfall have filled the local topographic lows they readily drain across these barriers and accumulate in the lower areas in the lake chains (e.g Scotia Halite Lake).

3.8 Surface and Groundwater Flow

3.8.1 Discharge Complex and its Regional setting

Surface Water

Winter rainfall produces large, shallow (e.g. up to about 0.2m deep in Scotia Halite Lake) ephemeral ponds in the topographically lower areas of the discharge complex. These ponds dry completely in the summer.

Lateral hydraulic gradients between the regional Parilla Sand aquifer and the discharge complex

The lateral hydraulic heads were measured at piezometer sites in the regional Parilla Sand aquifer at Scotia North and in the Yamba/Parilla Sand aquifer in Scotia Alluvial Lake, Scott Lake and Halite Lake in the discharge complex (Figure **8**). The calculated values of the lateral (freshwater) heads at constant elevation (Table **1**) are approximate because normalisation of the measured freshwater heads required large extrapolations of the measured values.

As expected, there is potential for regional groundwater flow from the Parilla Sand aquifer at Scotia North towards the discharge complex. However, measurements taken when surface water was present in some lakes (spring, 1991) show that the magnitude of the gradient varied considerably with location in the discharge complex (e.g. SN/20m to SAL 5 is 1.3 m; SN/20m to SSL/1 is close to zero). This range reflects differences in lateral heads within the

Table 1. Lateral (freshwater) Hydraulic Heads, Scotia North and Scotia Discharge Complex

Location	Piezometer	Aquifer	Date	SWL (mAHD)	Salinity (mg/L)	Density (g/cc) assumed 20 deg C	Mid pt slots (mAHD)	P actual (MPa)	P actual (MPa) @ 24.0mAHD	Hif (mAHD) @ 24.0mAHD
Scotia North	SN/20m	Parilla Sand	Nov-91	31.8	39500	1.0258	23.24	0.08614	0.0787	32.02
	SN/40m	Upper Renmark	Nov-91	33.47	30000	1.01926	3.19	0.3028	0.0947	33.65
	SN/60m	Upper Renmark	Nov-91	33.3	28000	1.01797	-16.8	0.5003	0.0929	33.47
Scotia Alluvial Lake	SAL5/2 SAL5/1; dry	Parilla Sand	Nov-91	29.26	133000	1.08783	24.01	0.05603	0.05614	29.72
	SAL 4	Parilla Sand	Nov-91	30.86	160000	1.10504	26.16	0.05095	0.07438	31.58
	SAL 2	Parilla Sand	Nov-91	30.93	175000	1.11446	25.93	0.05466	0.07576	31.72
	SAL 1	Parilla Sand	Nov-91	30.96	145000	1.09551	27.92	0.03267	0.07479	31.62
	SAL 6	Parilla Sand	Nov-91	31.02	140000	1.09232	23.62	0.0793	0.07524	31.67
	SAL 7	Parilla Sand	Nov-91	31.04	128000	1.08461	23.32	0.08214	0.0749	31.64
	SAL 8	Parilla Sand	Nov-91	30.99	144000	1.09488	25.28	0.06133	0.07508	31.65
Scotia Scott Lake	SSL 1	Parilla Sand	Nov-91	31.4	135000	1.08911	22	0.1004	0.08	32.15
Scotia Halite Lake	SHL 1	Parilla Sand (Geera Clay equiv.?)	Nov-91	29.42	270000	1.173	25.74	0.04231	0.0623	30.35
Scotia Middle Island	SHL/Land	Parilla Sand	Nov-91	30.4	93000	1.063	24.19	0.06468	0.0667	30.80
	SMI/20m	Upper Renmark	Nov-91	32.73	56000	1.03704	12.8	0.2028	0.08883	33.06
	SMI/60m	Upper Renmark	Nov-91	33.04	48000	1.03161	-27.1	0.6086	0.09148	33.33

discharge complex of up to about 1.5m (Table **1**). i.e. the hydraulic heads within the discharge complex are highly dependent on local conditions within the lakes. Although seasonal data are not available for the Scotia Discharge Complex, investigations of other groundwater discharge complexes indicate that the variations are likely to be seasonally dependent and strongly linked to evaporation and local accumulation of rainfall recharge.

Lateral hydraulic gradients between the regional Renmark Group aquifer and the Renmark Group aquifer beneath the discharge complex.

Lateral gradients between the regional Renmark Group aquifer and the Renmark Group aquifer beneath the discharge complex (Table **1**) indicate a potential for groundwater flow from Scotia North towards the discharge complex.

Vertical Hydraulic gradients between the Parilla Sand and the Renmark Group Aquifers.

At Scotia North, the vertical hydraulic heads (environmental water heads) between the regional Parilla Sand aquifer and the underlying Renmark Group aquifer (Table **2**) indicate a strongly upwards vertical gradient from the Renmark Group to the Parilla Sand.

The vertical hydraulic heads between the Yamba/Parilla Sand and the Renmark Group aquifers beneath the discharge complex were determined by combining the Yamba/Parilla Sand data from SHL/Land with that from the Renmark Group at nearby Scotia Middle Island (Fig. **8**). The gradient beneath the discharge complex is strongly upwards from the Renmark Group to the Yamba/Parilla Sand but its magnitude is lower than at the regional site at Scotia North.

3.8.2 Sub-environments of the Discharge Complex

Surface Water

The active lakes in the discharge complex respond to incoming local rainfall/runoff in three different ways.

(1) In lakes which are clay-surfaced, relatively flat and topographically high in the lake chain (e.g. Scotia Alluvial Lake; Figure **3**), autumn/winter rainfall/runoff first fills cracks in the clay surface and then forms very shallow ponds on the lower areas. Excess water runs off to lower lakes. In summer, the surface dries, the clays re-crack, and efflorescent salts are removed by aeolian deflation.

(2) In sand-surfaced lakes which are topographically intermediate in the lake chain and with a definite dish-shape (e.g Scotia Ironstone Lake; Figure **3**) the rainfall/runoff rapidly saturates the sands and then forms thin (typically 0.05m) sheets of surface water before spilling over the low topographic barriers to the adjoining, lower lakes.

(3) In the lower lakes in the chain which are terminal drainage areas for significant parts of the lake chain (e.g. Scotia Halite Lake), runoff accumulates forming large ponds up to 0.2m deep. The ponds gradually decrease in size and increase in salinity as the drier summer months approach. During summer, the terminal lakes are usually dry and covered by a salt crust deposited from the surface water.

Table 2. Environmental (Vertical) Hydraulic Heads, Scotia North and Scotia Discharge Complex

Site	Piezometer	Aquifer	Date	Zi	Hip	Zr	(density)a	(density)f	(density)i	Hin
Scotia North	SN/20m 39500 mg/L 31.80mAHD	Parilla Sand	Nov-91	23.24	31.8	31.8	1.0258	1	1.0258	31.80
	SN/40m 30000 mg/L 33.47mAHD	Upper Renmark	Nov-91	3.19	33.47	31.8	1.0235	1	1.01926	33.38
	SN/60m 28000 mg/L 33.30mAHD	Upper Renmark	Nov-91	-16.8	33.3	31.8	1.0215	1	1.018	33.27
Scotia Middle Island; near SHL	SHL/Land 93000 mg/L 31.80mAHD	Yamba Formation	Nov-91	24.19	30.4	30.4	1.063	1	1.063	31.80
Scotia Middle Island	SMI/20m 56000 mg/L 32.73mAHD	Upper Renmark	Nov-91	12.8	32.73	30.4	1.05 or 1.037	1	1.037	32.46 or 32.79
	SMI/60m 48000 mg/L 33.04mAHD		Nov-91	-27.1	33.04	30.4	1.038	1	1.0316	32.75

Assumptions:

(1) For SN/20m there is no information on the elevation of the top of the saturated zone so it has been assumed to be co-incident with the SWL in the piezometer. i.e. Zr = Hip

(2) For SN/20m the salinity profile from the midpoint of the piezometer slots to the top of the saturated zone is unknown and it has been assumed that the salinity is constant over this interval and equal to that in the piezometer. i.e. (density)a = (density)i

(3) For the piezometers SN/40m and SN/60m the average density (density)a has been calculated by assuming a linear change between adjacent piezometers.

(4) The piezometer SHL/Land, which is about 50m from the SMI piezometer nest, has been used as the uppermost piezometer in this set. Assumptions for this piezometer are the same as those for SN/20m.

(5) Two assumptions of the changes in density between SHL/Land and SMI/20m have been made.

(a) there is a linear change in salinity between the two piezometers (the same assumption as for the SN piezometer nest); or

or (b) the salinity at SHL/Land is representative of only a thin veneer of saline water and the salinity between the two piezometers is best represented by the salinity at SMI/20m.

SURFACE and GROUNDWATER SALINITY

3.9.1 Discharge Complex and its Regional setting

Surface Water

The one sample of surface water collected in this study (from Scotia Halite Lake) had a salinity of 374,000 mg/L. Considerably lower salinities occur in this lake immediately after major rainfall events.

Groundwater in the Regional Parilla Sand and the Yamba Formation/Parilla Sand

The Parilla Sand groundwater at Scotia North is considered to be typical of that entering the northern area of the discharge complex. It has a salinity of 40,000 mg/L (Table **3**).

Groundwater salinity in the Yamba/Parilla Sand sediments has been measured down core-holes at Scotia Halite Lake, Scotia Scott Lake, Scotia Alluvial Lake and Scotia Ironstone Lake and at the margins of the latter two lakes. Generalised iso-salinity contours for the N-S section across the discharge complex based on these measurements are in Figure **16**. Scotia Halite Lake, Scotia Scott Lake and Scotia Ironstone Lake all show a generally similar pattern of: (1) higher salinity water overlying lower within the lakes and; (2) for Scotia Ironstone Lake at least, lower salinity water overlying higher at the lake margin.

The iso-salinity contours at Scotia Alluvial Lake are more complicated (Figure **16**). Brines in the surficial clay layer are separated from high salinity water in the deeper underlying sands by an area of lower salinity water in the shallower sands immediately below the clay layer.

Profiles of salinity against depth for the individual corehole sites are presented in Figure **17.** Although the salinity varies widely in the upper part of the aquifer, all the salinity-depth profiles tend towards a constant salinity of about 125,000 mg/L near the base of the aquifer. This brine, which is about 3 times the salinity of the regional Parilla Sand groundwater at Scotia North, is widespread in the Yamba/Parilla Sand aquifer in the discharge complex. Because of its position in the deeper part of the aquifer it is considered to be the earliest formed brine in the discharge complex. This phase of hydrodynamic activity is designated Phase **I** and the brine as Scotia Lacustrine Brine, Phase I (SLB(I)). Subsequent hydrodynamic activity, including that of the present-day, is grouped under the general heading of Phase II. The various types of overlying surface and groundwaters are considered to be part of this second phase of hydrodynamic activity.

Groundwater in the Renmark Group

The salinity in the Renmark Group aquifer at Scotia North does not vary with depth and is 28,000mg/L in both SN/40m and SN/60m (Table **3**).

The salinity in the Renmark Group beneath the discharge complex (Table **4**, Figure **18**), is higher (46,00 to 54,000 mg/L) \than that in the Renmark Group at Scotia North. Beneath the discharge complex the salinity decreases with depth (54,000 to 52,000 to 46,000 mg/L in SMI/20m, 40m and 60m, respectively).

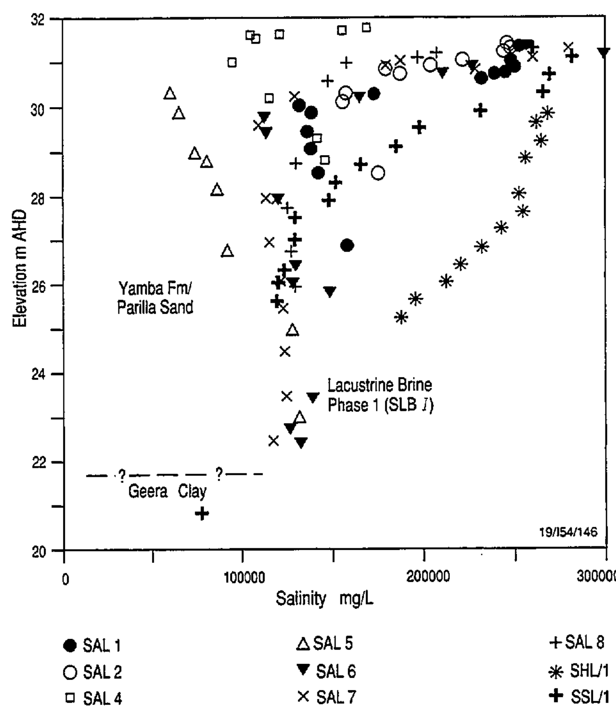


Fig. 17 Changes in groundwater salinity with depth for a variety of sites in the Yamba/Parilla Sand sediments of the discharge complex.

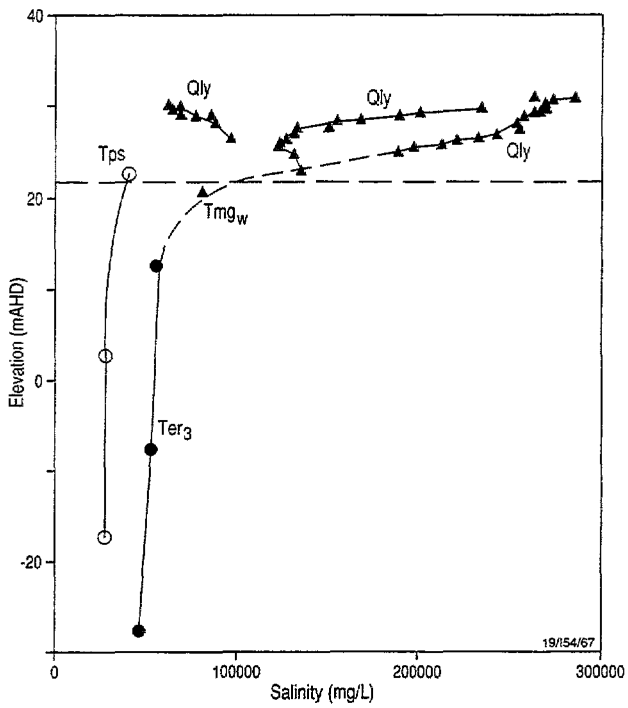


Fig. 18 Salinity-depth relationships between: (1) the regional Parilla Sand and Renmark Group aquifers at Scotia North, and (2) three contrasting sites in the Yamba/Parilla Sand aquifer, the weathered Geera Clay, and the Renmark Group beneath the discharge complex.

The only sample obtained from the Geera Clay has a salinity (262,000 mg/L) intermediate between those in the locally overlying Yamba/Parilla Sand and underlying Renmark Group.

3.9.2 Sub-environments of the Discharge Complex

Although there is a general decrease in salinity with depth within all of the active lakes in the discharge complex, in detail, three different types of profile can be discerned (SAL, Figure **19**; SSL, and SHL, Figure **20**).

(1) Profiles in which major salinity and other geochemical discontinuities occur at the sand-clay boundaries. This situation occurs in Scotia Alluvial Lake where there is a salinity minimum immediately beneath the surficial clay (e.g. SAL 1; Figure **19**).

