GOVERNMENT OF WESTERN AUSTRALIA

Hydrogeology of the Bremer Bay 1:250 000 Sheet

Hydrogeological Map Explanatory Notes Series

Water and Rivers Commission Report HM 3

1997

Water and Rivers Commission

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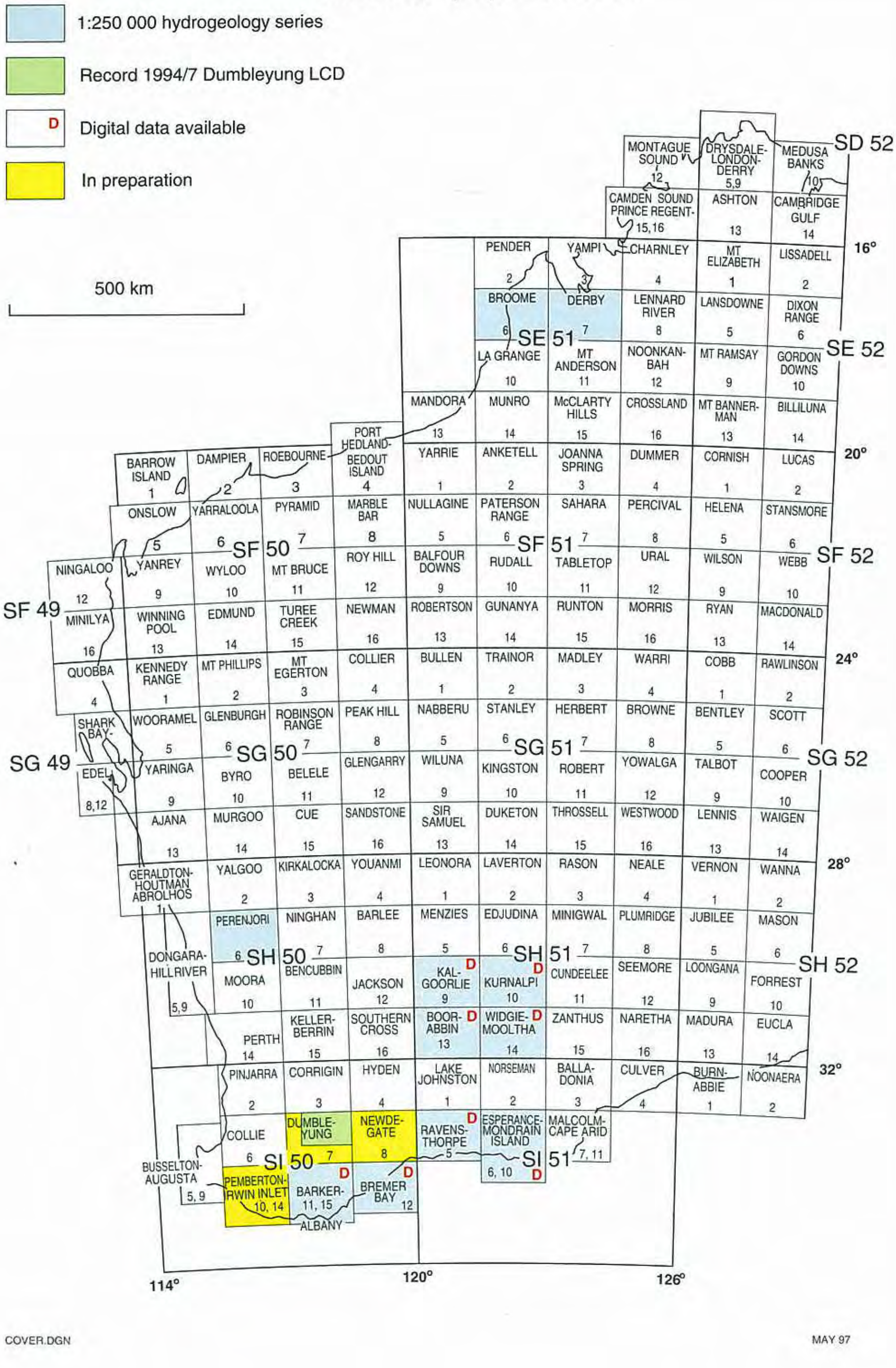

Cover Photograph: Pallinup Siltstone outcrop along the banks of Bremer River.