(2) Profiles in which there are minor discontinuities but a pronounced change in the slope of the salinity - depth profile at the sand-clay boundaries. This type of profile occurs for example in Scotia Halite Lake (SHL 1; Figure **20**).

(3) Profiles which are a relatively smooth curve of decreasing salinity with depth. In Scotia Scott Lake this situation occurs over a sedimentary section about 4 to 5m in thickness (SSL 1; Figure **20**).

These differences are related to differences in the ratio of vertical versus lateral flow which, in turn, is related to differences in permeability caused by the presence of clay and sand layers. In the section of Scotia Scott Lake where vertical movement appears dominant, there are several thin clay layers but the overall ratio of sand to clay is relatively high (slightly more than 2:1).

HYDROCHEMISTRY

3.10.1 Isotopic Data

δD and $\delta^{18}O$

Deuterium and oxygen stable isotope data (Tables **3** and **4**) provide little information on the sources of water in the discharge complex (potentially, local rainfall/runoff, regional Parilla Sand groundwater, and Renmark Group groundwater). Groundwaters from the regional Parilla Sand and Renmark Group aquifers at Scotia North are not distinctively different on a δD v $\delta^{18}O$ plot (Figure **21a**). Local rainfall -influenced Parilla Sand groundwater can be detected on δD v salinity plots (Figure **21b**) if its salinity is lower than that of the incoming regional Parilla Sand groundwater. However, these differences are obscured in higher salinity waters by the effects of evaporation, dilution and re-solution of salts.

Evaporation, dissolution of salts, and mixing in the discharge complex influence the relationships between δD and $\delta^{18}O$ (Figures **21a** and **22**), δD and salinity (Figure **21b**) and δD and Cl/Br (Figure **21c**).

The simplest of these relationships is the linear plot of δD v $\delta^{18}O$ data for the Parilla

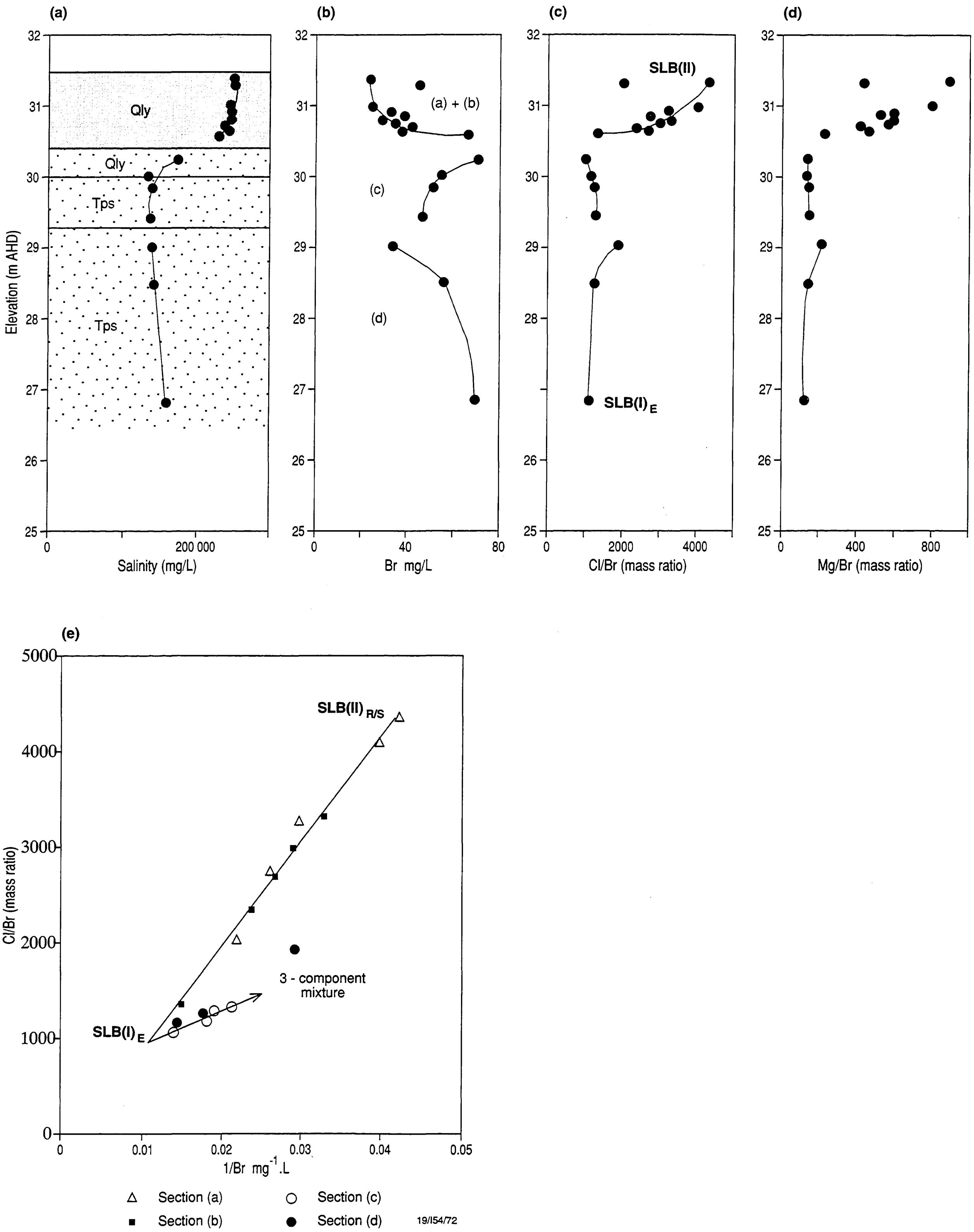


Fig. 19 Geochemistry of groundwater in the Yamba/Parilla Sand sediments at site SAL 1 in Scotia Alluvial Lake.

A-D Changes with depth showing three distinct segments to the profile

E Cl/Br v 1/Br showing the two distinct mixing lines.

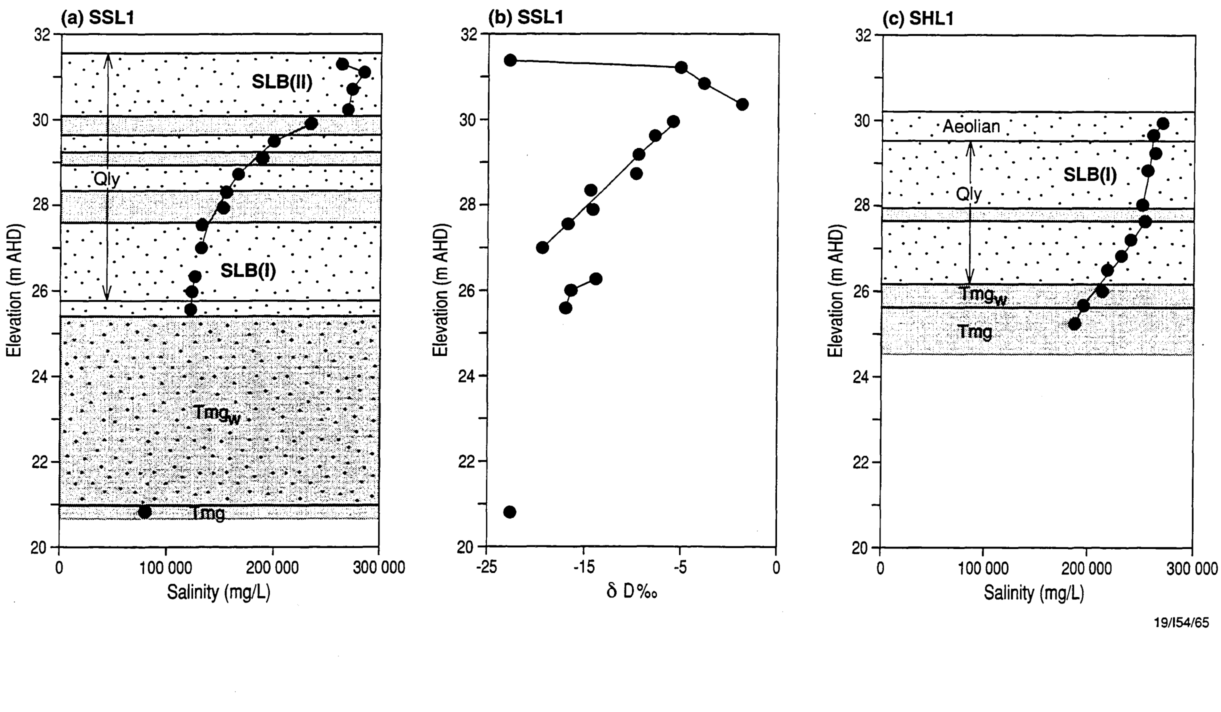


Fig. 20 Changes in salinity (a) and ∂D (b) with depth for site SSL 1 in Scotia Scott Lake, and changes in salinity with depth for site SHL 1 in Scotia Halite Lake.

Table 3. Chemical Composition of Regional Parilla Sand and Renmark Group Groundwater, Scotia North .

General data

Site	Sample	Date	Lab Ref	Average Depth (m)	Elevation (m AHD)	Salinity mg/L	pH	Alkalinity (meq/L)
Scotia North	SN/20m	Nov-90	900952	20.00	22.70	40000	6.51	5.20
	SN/40m	Nov-90	900951	40.00	2.70	28000	6.54	2.30
	SN/60m	Nov-90	900950	60.00	-17.30	28000	5.90	4.10

Major Ions (mg/L)

Lab Ref	Ca	Mg	Na	K	Sr	Li	Cl	SO4	NO3	Br
900952	967	1830	11400	174	16.8	0.39	18300	6840	33	56
900951	641	1230	8370	117	13.0	0.21	13800	4800	25	37
900950	688	1280	8170	107	12.9	0.22	13300	4930	24	37

Minor Ions (mg/L)

Lab Ref	Fe	Mn	Cu	Zn	Si	B
900952	5.5	0.39	0.060	<0.200	14.1	5.5
900951	27.3	0.71	<0.005	0.230	4.7	4.4
900950	17.9	0.35	0.060	0.150	4.7	4.5

Fractionated ions and isotopes

Lab Ref	∂ D (ppb)	∂ 18O (ppb)	∂13C (ppb)	87Sr/86Sr	%2sigma	36Cl/Cl (10^-15)	36CL (atoms/L)
900952	-32.0	-3.61	-4.6	0.71475	0.00150	70(5)	
900951	-33.1	-2.83	-12.4				
900950	-35.2	-4.51	-13.9	0.71456	0.00021	41(5)	9400(+/-1200)

Weight Ratios

Lab Ref	Ca/Br	Mg/Br	Na/Br	K/Br	Cl/Br	SO4/Br
900952	17	33	203	3.10	326	122
900951	17	33	226	3.15	372	129
900950	19	35	223	2.92	362	134

Non Br ion ratios

Lab ref	Sr/Ca	Na/Cl	1/Br
900952	0.017	0.623	0.018
900951	0.020	0.607	0.027
900950	0.019	0.614	0.027

Table 4. Chemistry of Renmark Group Groundwaters beneath Scotia Discharge Complex, Scotia Middle Island.

General data

Location	Sample	Date	Lab Ref	Depth below GL(m)	Elevation (m AHD)	Salinity mg/L	pH	Alkalinity (meq/L)
Scotia Middle Island	SMI/20m	Aug-90	900949	20.00	12.40	54000	6.240	2.600
	SMI/40m	Oct-90	900948	40.00	-7.60	52000	6.780	3.900
	SMI/60m	Nov-90	900947	60.00	-27.60	46000	7.460	5.900

Major Ions (mg/L)

Lab Ref	Ca	Mg	Na	K	Sr	Li	Cl	SO4	NO3	Br
900949	727	2320	17200	248	12.2	0.440	27400	6500		58.7
900948	757	2210	16600	237	12.3	0.430	27900	6240	159	66.4
900947	767	1790	14800	213	11.8	0.370	24800	4210	16	62.2

Minor Ions (mg/L)

Lab Ref	Fe	Mn	Cu	Zn	Si	B
900949	40.900	0.880	0.040	<0.200	1.170	3.800
900948	33.000	1.280	0.040	<0.200	6.100	3.690
900947	6.870	0.360	0.050	<0.200	4.830	3.610

Fractionated Ions and Isotopes

Lab Ref	∂ D (ppb)	∂ 18O (ppb)	∂13C (ppb)	87Sr/86Sr	%2sigma	36Cl/Cl (10^-15)	36CL (atoms/L)
900949	-27.7	-2.240	-12.1			64(5)	30700(+/-2800)
900948	-27.2	-2.950					
900947	-28.3	-2.450	-11.8	0.71418	0.00023	57(4)	23800(+/-2000)

Br Ion ratios

Lab Ref	Ca/Br	Mg/Br	Na/Br	K/Br	Cl/Br	SO4/Br
900949	12	40	293	4.2	467	111
900948	11	33	250	3.6	420	94
900947	12	29	238	3.4	399	68

Non Br ion ratios

Lab ref	Sr/Ca	Na/Cl	1/Br
900949	0.017	0.628	0.0170
900948	0.016	0.595	0.0151
900947	0.015	0.597	0.0161

Sand groundwater at Scotia North and the Yamba/Parilla Sand groundwater in the discharge complex (Figure **21a**). The slope of the Scotia δD v $\delta^{18}O$ line is about 4.5, which is intermediate between the slopes of the regional Parilla Sand groundwaters (Figure **22**) from throughout the Murray Basin, which range from about 2.3 to 6. The slope of the Scotia line is somewhat higher than that expected for evaporation from the capillary zone, which could indicate that evaporation from surface water is significant. On the other hand, the maximum δD values of groundwaters in the discharge complex are about -5‰ (Figure **21b**) whereas surface waters reach considerably higher ∂D values (e.g. 31‰ in SHL). This suggests that the groundwater δD values are capillary-evaporation limited.

The plots of δD v salinity indicate that, despite the simple linear δD v $\delta^{18}O$ relationship, the isotopic changes probably result from a complex combination evaporation in the discharge complex of a mixture of regional Parilla Sand groundwater and local rainfall, followed by mixing of the more and less evaporated waters. The δD v salinity plot (Figure **21b**) shows a general trend but with a significant scatter of data points and large deviations from the trend.

The scatter of data is probably caused by minor dissolution or precipitation of salts and/or mixing with other waters. The large deviations result from major recharge/dissolution events and precipitation of large quantities of salts. Waters whose data plot considerably below the main δD v salinity trend occur in the uppermost sand layer in Scotia Scott Lake after winter rainfall (SSL 1, Figures **20** and **21b**). There, recharge by rainfall dissolves surficial salts and infiltrates rapidly, with the result that the salinity is high but the near-surface δD values have the low values typical of almost non-evaporated rainfall. Waters whose data plot considerably below the main trend, probably form because ∂D has continued to increase by surface evaporation beyond the point where precipitation of halite and other evaporites limit the increase in salinity (e.g the highly saline surface water from SHL; Figure **21b**).

Mixing of groundwater types which differ in both their δD and Cl/Br values is evident from the data in Figure **21c**. Two types of mixing occur: (1) mixing between two waters which differ in both δD and Cl/Br; and (2) mixing of two waters with similar δD but different Cl/Br values (the line parallel to the x-axis in Figure **21c**).