Hydrogeology of the Bremer Bay 1:250 000 sheet

by

W. J. Dodson

Water and Rivers Commission
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Contents

Figures

Tables

Map

Appendix

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Abstract

The Bremer Bay 1:250 000 hydrogeological sheet covers the southern corner of the Yilgarn Craton, and parts of the Albany–Fraser Orogen and the Bremer Basin. The rocks include weathered and fractured gneiss, granitoid and schist, weathered fractured and fissured quartzite, and siltstone, sand, silt and clay. Quaternary surficial sediments form an extensive cover concealing Archaean and Proterozoic basement and Tertiary sedimentary rocks preserved in palaeodrainages.

Fractured rock aquifers occupy the northwestern half of Bremer Bay but contain only minor groundwater supplies that are difficult to locate. Bremer Basin sedimentary rocks occupy the southern portion of the map, but are generally poor sedimentary aquifers. The Werillup Formation is the oldest member of the Tertiary sequence and is the highest yielding aquifer on Bremer Bay. Quaternary coastal sediments contain groundwater but, due to poor access, the extent and distribution is not understood.

Most of the groundwater on Bremer Bay is saline and not utilised, except for small resources suitable for watering stock. Fresh groundwater is limited to the coastal areas, and includes the town water supply for Bremer Bay. Brackish groundwater is widespread in the higher rainfall areas of the southwest and near catchment divides in elevated areas. Small groundwater supplies perched above the regional watertable, and seasonal in occurrence, may be found sporadically throughout the sand plain.

Keywords: hydrogeological maps, groundwater, aquifers, salinity, Bremer Bay

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Figure 1. Location Map

1 Introduction

1.1 Location

The BREMER BAY[1] 1:250 000 hydrogeological sheet (SI 50-12 of the International Series), which is bounded by latitudes 34° 00' and 35° 00' S and longitudes 118° 30' and 120° 00'E, is at the southern edge of the 'Wheat Belt' of Western Australia. Land use in the area is rural, encompassing cropping, sheep farming and cattle produce particularly near the coast where rainfall is higher. The map sheet takes its name from the small townsite of Bremer Bay, named by the Surveyor General John Septimus Roe in 1848 in honour of Sir James Gordon Bremer, Captain of the 'Tamar'. Bremer Bay, located on the coast in the southeast, supports rural, tourism and local fishing industries. It is the only populated centre on BREMER BAY, other than a roadhouse and small community at Wellstead; the remainder of the map sheet is sparsely populated. The nearby Fitzgerald River National Park, which occupies approximately a third of the land surface of BREMER BAY, attracts a seasonal influx of tourists and recreational fishermen.

The sheet area is reached via the South Coast Highway, which connects Jerramungup, ten kilometres north of BREMER BAY to Albany, ninety-five kilometres to the west (Fig. 1). A sealed road connects Bremer Bay with the South Coast Highway and the remainder of the rural area is serviced by a network of gravel roads. Access to the coast, except Cape Riche, Beaufort Inlet and Bremer Bay, is by four-wheel-drive vehicle only, over rough tracks through sand dunes. Access to the Fitzgerald River National Park is by gravel roads and rough tracks only.

1.2 Climate

The area has a Mediterranean-type climate with cool, wet winters and warm to hot, dry summers. The average monthly minimum and maximum temperatures for Bremer Bay range from 14° to 26° C during summer months, and from 7° to 16° C during winter months. Areas near the coast often receive a cooling southeasterly sea breeze by early afternoon throughout the summer months.

Average annual rainfall is 630 mm for Bremer Bay, but ten kilometres north of BREMER BAY, at Jerramungup, it is 373 mm. This illustrates the sharp decrease in rainfall from south to north across the map sheet. Most of the rain comes during the winter months and is associated with moist air in low-pressure systems passing over, or to the south of, the area. The wettest month is June and the driest, January.

Although average monthly pan evaporation is not recorded for Bremer Bay it is about 1400 mm per annum for Albany and exceeds average rainfall for eight months of the year. Pan evaporation for Jerramungup is about 1600 mm per annum.

1.3 Physiography

The physiography of BREMER BAY is influenced by the geology, with the coastline being dominated by high rocky headlands between sandy beaches. The rocky headlands may reach 100 m Australian Height Datum (m AHD) and are overlain by precipitous cliffs of shelly sandstone rising to elevations of 180 m, as at Cape Knob. At Warramurrup Hill the shelly sandstone is overlain by eolian dune sand to elevations greater than 200 m AHD. This coastal landscape typically extends one or two kilometres inland from the shoreline, and up to six kilometres inland north of Wray Bay (Fig. 2).