$^{36}Cl/Cl$ ratios

The $^{36}Cl/Cl$ ratio of the regional Parilla Sand groundwater at Scotia North (70) is the same, within experimental error, as those of two highly saline samples from the Yamba Formation/Parilla Sand (71 and 69) in the discharge complex (Tables **3** and **4** and Figure **16**). All three ratios are considerably different from the ratio in the Renmark Group at Scotia North (41). This implies that the Renmark Group aquifer is not and has not been a significant source of groundwater in the discharge complex.

The $^{36}Cl/Cl$ ratios in the Renmark Group groundwaters underlying the discharge complex are 64 and 57 (Figure **16**), which is significantly higher than the value for the Renmark Group at Scotia North (41). The higher ratios in the Renmark Group underlying the discharge complex indicate that chloride has reached the Renmark Group from the overlying

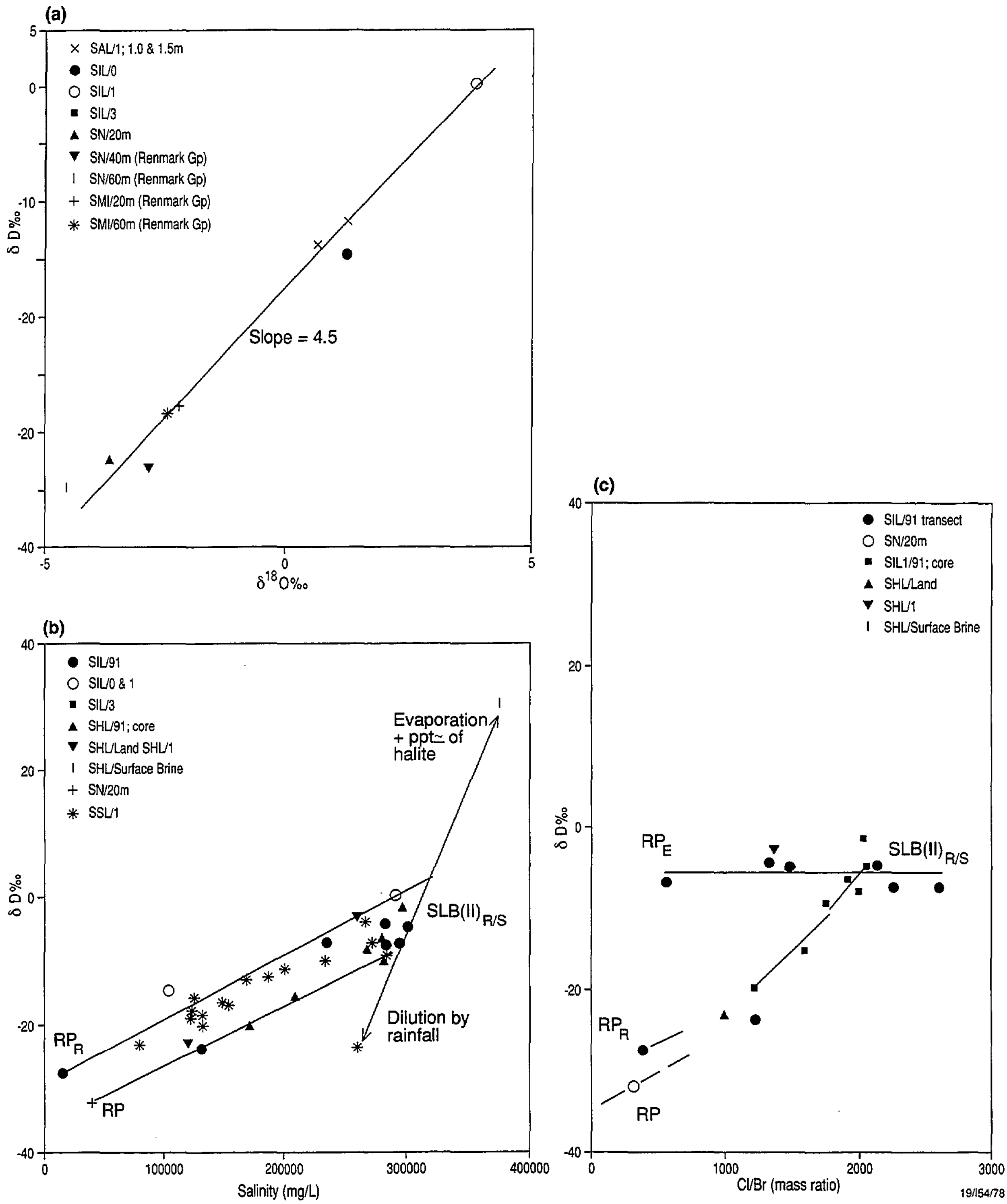


Fig.21 Examples of the relationship of ∂D and ∂18O to other chemical parameters of Scotia Parilla Sand and Yamba/Parilla Sand groundwaters.

(a). ∂D v ∂18O for the Parilla Sand and Renmark Group aquifers.

(b). ∂D v salinity showing the scatter caused by the presence of the two isotopically slightly different waters.

(c). ∂D v Cl/Br showing mixing between two waters with similar ∂D but different Cl/Br, and mixing between regional Parilla Sand or regional Parilla Sand groundwater plus rainfall with and evaporated water of higher ∂D and Cl/Br.

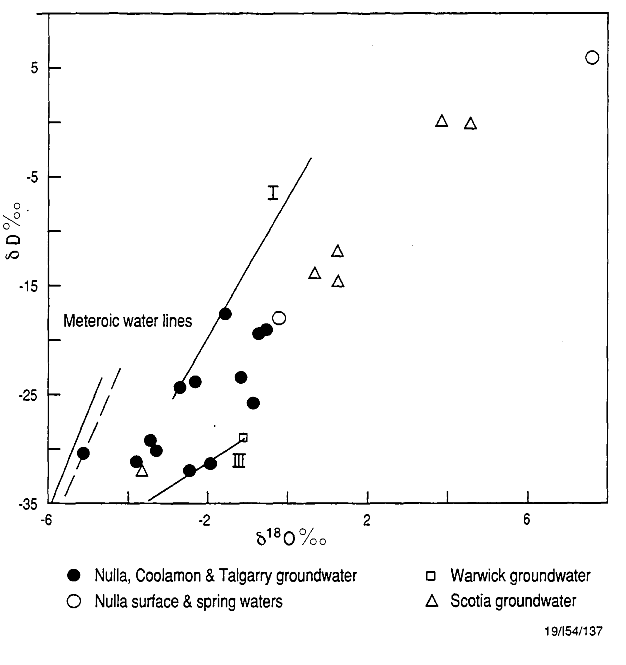


Fig. 22 Comparison of ∂D to ∂18O in the Yamba/Parilla Sand groundwater of the Scotia Discharge Complex groundwater to the Murray Basin -wide trends for the Parilla Sand.

Yamba Formation/Parilla Sand *via* the Geera Clay.

$^{87}Sr/^{86}Sr$ ratios

The $^{87}Sr/^{86}Sr$ ratios (**Tables 3** and **4** and Figure **16**) for groundwater in the Parilla Sand and Renmark Group at Scotia North, the Yamba Formation/Parilla Sand and the weathered zone of the Geera Clay beneath the discharge complex, and the underlying Renmark Group all lie in the narrow range 0.71407 to 0.71475. This range is considerably higher than the value for present-day seawater (0.70915). Most likely, the radiogenic $^{87}Sr/^{86}Sr$ ratios have been inherited from a common source in the recharge zone at the northern margin of the Murray Basin.

The lower values in the range are for a groundwater from the weathered area of the Geera Clay (0.71407) and for the Renmark Group below the discharge complex (0.71418). These slightly lower values could indicate the presence of a minor amount of Miocene Sr from the Geera Clay.

3.10.2 Major Ion Chemistry

3.10.2.1 Parilla Sand and Yamba Formation/Parilla Sand

The relationships between the major ion chemistry of the regional Parilla Sand groundwater at Scotia North and the groundwaters in the Yamba/Parilla Sand sediments of the discharge complex have been examined using three criteria.

(1) Differences between the Cl/Br ratios of the waters, as displayed by graphs of Cl/Br against 1/Br (chosen because mixing of two different waters will produce a linear relationship).

(2) Comparison of the actual major ion composition of the discharge complex groundwater with that predicted during evaporation of the Scotia North regional Parilla Sand groundwater.

(3) Analysis of the major ion composition of the regional and discharge complex waters using salt norm (SNORM) calculations.

Cl/Br Ratios

A graph of Cl/Br against 1/Br for all of the Scotia North and Yamba/Parilla Sand data is in Figure **23**(a) and an interpretation of this data is in Figure **23**(b). On this basis the following types of groundwater (Table **5**) are recognised.

Regional Parilla Sand Groundwater and its Dilution and Evaporation Products:

(1) Regional Parilla (RP). This is the regional Parilla Sand groundwater at Scotia North. It has a Cl/Br ratio of 330 and a salinity of 40,000 mg/L.

(2) Regional Parilla diluted by rainfall (RP_R). This water has a Cl/Br ratio similar to that of the regional Parilla water but a lower salinity (e.g. 15,000 mg/L.

(3) Evaporated Regional Parilla (RP_E). This water has a similar Cl/Br ratio but a higher salinity (e.g. 291,000 mg/L) than the regional Parilla groundwater.

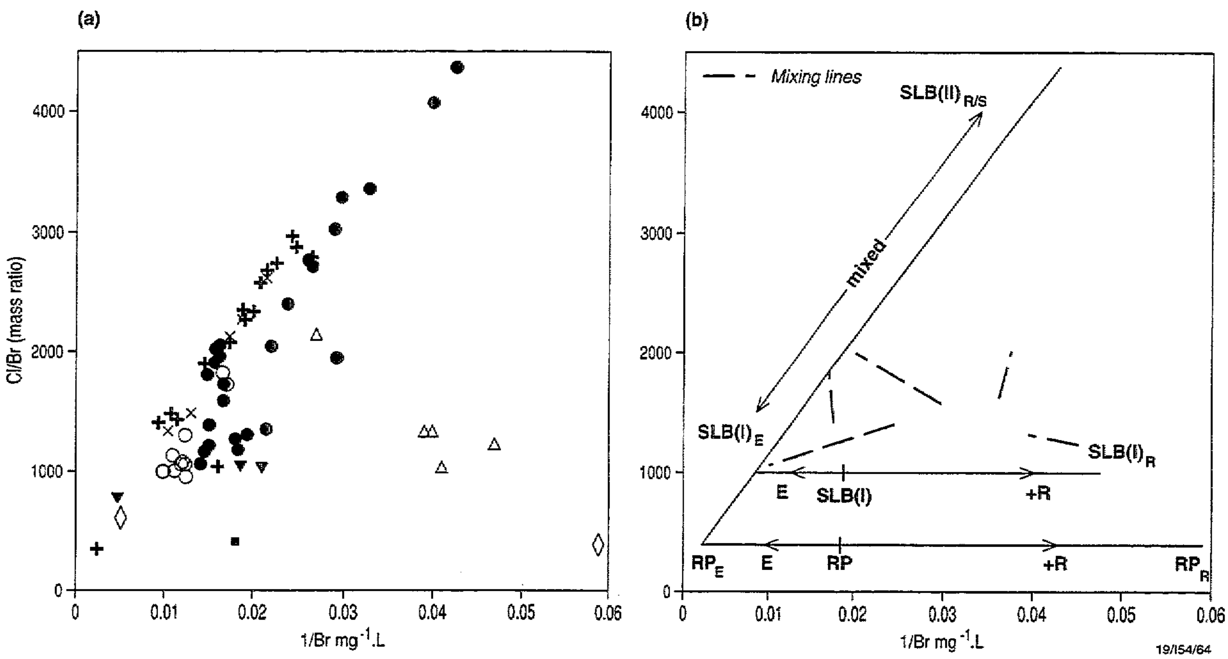


Fig. 23 (a) Relationship of Cl/Br to 1/Br and (b) an interpretation of these relationships for the Parilla Sand and Yamba Formation groundwaters. Mixing will result in linear relationships on this type of plot.

Table 5. Major Classes of Surface Water and Groundwater in the Regional Parilla Sand and Yamba Formation/Parilla Sand Aquifers, Scotia North and Scotia Discharge Complex

Type	Abbreviation	Location	Salinity (mg/L)	pH	∂D (‰)	$\partial^{18}O$ (‰)	Cl/Br (mass ratio)
Regional Parilla Groundwater	*RP*	SN/20m	40,000	6.5	-32	-3.6	330
Regional Parilla Groundwater; diluted by Local Rainfall(R)	RP_R	SIL 4/91	15,000		-28		390
Regional Parilla Groundwater; evaporated(E)	RP_E	SIL/1	291,000		0.3	3.9	355
Scotia Lacustrine Brine, Phase I	*SLB-1*	SSL/1(piezometer)	125,500	7.7			1020
		SSL/1(5.68m)	123,000		-18		
Scotia Lacustrine Brine Phase I; diluted by Local Rainfall	$SLB(I)_R$	SAL 5(2.08)	67,000	5.0			1020
		SHL/Land	120,200	7.15	-23		1010
Scotia Lacustrine Brine Phase I: evaporated(E)	$SLB(I)_E$	SAL 2(1.38m)	156,000	5.3			990
		SIL/O	146,000		-14	1.3	1040

Table 5 (continued). Major Classes of Surface Water and Groundwater in the Regional Parilla Sand and Yamba Formation/Parilla Sand Aquifers, Scotia North and Scotia Discharge Complex

Type	Abbreviation	Location	Salinity (mg/L)	pH	∂D (‰)	$\partial^{18}O$ (‰)	Cl/Br (mass ratio)
Scotia Lacustrine Brine Phase II; Rainfall or Evaporated Rainfall Containing Re-dissolved Salts(R/S)	*SLB (II)* $_{R/S}$	SAL 1/0.08m	252,000	6.1			4400
		SIL 1/91 (Core)	296000		-1	3.1	2020
Scotia Lacustrine Brine Phase II; Evaporation of (?)a Mixture of SLB (II) $_{R/S}$ *and* RP_E	*SuB (II)* $_E$	SHL SurfaceWater	374,000	7.3	31		750

			SNORM(mole%)			
			Na_2Cl_2 (Na_2SO_4)	$MgCl_2$ ($MgSO_4$)	$CaSO_4$ ($CaCl_2$)	K_2Cl_2 (K_2SO_4)
Regional Parilla Groundwater	*RP*	SN/20m	71	8 (11)	4	0.6
Scotia Lacustrine Brine, Phase I	*SLB-1*	SSL/1(piezometer)	68	4 (26)	2	0.4
Scotia Lacustrine Brine Phase II	*SLB (II)* $_{R/S}$	SAL 1/0.08m	59 (3)	0 (38)	0.4	0 (0.3)
Scotia Lacustrine Brine Phase II	*SuB (II)* $_E$	SHL SurfaceWater	57	10 (32)	0.1	1.0

Scotia Lacustrine Brine Phase I and its Dilution and Evaporation Products::

(4) Scotia Lacustrine Brine, Phase I (SLB(I)). This is the brine which occurs in the deeper parts of the Yamba/Parilla Sand aquifer. It has a much higher Cl/Br ratio (1000) and salinity (125,000 mg/L) than the Regional Parilla Sand water.

(5) Scotia Lacustrine Brine, Phase I, diluted by rainfall ($SLB(I)_R$)

(6) Scotia Lacustrine Brine, Phase I, concentrated by evaporation ($SLB(I)_E$)

Scotia Lacustrine Brine Phase II and its Derivatives::

(7) Scotia Lacustrine Brine, Phase II ($SLB\ (II)_{R/S}$). This brine has formed by re-solution of evaporite efflorescences by rainfall. It is the most distinctive of the variety of surface and groundwaters formed during Phase II. It has a high salinity (252,000 mg/L) and an extremely high Cl/Br ratio (4400). It occurs mainly in the shallower sediments in some areas of the discharge complex.

Most groundwater in the discharge complex is mixtures of these groundwater types. Mixing between two of the major types ($SLB(II)_{R/S}$ and $SLB(I)_E$) is readily evident in Figure **19(e).** Three-component mixing is also extensive (Figures **19(e)** and **23(b)**).

Surface water in the discharge complex is typified by the brine in Scotia Halite Lake which forms after winter rainfall. ($SuB(II)_{E;}$ Table **5**). It has complex origins and is best explained as evaporated groundwater altered by rainfall re-solution of evaporites precipitated during summer.

Geochemical Modelling

Geochemical calculations (Chambers et al., 1995) of the predicted evaporation path of the regional Parilla Sand groundwater (SN/20m) indicate that significant modification in the major ion chemistry of the groundwaters (other than those due soley to evaporation) have occurred within the discharge complex. i.e. the changes in the Cl/Br ratios described above are not solely related to changes in Br concentrations.

The molal composition of the regional Parilla Sand groundwater at Scotia North is shown in Table **6**, and ion concentrations and solids expected in an equilibrium evaporation at 25°C are shown in Figure **24.**

The Scotia regional Parilla Sand groundwater is chemically different from seawater. Equilibrium evaporation of the Scotia North Parilla Sand groundwater would produce glauberite, before halite saturates, through reaction of the brine with gypsum.

$$CaSO_4 . 6H_2O + 2Na^+ + SO_4^{2-} = CaNa_2(SO_4)_2 + 6H_2O$$

The most notable difference from seawater is that bloedite is predicted to saturate in the presence of glauberite and then more is formed by reaction of the brine with glauberite. This reaction also produces anhydrite.

$$CaNa_2(SO_4)_2 + Mg^{2+} + SO_4^{2-} + 4H_2O = MgNa_2(SO_4)_2 \cdot 4H_2O + CaSO_4$$

Subsequently, bloedite is replaced by polyhalite and epsomite in reaction with the brine.

$$2MgNa_2(SO_4)_2 \cdot 4H_2O + 2Ca^{2+} + SO_4^{2-} + 2K^+ + H_2O$$
$$= K_2MgCa_2(SO_4)_4 \cdot 2H_2O + MgSO_4 \cdot 7H_2O + 4Na^+$$

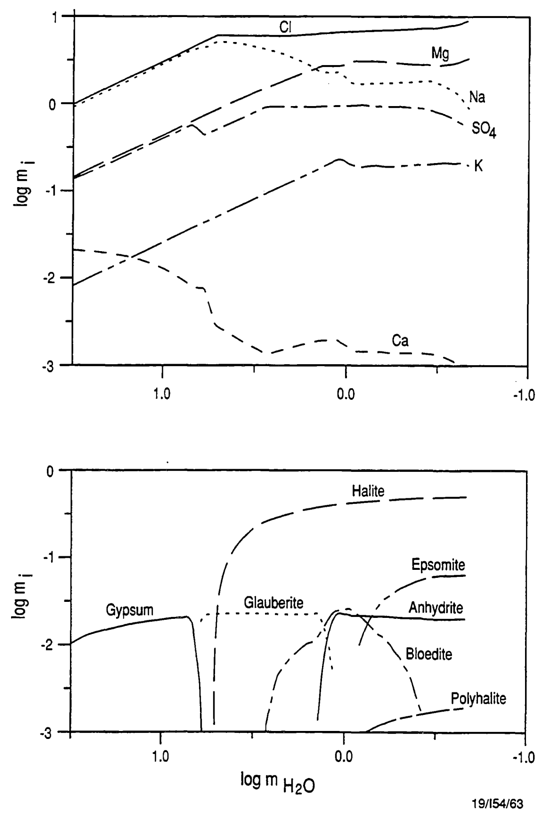


Fig. 24 Equilibium evaporation of Scotia regional water. Upper portion shows molalities of major solutes and lower section shows solids in equilibrium from 1kg water as H_2O is removed in evaporation at 25°C.

These differences are also evident in the plots of Mg and SO_4 relative to Cl concentration (Figure **25**).

Table 6. Molal Composition of Regional Parilla Sand Groundwater at North Scotia

	Concentration (molal)
Na	0.50322
K	0.00452
Mg	0.07640
Ca	0.02450
Cl	0.53481
SO4	0.09011
Br	0.00063

The composition of shallow groundwater samples from Scotia Ironstone Lake (Table **7**) are compared with the expected compositions of the evaporated regional Parilla Sand waters in Figure **25.** These plots show enhanced Mg and SO_4 concentrations compared to the evaporated regional water, while Na appears to be reduced in some cases. The higher ionic strength relative to Cl concentration reflects the addition of the divalent ions.

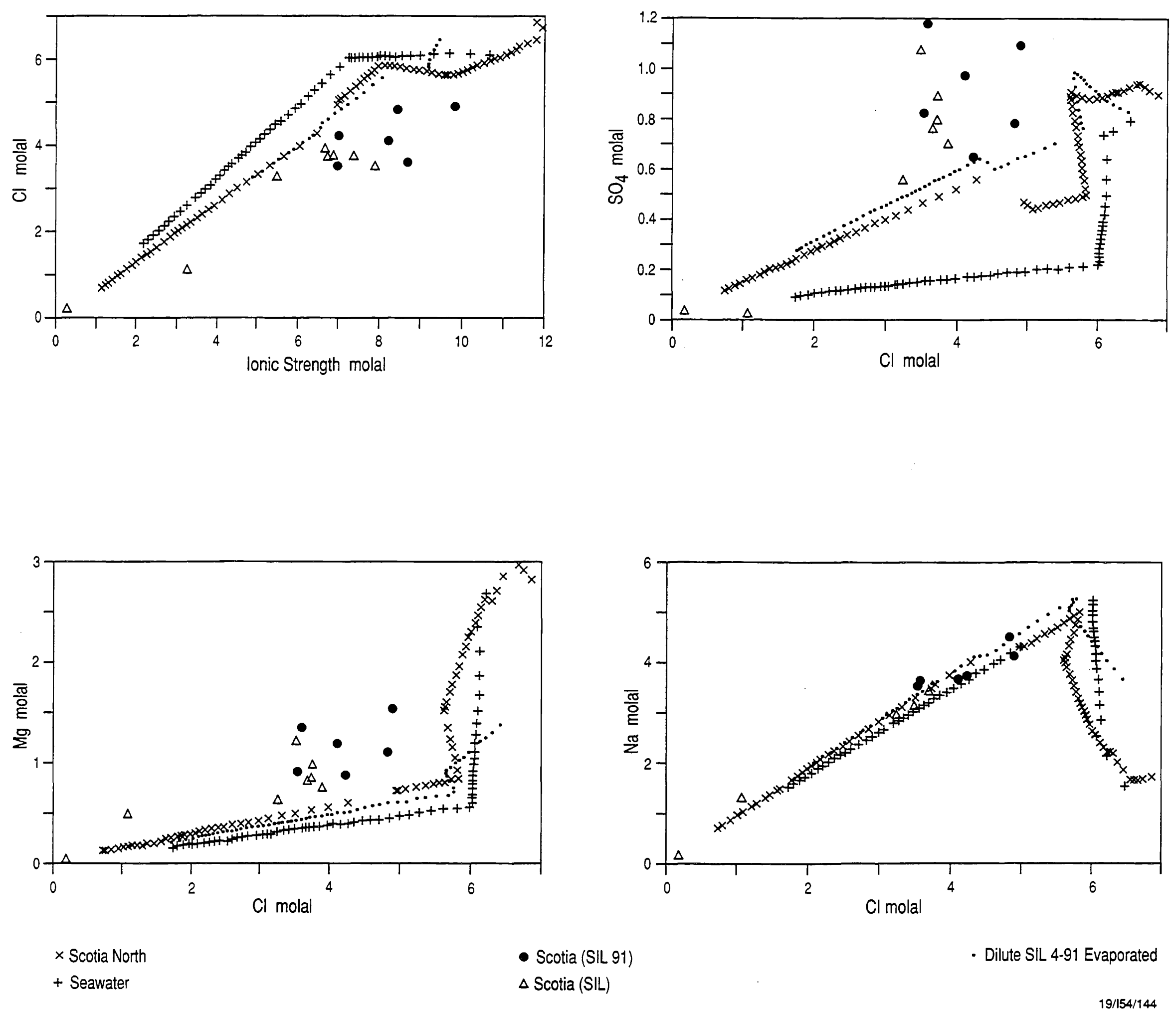


Fig. 25 Comparison of the ionic composition of shallow groundwater from transects along (SIL) and across (SIL 91) Scotia Ironstone Lake (Figure **3.4**) with the compositions expected from equilibrium evaporation (at 25°C) of the regional Parilla Sand groundwater at Scotia North and a relatively low salinity sample from SIL 91 (SIL 4/91). Seawater evaporative concentration is also included.

Table 7. Molal Composition of Shallow Groundwater from Scotia Ironstone Lake

	Na *molal*	*K* *molal*	*Mg* *molal*	*Ca* *molal*	*HCO3* *molal*	*Cl* *molal*	*SO4* *molal*
SIL 1	3.729	0.0213	0.870	0.0067	0.0009	4.236	0.649
2	4.511	0.0261	1.103	0.0032	0.0023	4.836	0.783
3	3.665	0.0184	1.186	0.0048	0.0009	4.117	0.970
4	3.626	0.0242	1.274	0.0050	0.0018	3.710	1.087
5	3.479	0.0221	1.277	0.0053	0.0023	3.514	1.099
6	3.646	0.0240	1.345	0.0048	0.0023	3.592	1.178
7	3.535	0.0214	1.194	0.0048	0.0023	3.481	1.093
8	3.789	0.0215	1.223	0.0033	0.0023	3.687	1.155
9	3.976	0.0239	1.306	0.0055	0.0023	3.797	1.218
10	3.527	0.0194	1.220	0.0055	0.0023	3.680	1.147
12	3.679	0.0230	1.189	0.0073	0.0023	3.611	1.075
14	4.182	0.0278	1.105	0.0051	0.0023	4.041	1.059
15	3.570	0.0211	0.953	0.0068	0.0009	3.714	0.895
17	3.657	0.0214	0.906	0.0072	0.0022	3.609	0.794
18	3.529	0.0227	0.907	0.0078	0.0022	3.544	0.819
19	3.630	0.0222	0.927	0.0078	0.0022	3.669	0.759
SIL 91/1	3.207	0.0196	0.778	0.0066	0.0020	3.440	0.710
/2	3.665	0.0182	0.753	0.0078	0.0022	3.874	0.698
/3	2.958	0.0159	0.645	0.0112	0.0022	3.234	0.550
/4	0.180	0.0009	0.023	0.0042	0.0021	0.189	0.031
/6	3.400	0.0189	0.856	0.0072	0.0022	3.708	0.790
/7	3.476	0.0174	0.924	0.0063	0.0022	3.704	0.879
/8	3.089	0.0183	1.210	0.0062	0.0022	3.445	1.053
/9	1.274	0.0079	0.487	0.0110	0.0021	1.372	0.467

Calculations of the deviations from the predicted evaporation path for waters with Cl ≤ 4.25 m (the concentration at which glauberite is predicted to form in an evaporated regional water) are shown in Table **8**. The values show a variety of relationships. For example, some waters have a deficiency of Na and SO_4, which suggests that re-solution of Mg-rich epsomite and bloedite and precipitation of glauberite may have occurred.

Table 8. Excess Concentrations of Cl, Na, Mg and SO_4 Over those Expected For Evaporated Regional Parilla Sand Groundwater

SAMPLES	*Cl molal*	*Excess Na molal*	*Excess Mg molal*	*Excess SO4 molal*
SIL 1	4.235	-0.26	0.26	0.10
3	4.116	-0.21	0.60	0.43
6	3.59	0.27	0.83	0.70
8	3.543	0.19	0.40	0.35
SIL 91/1	3.682	-0.03	0.31	0.28
/2	3.882	0.02	0.20	0.19
/3	3.248	-0.09	0.18	0.12
/4	0.19	0.00	0.00	-0.02
/6	3.729	-0.09	0.33	0.30
/7	3.742	-0.01	0.46	0.40
/8	3.502	-0.15	0.73	0.61
/9	1.089	0.27	0.34	-0.14

Salt Norms

An alternative way of looking at the changes in major ion composition of the groundwater is to compare the salt norms (as calculated by the computer program SNORM; Bodine and Jones, 1987) of the regional Parilla Sand groundwater with those of groundwater in the discharge complex. The salt norms are the composition of the equilibrium salt assemblage which would be precipitated if the water was evaporated to dryness.

Salt norms (in mole %) for the regional Parilla Sand groundwater at Scotia North and a series of samples from core-hole SAL 1 in Scotia Alluvial Lake are presented in Table **9** and in Figure **26**. These samples were chosen because their Cl/Br ratios lie along a well-defined mixing line (Figure **19e**) between an evaporated Scotia Lacustrine Brine Phase I ((SLB(I)$_E$) and a brine formed by re-solution of salt by rainfall (SLB(II)$_{R/S}$). The differences between the

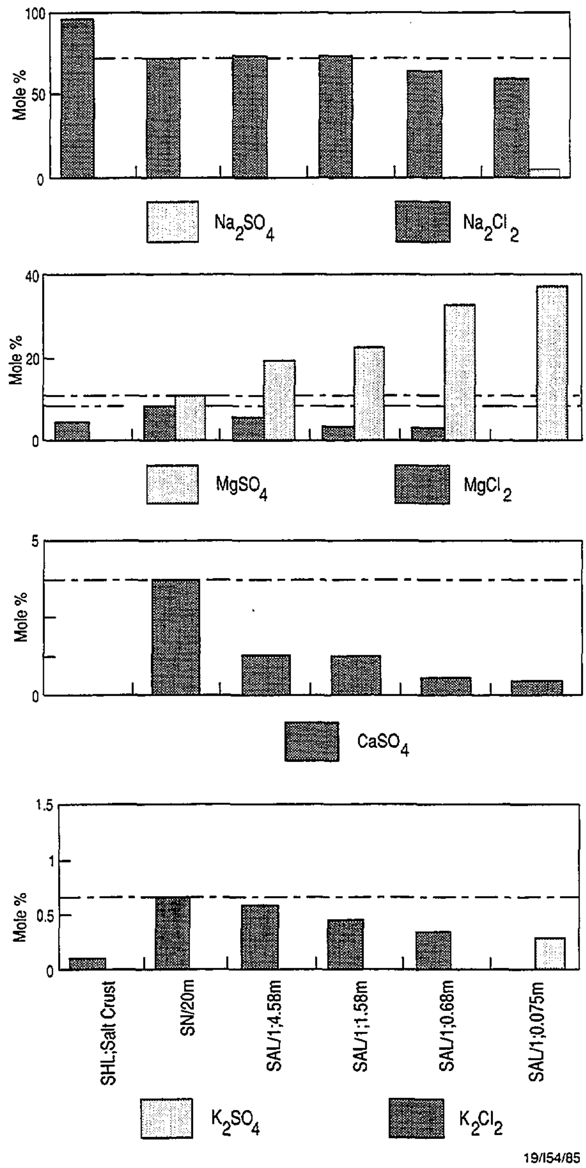


Fig. 26 Comparison of the normative salt content (in mole %) of the Parilla Sand groundwater at Scotia North with a series of samples from the Yamba/Parilla Sand in Scotia Alluvila Lake and a surficial salt crust from Scotia Alluvial Lake. The Cl/Br ratios of the SAL samples increase from left to right on the diagram.

various samples indicate that, as the Cl/Br ratio increases: (1) the Na content becomes lower and, for the R/S-dominated sample, the counterion becomes partly SO_4 rather than exclusively Cl, (2) the Mg content becomes higher and the ratio $MgSO_4/MgCl_2$ increases; (3) the $CaSO_4$ content decreases; and (4) the K content decreases and, for the R/S dominated sample, the counter-ion becomes partly SO_4 rather than exclusively Cl.

The R/S end-member of this series contains almost exclusively NaCl and $MgSO_4$, with a small proportion of Na_2SO_4 (about 3%) and a trace of K_2SO_4 (about 0.3%).

3.10.2.2 Renmark Group

The regional Parilla Sand and Renmark Group groundwaters at Scotia North have generally similar ratios of major ions to Br (Tables **3** and **4**).

Beneath the discharge complex the Renmark Group groundwaters appear to have been altered by downwards movement of more than one type of groundwater and/or salt. The Na/Br and Cl/Br ratios in the Renmark Group beneath the discharge complex are higher than at Scotia North and they decrease with increasing depth (e.g. Cl/Br decreases from 470 to 420 to 400). This is consistent with downwards movement of groundwater or salt from the overlying discharge complex into the Renmark Group. However, the Mg/Br and SO_4/Br ratios in the deepest part of the aquifer are lower than those in the Renmark Group at Scotia North (29 c/f. 34 and 70 c/f. 130), indicating the presence of a third type of groundwater or salt (other than regional Renmark Group groundwater and Yamba/Parilla Sand discharge complex groundwater salts) in the Renmark Group beneath the discharge complex.

The normative salt compositions (Table **9**; Figures **26** and **27**), and in particular the $MgSO_4/MgCl_2$ ratio, are also consistent with two different inputs of groundwater or salt to the Renmark Group underlying the discharge complex. At Scotia North, the ratio in the Renmark Group is almost constant at about 0.43. In the Yamba/Parilla Sand of the discharge complex the ratio varies widely but all measured values are lower than that in the Parilla Sand at Scotia North (0.73), and a ratio of 0.15 is probably the most pertinent. In the Renmark Group beneath the discharge complex the ratios increase with depth (from 0.84 in SMI/40m to 1.64 in SMI/60m) which is consistent with the addition of low $MgSO_4/MgCl_2$ salt from the overlying Yamba/Parilla Sand aquifer (Figure **27**). However, these ratios are much higher than those in Renmark Group waters at Scotia North. i.e. the Renmark Group aquifer beneath the discharge complex shows signs of influence by an earlier salinisation phase, possibly by downwards-moving connate salt from the Geera Clay.

3.10.3 Distribution of Groundwater Types in the Discharge Complex

The distribution of the various types of groundwater in an individual active lake and how the lake groundwaters interface with the other types of groundwater at the lake margins have been investigated at Scotia Ironstone Lake.

Table 9. Calculated Salt Norms of Groundwater and Evaporites, Scotia North and Scotia Discharge Complex

Concentrations are in mole%

	Lab. Reference	Na2Cl2	Na2SO4	K2Cl2	K2SO4	MgCl2	MgSO4	MgCO3	CaCl2	CaSO4
<u>Renmark Group</u>										
SN/40m	900951	72.9		0.6		5.91	13.9	0.3		6.4
SN/60m	900950	71.5		0.55		5.99	14.38	0.68		6.91
SMI/20m	900949									
SMI/40m	900948	76.4		0.64		8.58	10.11	0.26		4
SMI/60m	900947	77.2		0.65		10.6	6.45	0.58		4.59
<u>Scotia Halite Lake</u>										
Salt Crust	910323	95.9		0.08		4			0.03	
Surface Brine	910305	56.9		0.95		10.3	31.8			0.08
<u>Parilla Sand</u>										
SN/20m	900952	71		0.64		8.2	11.2	0.01		3.7
<u>Yamba/Parilla Sand</u>										
Scotia Alluvial Lake										
SAL/1;0.05-0.	900107	59	2.75		0.28		37.6	0.06		0.37
SAL/1;0.65-0.	900113	63.2		0.32		2.4	33.4	0.18		0.49
SAL/1;1.55-1.	900119	71.9		0.43		2.89	23.3	0.16		1.25
SAL/1;4.55-4.	900124	72.3		0.56		5.34	20	0.57		1.25

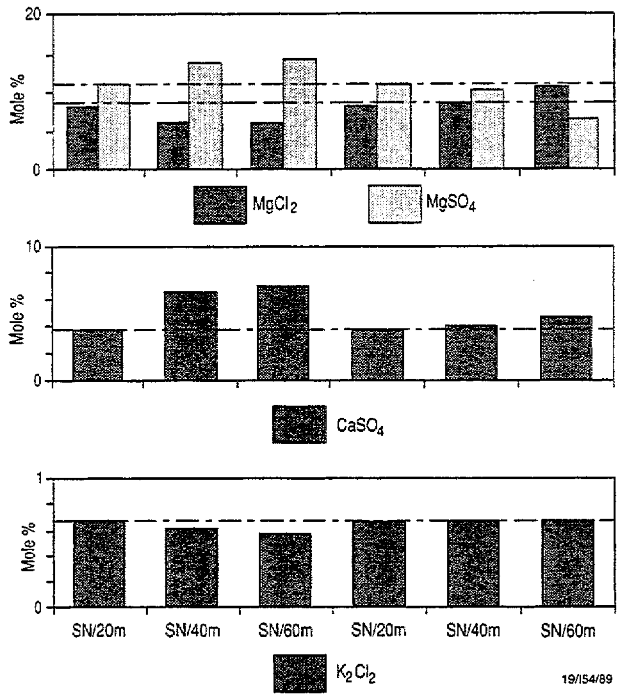


Fig. 27 Comparison of the normative salt content (in mole %) of the Parilla Sand and Renmark Group aquifers at Scotia North (SN) and the Renmark Group aquifer underlying the discharge complex at Scotia Middle Island (SMI).

The data from the N-S and E-W shallow groundwater transects (Figures **4**, **28**, **29** and **30**) show that there is an area of high salinity water (300,000 to 350,000 mg/L) in the centre of the lake and that the salinity decreases towards the margins.

Figure **28** shows the salinity, δD, Cl/Br (and Mg/Br) ratios across the N-S transect from the northern margin, where the lake adjoins the reworked sand of the overlying Woorinen Dune and the underlying Parilla Sand, to the southern margin where the Yamba Formation deposits form Scotia Middle Island (Figures **15** and **16**). Near the base of the Woorinen Dune (at SIL 4/91) there is a relatively low-salinity water with a Cl/Br ratio similar to that of the regional Parilla Sand groundwater at Scotia North. This is probably regional Parilla Sand groundwater diluted by rainfall (RP_R) which has preferentially recharged the reworked sands at the base of the Woorinen Dune (Figure **31**). From this point towards the lake, the salinity and δD ratios increase abruptly, and the Cl/Br ratios more progressively. This indicates the effects of evaporation (which effects salinity and δD) superimposed on mixing (which effects all three). i.e. as the regional Parilla Sand groundwater (± local rainfall) flows into the lake it evaporates and mixes with the $SLB(II)_{R/S}$ water which enters the shallow sediments after rainfall. Similar processes are evident along the east-west transect (Figure **29**) except that evaporated regional Parilla Sand water (RP_E) is evident at the eastern margin (SIL 1) and there is a water centred on SIL 9 which has an abnormally high Na/Cl ratio, possibly because of re-solution of glauberite.

The decrease in salinity, δD and Cl/Br at the southern margin reflects mixing of the lake brine with groundwater beneath Scotia Middle island. The position of these waters on the graph of Cl/Br against 1/Br (Figure **23a**) indicates that the mixing water is Scotia Lacustrine Brine Phase I (SLB (I)).

Depth profiles of salinity, δD, Br, Cl/Br and Mg/Br at SIL 1/91 show SLB $(II)_{R/S}$ water (mixed with RP and/or RP_E) overlying SLB(I).

The spatial distribution across Scotia Ironstone Lake in an approximately N-S direction of the excess or deficiency in Mg, Na and SO_4 (from those predicted from evaporation of regional Parilla Sand groundwater) is shown in Figure **30**. At the northern margin there is an area of regional Parilla Sand groundwater diluted with local rainfall. Within the lake (between sites SIL 3 and 8) excess Mg and excess SO_4 increase progressively from the northern margin towards the topographically lowest area of the lake near the southern margin. There is a correlation between the increase in Mg and the increase in SO_4 (although they are not equivalent) which suggests that the redissolved Mg and SO_4 - containing salts are concentrating in the topographically lower areas of the lake.

Na shows no clear-cut pattern in a north-south direction (Figure **30**) with both Na-excesses and deficiencies occurring in the lake. However, Na/Cl ratios along the E-W transect (Transect SIL; Figures **4** and **29**) indicate a tendency for Na-deficient waters at the margin and Na-excess waters towards the middle of the lake.

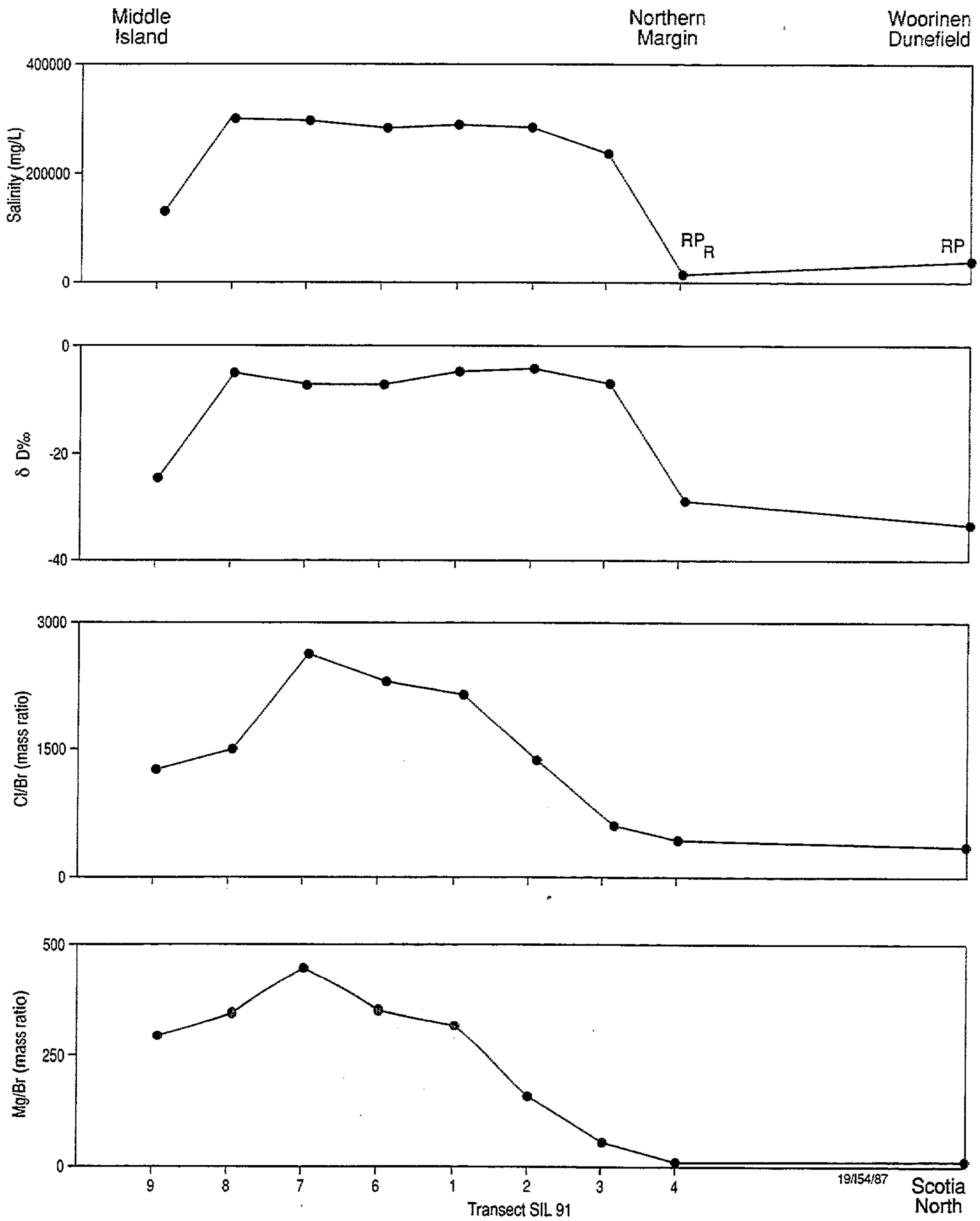


Fig. 28 Scotia Ironstone Lake: variations in geochemistry of shallow groundwater along a north-south transect .

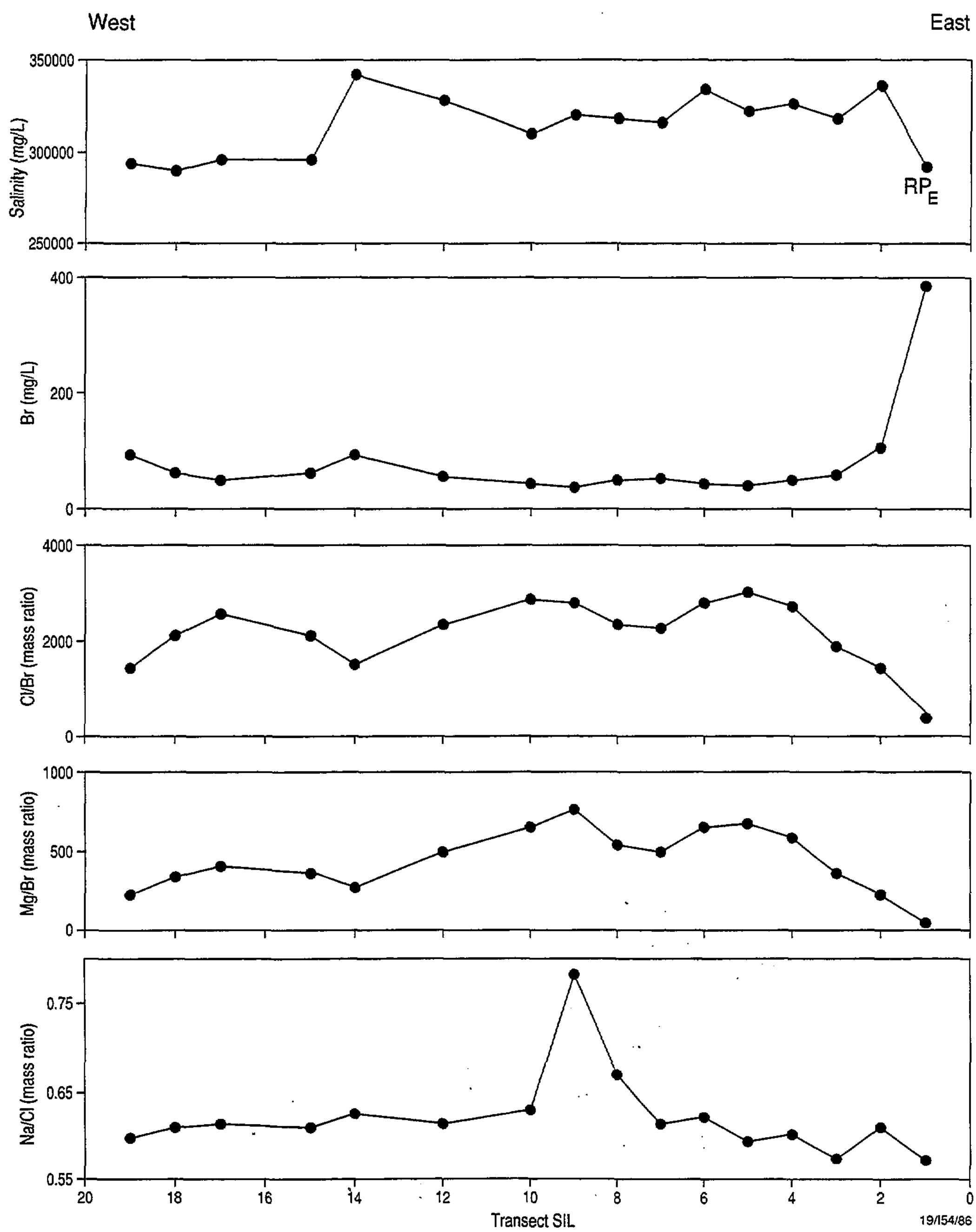


Fig. 29 Scotia Ironstone Lake: variations in geochemistry of shallow groundwater along an east-west transect.

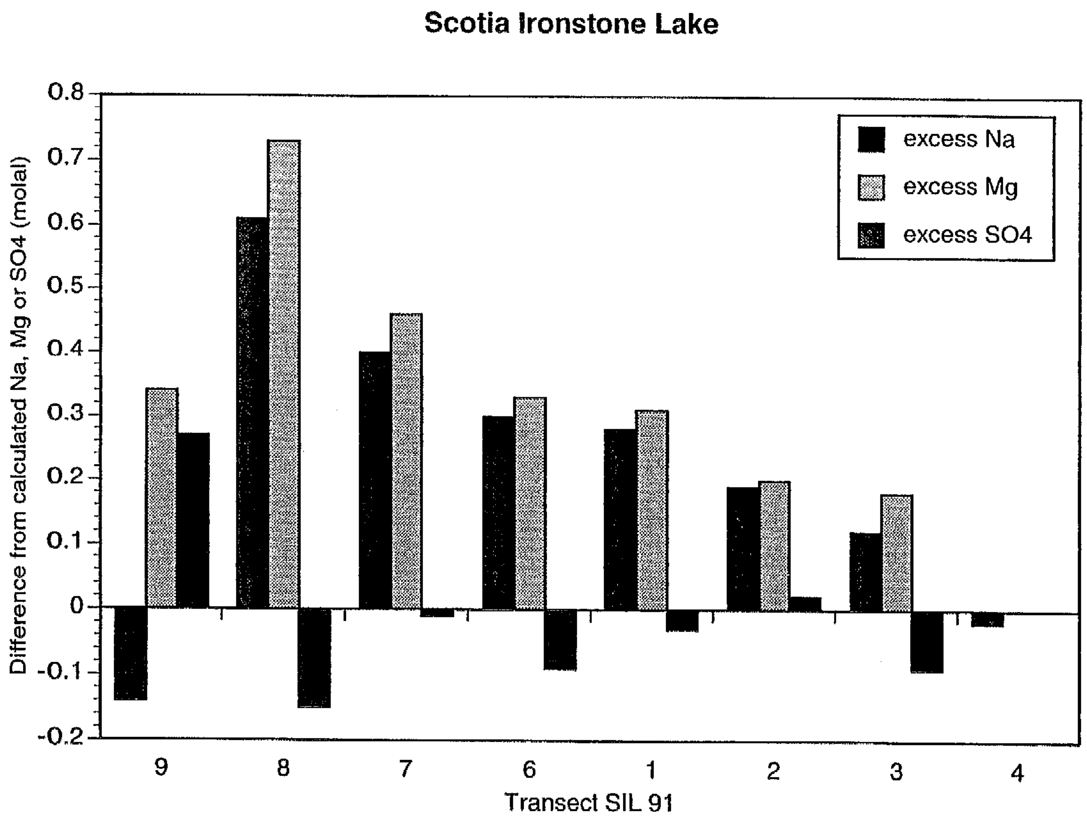


Fig. 30 Variations north-south across Scotia Ironstone lake in the amount of excess Mg and SO4 and excess or deficiency of Na in the lake groundwater compared to the values calculated for evaporation of regional Parilla Sand groundwater.

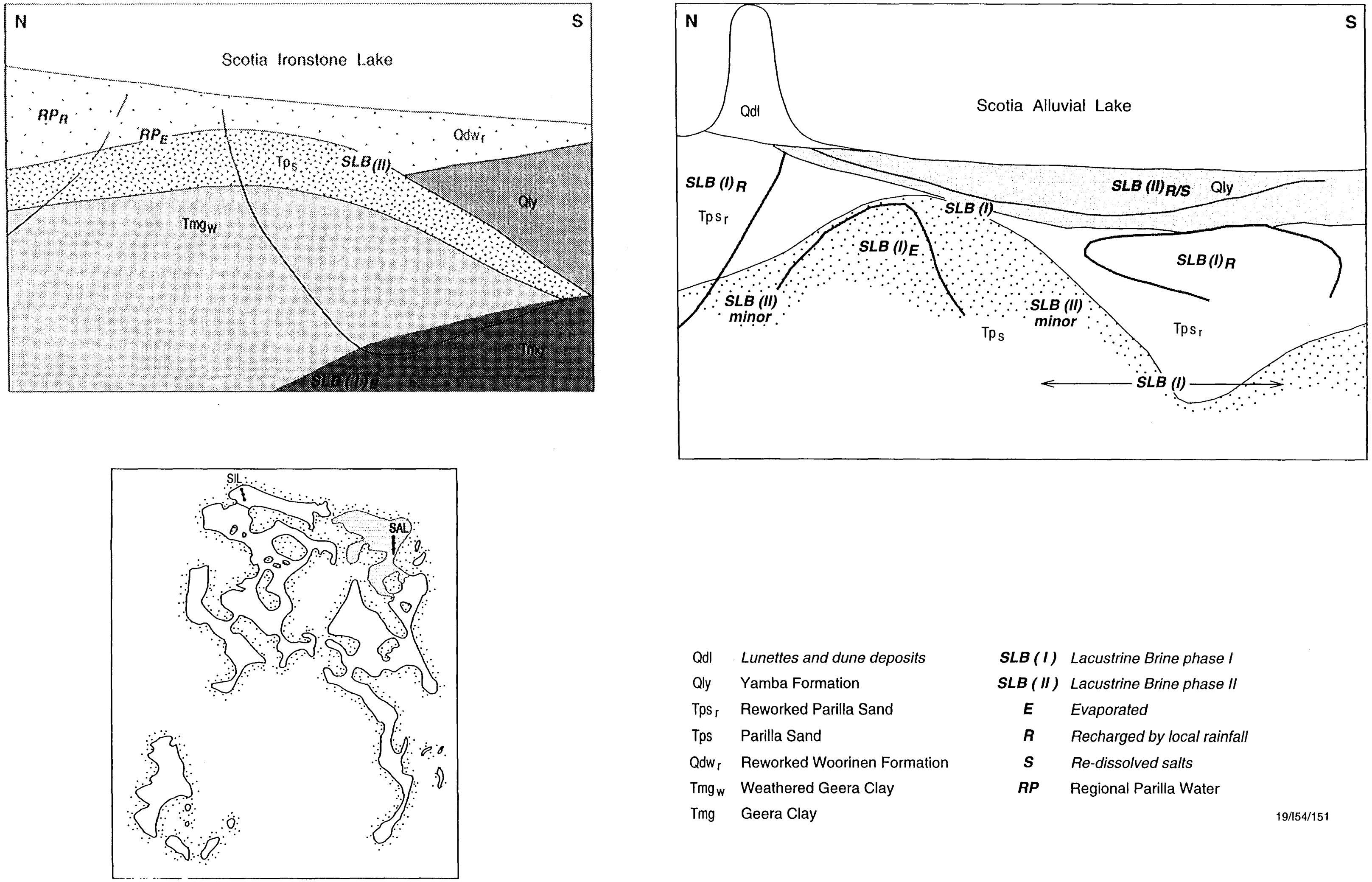


Fig. 31 Distribution of of groundwater types in two contrasting active lakes in the discharge complex. Scotia Ironstone Lake is a sand-surfaced lake whose northern margin is close to the maximum extent of the (paleo) discharge complex. Scotia Alluvial Lake is a clay-surfaced lake whose northern margin is some distance from the paleo-margin of the discharge complex.

DISCUSSION

3.11 Sources of Salt and Groundwater

3.11.1 Discharge Complex (Parilla Sand/Yamba Formation)

The hydraulic heads are presently directed towards the discharge complex both laterally from the Parilla Sand and vertically upwards from the underlying Renmark Group, which makes both of these aquifers potential sources. However, the co-incidence of the $^{36}Cl/Cl$ ratios of the regional Parilla Sand and Parilla/Yamba Formation, and their clear distinction from the much lower Renmark Group values, is strong evidence that the Parilla Sand aquifer is the source of saline groundwater for the discharge complex.

The other source of water for the discharge complex is local rainfall. This input has considerable influence in the discharge complex, as indicated by the volumes of surface water which accumulate in the lower lakes during winter. The influence of local rainfall on the groundwater is difficult to detect isotopically and is directly evident mainly in the form of salinities which are lower than that of the regional Parilla Sand groundwater. These areas of low salinity are not extensive, but there is considerable indirect evidence, in the form of isotopic evidence for a surface water component in the evaporation process, rainfall dissolution and transport in the redistribution of salts in the complex, and the highly variable values of the lateral hydraulic heads within the complex, that rainfall recharge/runoff is a major water source and hydrodynamic influence on the discharge complex.

3.11.1 Renmark Group underlying the Discharge Complex

In the Renmark Group underlying the discharge complex the higher salinity compared to the regional Renmark Group and the decrease in salinity with depth within the aquifer indicate that groundwater and/or salt has moved downwards from the overlying sediments.

The increased $^{36}Cl/Cl$, Na/Cl and Cl/Br ratios in the Renmark Group beneath the discharge complex and their decrease with depth indicate that salt from the Yamba/Parilla Sand deposits of the discharge complex has moved downwards through the intervening Geera Clay and reached the Renmark Group. This implies that salt in the Geera Clay would have also moved downwards into the Renmark Group. This is supported by the $MgSO_4/MgCl_2$ ratios of the deeper waters in the Renmark Group, which are different from both the indigenous Renmark Group waters and the Yamba/Parilla Sand groundwater. It is not clear whether this salt which has been displaced from the Geera Clay is original (Miocene) connate water or a later generation of porewater emplaced before the onset of groundwater discharge activity.

3.12 Present-day Hydrodynamic Processes

3.12.1 Parilla Sand and Yamba Formation/Parilla Sand

3.12.1.1 Types of inputs

The direction of lateral hydraulic gradients from the regional Parilla Sand aquifer towards the lacustrine Yamba/Parilla Sand sediments of the discharge complex is consistent with the view that the Parilla Sand groundwater is the source of the salt. However, the large variation of the lateral hydraulic head with location within the discharge complex suggests that rainfall/runoff recharge, and the ways in which it is localised and concentrated is currently the major influence on the hydrodynamics of the discharge complex.

This rainfall/runoff does not take the form of intense localised runoff into the discharge complex (other than after major storms) because the catchment around the discharge complex is not large and infiltration is favoured by the high permeability of the Woorinen Dunes. However, it does interact with the discharge complex by:

(1) locally recharging the surrounding groundwater system through permeable deposits such as reworked sands at the base of Woorinen dunes. and, probably, sands filling former drainage channels into the discharge complex (Figure **32**); and

(2) concentrating within topographically lower areas as a result of surficial flow between the interconnecting lakes.

Two variations of theme (1) occur at the northern margin of the discharge complex. To the north-west, the active lake Scotia Ironstone Lake lies close to the (former) margin of the discharge complex. As a result, the active lake margin is separated from the regional Parilla Sand aquifer and its overlying Woorinen Formation dunes by a relatively narrow zone of reworked sand and its associated lense of lower salinity groundwater. (Figures **8**, **13** and **32**). In contrast, at the northern margin of Scotia Alluvial Lake the former margin of the discharge complex is separated from the active lake by a broad low-lying area of Parilla Sand and overlying reworked Parilla Sand (Figures **8**; **12** and **32**). There, the zone of lower salinity water is much broader

3.12.1.2 Interaction with the lakes

The local rainfall and regional groundwater inputs to the discharge complex interact with the various sand and clay layer configurations in individual lakes to produce a diversity of hydrodynamic environments. The presence of surficial sand or clay layers, together with the topography, is an important determinant of the nature and extent of vertical recharge to the lakes.

Sand-Surfaced Lakes

The hydrodynamic processes in sand surfaced lakes of the Scotia Discharge Complex are summarised in Figure **32**, using Scotia Ironstone Lake as an example.

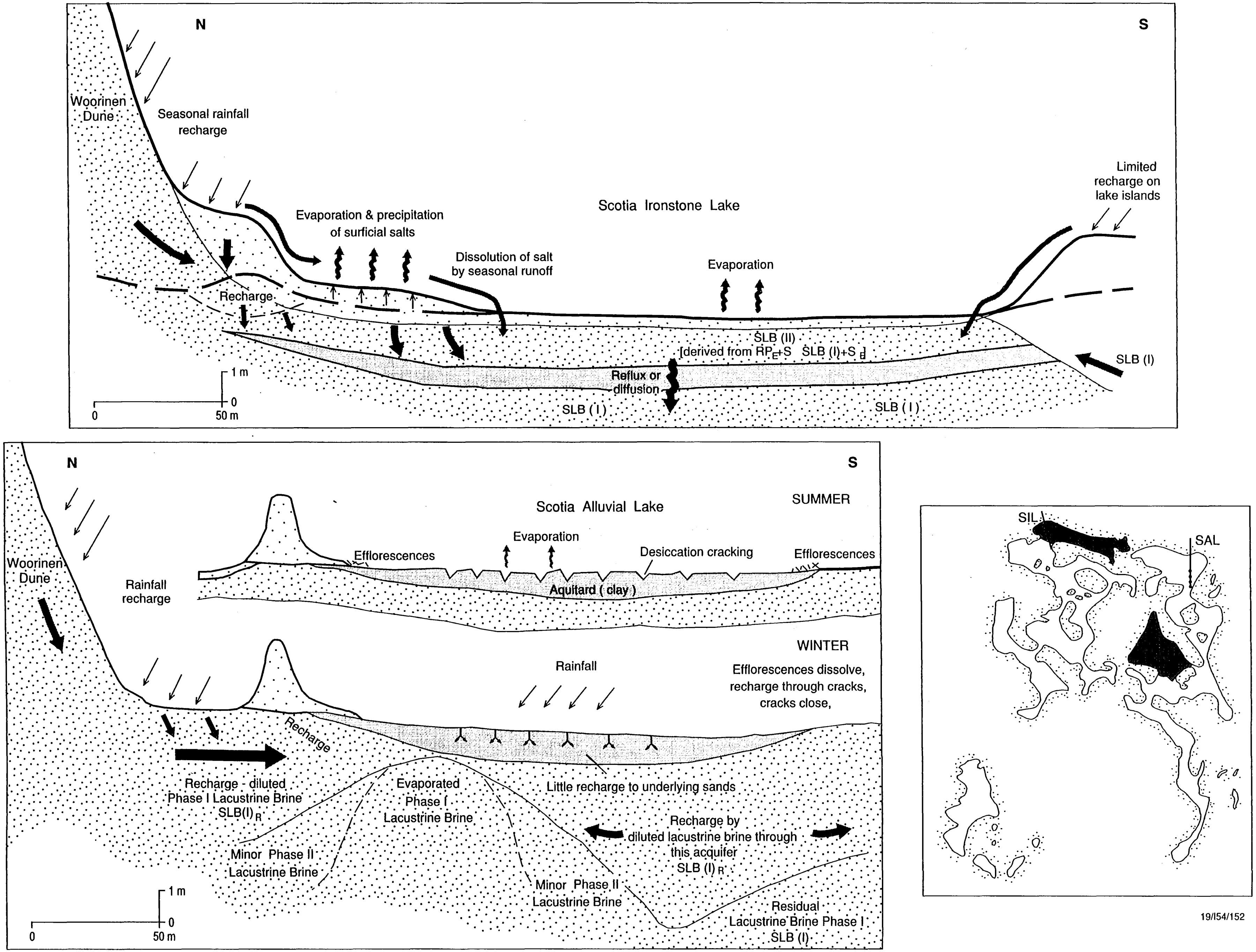


Fig. 32 Hydrodynamic processes in two contrasting active lakes in the discharge complex. Scotia Ironstone Lake is a sand-surfaced lake whose northern margin is close to the maximum extent of the (paleo) discharge complex. Scotia Alluvial Lake is a clay-surfaced lake whose northern margin is some distance from the paleo-margin of the discharge complex.

Surficial sand layers overlying clay in the topographically lower areas of the lakes are a favourable location for the accumulation and preservation of brines formed by rainfall dissolution of efflorescences. Because the brines saturate the surficial sand, they rarely evaporate to dryness and are present throughout most of the summer.

The way in which the shallow brines interact with the underlying groundwaters depends on the effective vertical permeability which in turn depends on the number and thickness of the underlying clay layers. If the underlying clay layers are thin, the brines move downwards by advection. If the underlying clays are thick, the brines are vertically static but are a source of salt for downwards diffusion.

In Scotia Scott Lake the relatively smooth, non-linear relationship of salinity to depth (Figure **20(a)**) indicates that the shallow brine is moving advectively downwards through the underlying sand and clay layers. i.e a Phase II Scotia Lacustrine Brine is in the process of advectively displacing the Scotia Lacustrine Brine Phase I. However the discontinuity at about 26.5 m in the δD against depth profile (Figure **20**) suggests that there are additional complications. Scotia Halite Lake is also a potential site for advection but the data are inconclusive because the Yamba /Parilla Sand sequence is relatively thin (about 4 m) and the salinity profile (Figure **20(c)**) is not sufficiently well-defined for use as an indicator of advection or diffusion.

Clay-Surfaced Lakes

In clay-surfaced, relatively flat and topographically high lakes the water table in the dry season can drop sufficiently for evaporation to almost cease and extensive cracking of the clays to occur. At the start of the wet season rainfall/runoff first fills cracks in the clay surface and then forms very shallow ponds on the lower areas. In summer, the surface dries and surface salts are removed by aeolian deflation. Salts in the cracks are redissolved and returned to the clay porewater (Figure **32**).

Scotia Alluvial Lake is an example of a lake with a relatively thick (1 to 2 m) surface clay layer (Figures **8** and **16**) underlain by a significant thickness of sand (about 7m).

Beneath the clay layer the iso-salinity pattern is complex (Figure **16**) and there is a salinity minimum at the base of the clay layer (Figure **19a**). This minimum indicates that downwards movement of salt from the highly saline brines in the clays is insufficiently fast to influence the lower salinity groundwater which are flowing lakewards beneath the clay. i.e. the clay layer is an effective hydrodynamic barrier which: (1) minimises the effects of evaporation-induced upwards movement of underlying brine because the water table is considerably lower than the sediment surface; and (2) prevents advective downwards movement of salt because of its low permeability.

The iso-salinity pattern (Figure **16**) suggests that the lower salinity water beneath the clay layer enters the lake mainly through what may be a relatively high permeability sediments filling a prior stream channel in the underlying sand. Thus, in the section shown in Figure **16** the incoming water would be flowing at right angles to the section through the area bordered by the 120‰ contour (Figure **32**).

Profiles of salinity, Br or Cl/Br against depth (e.g. SAL 1; Figure **19**) indicate that there may be up to four different types of water beneath the lake. The Cl/Br ratios indicate the that $SLB(I)_E$, $SLB(II)_{R/S}$ and a 3-component mixture are involved. Analysis of all the core-hole data on the SAL transect by this method gives the complex array of the Scotia groundwater types shown in Figure **31**.

Lake Margins

Two types of lake margin occur in the Scotia Discharge Complex:

(1) Those where the active lake margin and the maximum former extent of the discharge complex are almost coincident. Under these circumstances the incoming water is usually a mixture of regional Parilla Sand groundwater and local rainfall recharging the reworked sands at the base of the dune (e.g. Scotia Ironstone Lake, northern margin; Figure **32**)

(2) Those in which the margin of the active lake occurs some distance from the maximum former extent of the discharge complex. Under these circumstances the low salinity lense influenced by rainfall can be extensive (Figure **32**) and the incoming groundwater is a mixture of local rainfall and Scotia Lacustrine Brine Phase I.

3.12.2 Renmark Group/Geera Clay

There is at present no potential for advective movement of groundwater downwards from the discharge complex through the underlying Geera Clay and into the Renmark Group. Because the hydraulic gradients are upwards, diffusion through the Geera Clay is the most likely process by which salt moves downwards into the Renmark Group aquifer.

3.13 Hydrochemical Processes

The Cl/Br ratios of the Yamba/Parilla Sand waters are all high compared to those of the regional Parilla Sand groundwater. i.e. there are no low Cl/Br waters which would result from the precipitation of halite. The overall high Cl/Br ratios could result from removal of Br^- from the groundwaters into the sediments, for example by interaction with clays. Alternatively, Br^- could be exported from the discharge complex by UV-catalysed conversion to elemental Br and subsequent volatilisation; by conversion to bromoform by the metabolic activities of algae; and/or by aeolian deflation of Br-rich evaporites from the lake margins and clay-surfaced lakes.

Not all of the deviations in water chemistry from that predicted from evaporation of regional Parilla Sand groundwater are related to changes in Br. Compared to that predicted for an evaporated regional Parilla Sand groundwater of the same Cl concentration the discharge complex groundwaters have considerably higher Mg and SO_4, marginally higher or lower Na concentrations and marginally lower K concentrations. The Mg deviations could result from mixing of regional Parilla Sand groundwater with an evaporation product of this water which has evaporated well beyond halite saturation. However, mixing does not account for the SO_4 concentrations or the high Na concentrations which are outside a mixing range involving only regional Parilla Sand groundwater and its evaporation products. Most likely the excess Mg and SO_4 are provided by a water consisting of local rainfall plus redissolved $MgSO_4$ and other salts, and the Na excess is related to the dissolution of glauberite and halite and the Na deficiency to the precipitation of glauberite. The water comprising $MgSO_4$ + NaCl redissolved in local rainfall is the R/S water which is one of the major mixing end-members in the discharge complex.

There are no Mg or SO_4-deficient waters to counterbalance those with excess $MgSO_4$, or K-rich waters to counteract those with a K-deficiency. The lower than expected K concentrations could result from reaction with clays. However, some of the imbalances may be due to selective deflation of salts from the discharge complex. The basis of the selective deflation mechanism is the seasonal lacustrine cycle of wetting during winter followed by progressive drying and deflation of sediment and surface salt during summer. Deflation will occur selectively at the lake margins because they will dry first. In some types of lake, complete drying and deflation of the central area may be minimal. This situation occurs in those Scotia lakes where a significant thickness of surficial sand overlies the lacustrine clay layers. The hydrodynamic processes involved in this type of situation are illustrated in Figure **32** and the way in which these processes can result in selective deflation of salt from the lake is shown schematically in Figure **33**.

A hydrodynamic situation is envisaged in which winter rainfall-runoff from the higher ground around the lakes and rain falling directly on the marginal areas flows over the surface and through the upper sandy sediments towards the topographically lower areas in the centre of the lake (Figure **32**). If these areas have surficial clay then the water will fill desiccation cracks and the remainder stay perched on the surface where it will evaporate readily (Figure **32**). If they are sandy, the water rapidly infiltrates and evaporation will probably involve both surface and capillary water, and will therefore be slower. The slower rate of evaporation will lead to a situation in which the winter high water table in the sands will decline more slowly than in the clay-surfaced lakes, with the result that a brine persists in the surficial sand for a large proportion of the year.

During the transition from wet to dry conditions the lake margins will be washed by rainfall with gradually decreasing frequency and there will be correspondingly longer dry periods in which evaporation will be dominant and salt efflorescences will form at the surface before being washed into the lake by the next rainfall event (forming the R/S waters). Gypsum may resist this re-solution process because of its relatively low solubility but the other salts predicted to precipitate during the evaporation of the regional Parilla Sand groundwater should be readily dissolved and washed to the lake. As the frequency of rainfall events decreases and the length of evaporation events increases, the composition of the salts being washed into the

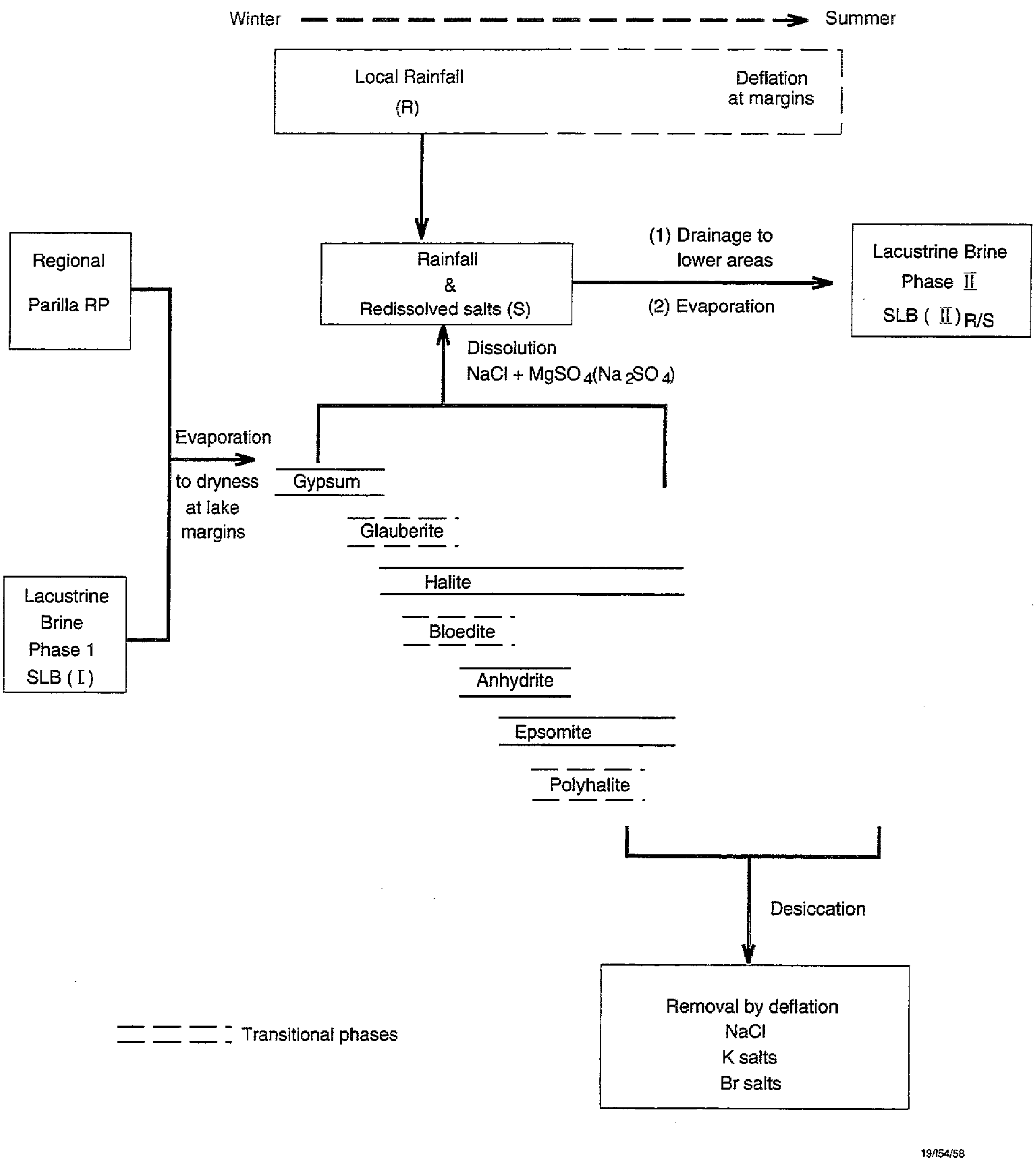


Fig. 33 Processes involved in the selective deflation of salts from discharge complexes.

lake should evolve (Figure **33**). The earlier deposited minerals will tend to be washed into the lake and retained in the system, whereas the later-formed minerals will not concentrate in the surficial sediments till evaporation becomes dominant. Under these conditions, Br salts, K salts and halite, which precipitates over a wide range of ionic strengths, should be among the salts preferentially deflated from the system.

3.14 Lithostratigraphic Model and Associated Brine Evolution of the Scotia Discharge Complex

3.14.1 Lithostratigraphic Model

The Hamley Fault and associated structures has had continued episodic activity through time. Within the Geera Clay at Scotia, a distinct palaeosol is present at 19m AHD below Middle Island (Figure **12**) but is not present offstructure and to the north in Scotia North (Scotia 2, Anabranch 10). Additionally, the anticlinal or domed structure continued developing during and after Parilla deposition, and subsequent groundwater discharge from the Parilla would have commenced directly over the crest. With the ensuing deflation, this central area of Geera Clay weathered preferentially as is seen in the section Figure **12**. A regional structure, running northwest-southeast across Scotia along the peninsula between Halite and Scott Lake (TM imagery), coincides with anomalous isolated ferruginous? Parilla outcrops to the northwest within the Woorinen dunes (airphoto interpretation), and corresponds with an anomalous disruption in the stratigraphic section from Halite Lake to the north.

The northern side of this structure was downfaulted, leaving the central Middle Island area to develop a deeper weathering profile in the Geera Clay. This structural discontinuity probably increased the upflow of groundwater in the Parilla Sand. Depending on the type of rupture caused within the Geera Clay, a conduit could have also been created for upward movement of Renmark groundwater. For whatever combination of causes, this site, intersected in Scotia Scott Lake 1, has had the deepest erosion or deflation of the Geera Clay and the thickest lacustrine sequence in the complex. The relative timing of subsequent events is more difficult to establish unequivocally. The lithostratigraphic model (Figures **8** and **11**) presents an interpretation where the earliest playa deposits predate the development of this structure in Scott Lake. An alternative may be that the latter was established first, and that unit S7 is equivalent to S4, making the underlying S5 and S6 units the oldest lacustrine deposits. Whatever model, the overlying stratigraphic units indicate that this structure is still actively subsiding within the narrow zone between two structural margins of Scott Lake.

The model (Figures **8** and**11**) implies that the proto-Scotia Lake was at a higher elevation, with remnants of its deflation/lacustrine events still preserved as the highest topographic features within the central complex (Figure **8**). The Parilla Sand was subsequently eroded/deflated away from a broader (wider concentric area) to lower levels to produce units S5 and S6. Subsequent lacustrine deposits (S8) indicate deeper deflation to the northwest in Ironstone Lake. This trend is also implied from the surface topography of the outer lakes at present (Figure **10**), and indicates a pattern of deflationary evolution of the complex.

If provenance is considered for a deflation playa developing on a rising domal structure, then the sediment sources could only be local except for aeolian sand transported in the Woorinen dunefield system. Other sand and clay could only be derived from the Geera Clay and Parilla Sand locally. No fluvial sources could be anticipated. The repeated erosion and reburial of the Geera core would contribute little clay and even less with accumulation of the Yamba sequence. This model is compatible with the observed increasing predominance of sands in the lacustrine deposits.

The evolution of the Scotia Lake landform and its sedimentary sequence are summarised below, and relate to Figure **34**.

1 Movement on Hamley Fault uplifts the northwestern side, creating a steeper erosional scarp of Parilla Sand (Tps). Groundwater flow is brought to surface against the domed or antiformed Geera Clay (Tmg) aquiclude.

2 A standing lake develops at the edge of the lower slope in the Parilla Sand, above Geera Clay on the structure. This lake may have been an open system with a southerly outflow.

3 An onset of fluctuating aridity initiates Woorinen? deflation of the Geera Clay surface. Accumulating low-relief bedforms of pelleted sediments alternate with lacustrine clay and sand deposits (Qly_1). A gypsum hardpan develops in the upper part of this sequence. Oxidation and weathering develops in the upper part of the Geera Clay (Tmg_w) on structure.

4 Local or regional surface drainage erodes into the Parilla Sand on the eastern side of the salina, bypassing the thicker central Yamba deposits. With channel fill and stagnation of this drainage, the salina fills and Scotia lake enlarges. Parilla Sand is reworked and re-deposited (Tps_r).

5 **I** The lake expands to its maximum size. Springs and ironstone precipitation are active on the peripheral sandy margins. Rainfall-induced re-solution of salt and alternating deflation events operate seasonally at non-spring margins. Thin surficial clay develops over the reworked sand. This large homogeneous system produces the first phase of lacustrine brine (SLB(I)) of a uniform salinity across the complex.

IIa The larger peripheral lake contracts to its present size, and deflates down to near the top of the Parilla at the margins. A spring zone develops at the present lake margin efluxing either regional Parilla water (RP) or SLB(I) sources. The proximity of Parilla Sand to the surface allows initial reflux of evaporated SLB(I) with little addition to the second phase lacustrine brine (SLB(II)). Elsewhere SLB(II) processes are active.

6 **IIb** Deflation of the surrounding region continues and Woorinen dune systems (Qdw) develop over the Parilla Sand landscape. Parilla Sand partly deflates towards the lake periphery of the salina complex, lowering lake floor levels on the northern and (?)southern sides of the complex. General west to east migration of sand maintains a higher lake floor level centrally

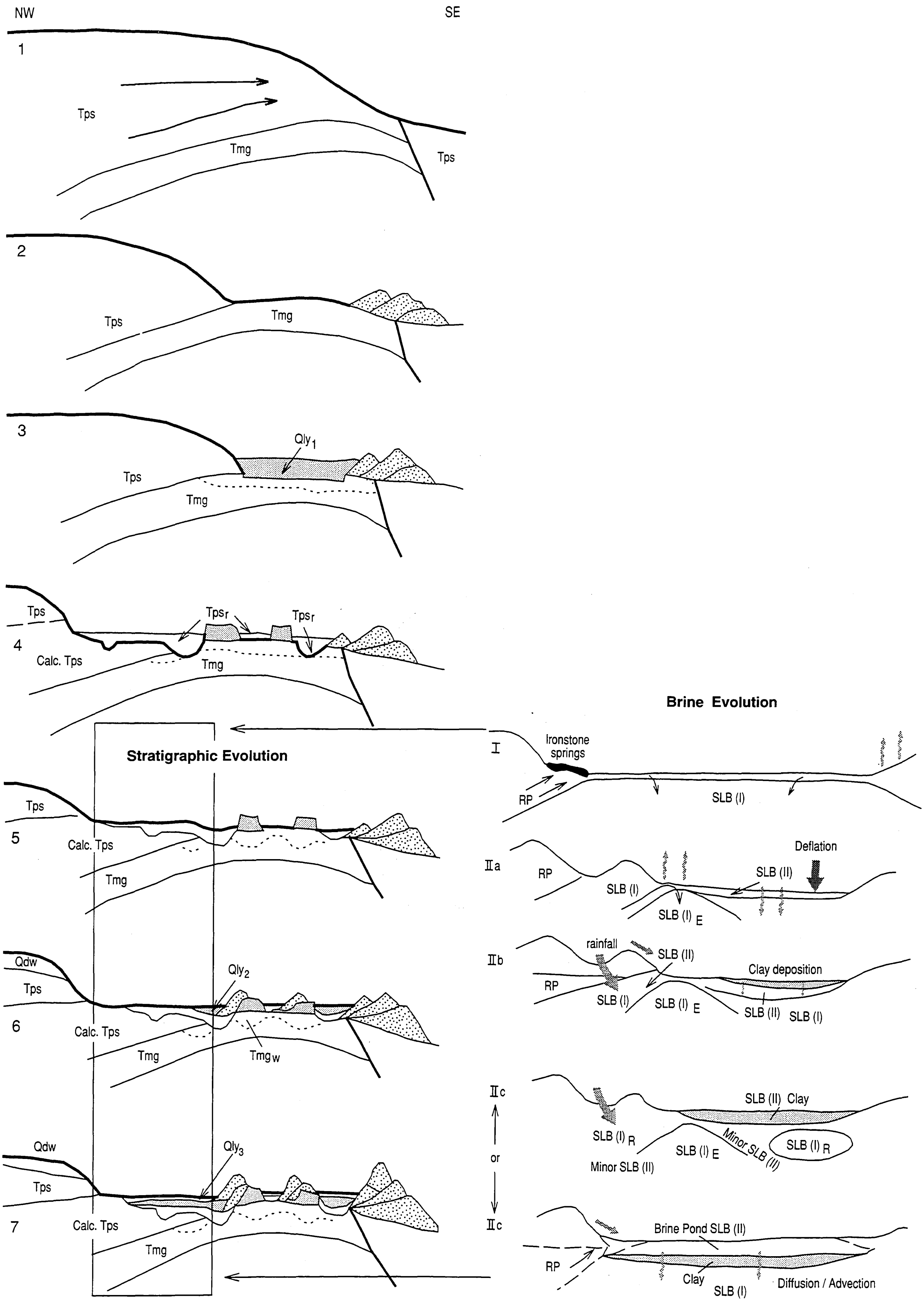


Fig. 34 Model of the stratigraphic and hydrodynamic evolution of the Scotia Discharge Complex

where remnant early clayey lacustrine deposits are cores for accretion (Figure **10**).

The water table drops and spring activity diminishes, and deflation is active. Aeolian pelleted clay and lacustrine clay (Qly_2) continue to be accumulate in the complex. SLB(II) processes become more important and SLB(II)-influenced brines overlie $SLB(I)_E$.

7 **IIc** Deflation is again active. Lunette deposits alternate with thin lacustrine clays (Qly_3). Collectively clay deposits accumulate.

At any stage, the lake floor may be either a clay or a sand. A sand surface over clay allows the persistence of a brine pool and the dominance of SLB(II) processes, moving salt down. Clay at the lake surface limits the hydraulic potential for advective downwards movement of brine allowing the intrusion and entrainment of incoming waters into the underlying sediments to become significant.

3.15 Predicted Disposal Basin Hydrodynamics

The most favourable feature of a Scotia-type discharge complex for the storage of saline waste water is the potential for advective reflux of the brines formed by evaporation. This advection would occur in the naturally-occurring advective sites, and in other sites of relatively high vertical permeability where the increased downwards hydraulic head would change the dominant process from diffusion to advection. However, the increased storage capacity for disposal water generated by these reflux processes would be limited by the unusual thinness of the underlying Parilla Sand sequence and the prior existence of natural brines beneath the discharge complex.

The potential for vertical leakage of disposal water into the Renmark Group aquifer is not high. Reversal of the natural hydraulic gradient between the discharge complex and the underlying Renmark Group aquifer would not occur till about 1 m (freshwater equivalent) of extra hydraulic head had been generated by the disposal water. In such a situation, the low permeability of the Geera Clay would prevent rapid advective downflow of brine. Of more concern would be the potential for lateral flow of disposal water into the adjacent regional Parilla Sand aquifer. The regional hydraulic head about 1 km to the north would be equal to that in the discharge complex if an additional hydraulic head of up to 2m was produced by the disposal water. Because the surrounding aquifer is not hydrodynamically isolated from the discharge complex, the disposal water could leak rapidly until the induced disposal basin hydraulic head equilibrates with the regional hydraulic head.

CONCLUSIONS

(1) The Yamba Formation lacustrine sediments of the Scotia Groundwater Discharge Complex overlie a stratigraphic sequence comprising the regional Parilla Sand aquifer, the Geera Clay aquitard, and the Upper Renmark Group aquifer.

(2) The lithostratigraphic evolution of the discharge complex involved: (a) movement on the Hamley Fault uplifting the northwestern side bringing groundwater flow to the surface and forming a standing lake (the proto-Scotia Lake) on the exposed domed or antiformed Geera Clay aquiclude; (b) onset of fluctuating aridity producing dry/wet cycles which resulted in deflation of the Geera Clay and oxidation/weathering of its upper surface, together with accumulation of a Yamba Fm. sequence stabilised by the development of a gypsum hardpan; (c) establishment of surface drainage which eroded into the Parilla Sand on the eastern side of the complex, bypassing the central core of Yamba sediments; (d) channel fill and stagnation of this drainage, filling the salina and expanding Scotia lake to its maximum size, and depositing thin surface clay layers over the reworked Parilla Sand sediments; (e) contraction of the larger peripheral lake to its present size and deflation to near the top of the Parilla Sand at the margins; (f) continuing deflation, development of Woorinen dune systems over the Parilla Sand landscape, accumulation of aeolian pelleted clay in lunettes and lacustrine clay deposits in the lakes.

(3) These processes have produced two distinctive hydrolithostratigraphic features. (a) An unusual (for the Murray Basin) lithostratigraphy in which the older lacustrine clays and sands are largely restricted to the central area because recent deflationary events have expanded the discharge complex, removing most of the readily eroded older deposits at the margins. Consequently, there are no major permeability barriers between aquifers in the currently active lakes and the adjacent Parilla Sands and Woorinen Formation. (b) The exposure and deflation of the Geera Clay during some phases of evolution has provided a clay source for the discharge zone, and subsequent reworking of this clay into layers has produced both sand and clay surfaced lakes underlain by sand and clay layers of various thickness. These clay layers have considerably modified the permeability distribution, reducing the vertical permeability in absolute terms and creating a situation where, compared to the hypothetical situation of a predominantly sand aquifer, the ratio of the vertical to the horizontal permeability is low.

(4) The hydrodynamic evolution of the discharge complex can be divided into two major phases which left an imprint on the present-day groundwaters. Phase I occurred when the lake was close to maximum size. At the margins, springs and iron precipitation were active where the Parilla Sand was exposed and summer deflation processes were significant elsewhere. A widespread groundwater brine of salinity about 125,000 mg/L was formed from the local regional Parilla Sand groundwater and redissolved efflorescences depleted in K and Br by aeolian deflation. Phase II spans a range of more recent events and includes a wide range of currently active hydrodynamic processes in the modern lakes.

(5) The potential for brine reflux generated by the presence of surface or near-surface brines is greatest in basin-shaped sand-surfaced lakes, or lakes which are the terminus for surface drainage in the lake chain. In the sand-surfaced lakes brines saturate the uppermost sand layer and form ephemerally at the surface. The potential for reflux is greatest in lakes where the clay layers are thin and lateral groundwater movement through the sand layers is slow.

4. APPENDIX

4.1 Methods

4.1.1 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.

4.1.2 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.

4.1.3 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.

4.1.4 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).

4.1.5 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:

$$v_x = -K_x [\delta H_{if}/\delta x]$$

$$v_z = -Kz[\delta H_{in}/\delta z]$$

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

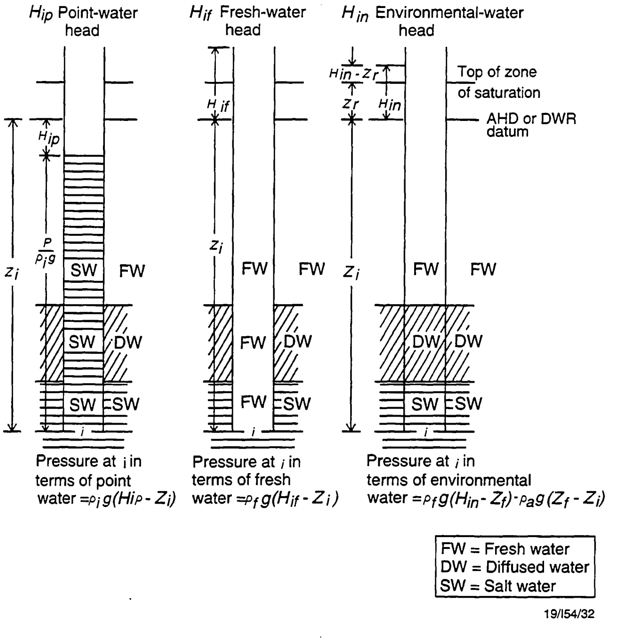


Fig. 35 Hydraulic heads in groundwater of variable density

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.

4.1.6 Logging

4.1.6.1 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.

4.1.6.2 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.

4.1.6.3 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.

4.1.7 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.

4.1.9 Imagery interpretation

4.1.9.1 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.

4.1.9.2 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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