Inland from the coast the elevation falls quickly to about 50 m AHD and then rises gently northward to about 100 m over a distance of 15 to 20 km to the northern limit of yellow and white sand plain. The area has little relief, with poor drainage and numerous perennial and intermittent lakes and swamps. Perennial lakes are commonly the deepest, with steep slopes on the northwest side and a gentle slope on the southeast side. Intermittent lakes are much shallower, with eolian dune sand generally accumulated to the south and east.

Coastal sloping hills rise from an elevation of about 100 m AHD, approximately 30 km inland, on a line roughly parallel with the coast, to an average elevation of 300 m AHD where the gently undulating plateau of the wheat belt begins. Overlying the plateau are isolated outcrop of sedimentary rocks, which form 'breakaways'

[1] *sheet names are printed in capitals to distinguish them from similar place names*

Figure 2. Physiography

that rise to ten metres above the surrounding countryside and have a thin lateritized cap overlying siltstone. Breakaways are also formed by remnant duricrust of massive ferricrete overlying pallid, white clay formed during weathering of the granite–gneiss rock.

The peaks of the Mount Barren Range, within the Fitzgerald River National Park, dominate the eastern third of the BREMER BAY land surface. Thumb Peak, Mid Mount Barren, Woolbernup Hill, Mount Bland and West Mount Barren have peaks exceeding 300 m AHD and create a rugged panorama. Thumb Peak is the highest point, and has an elevation of 500 m. Flat topped mesas of Tertiary sedimentary rock dissected by recent drainage occur sporadically throughout the low land of the national park.

The Pallinup, Bremer, Gairdner and Fitzgerald Rivers flow southeast to the Southern Ocean and are the main drainages across BREMER BAY. Drainage is intermittent and river beds commonly contain stagnant pools of saline water. The Pallinup, Bremer, Gairdner and Fitzgerald Rivers are deeply incised and steep cliffs of siltstone characterise their banks. In the west, the Pallinup River has also exposed granite–gneiss outcrop, and in the northwest, its tributaries have further exposed basement rocks.

1.4 Vegetation

There are six vegetation systems, defined by Beard (1976), aligned approximately parallel to the coast: Cape Riche, Bremer, Qualup, Jerramungup, Chidnup and Barren Ranges. This alignment reflects the influence of climate, and the effect of geology influencing topography and soil type.

The coastal vegetation consists of two of these systems, the Cape Riche and the Bremer, which have an intricate mosaic of mallee-heath, coastal dune scrub on drift sand and low scrub on granite–gneiss outcrop. The exception is the occurrence of yate woodland along the coast south of Cape Riche.

The three vegetation systems inland of the coastal vegetation are divided roughly by geologic and topographic boundaries. The Qualup system extends inland from the coastal vegetation system to the edge of sand plain and consists essentially of mallee and mallee-heath shrub lands and sporadic mallee and yate woodland. The many swamps and small depressions of the sand plain support either yate woodland or paperbark scrub. The Jerramungup system covers the coastal sloping hills of the granite–gneiss rock and consist of mallee and mallee-heath and patches of yate woodland in valleys.

The Chidnup system is found at the beginning of the wheat belt 'plateau', where the average elevation is 300 m AHD and the topography is flat to gently undulating. This system consists of mallee with some valleys of eucalypt woodland and mallee on the watershed between the south-draining rivers of BREMER BAY and the northward-draining chain of salt lakes in the Avon catchment.

The Fitzgerald River National Park consists of the Qualup system of mallee and mallee-heath and the unique Barren Ranges system, which harbours a number of endemic eucalyptus species of mallee-heath, mallee and coastal scrub.

North of the coastal vegetation, much of BREMER BAY is cleared for agriculture, except for the area bounded by the Fitzgerald River National Park. Native vegetation survives in nature reserves, road reserves, around isolated swamps and in small private remnant vegetation areas.

1.5 Previous investigations

The first geological investigations in BREMER BAY concentrated on the Fitzgerald River lignite beds (Roe, 1852; Gregory, 1861; Dixon, 1884; Woodward, 1890). Later Cockbain (1968) and Cockbain and van de Graaff (1973) described the lignite deposit and the Tertiary sedimentary sequence in detail. Earliest investigations included a petroleum exploration bore, drilled in 1921, through 108 m of Proterozoic metasedimentary rocks (Maitland, 1922), and named Jonacoonack No. 1 by Cockbain and van de Graaff (1973).

Mineral exploration has provided the most comprehensive insight into the geology of BREMER BAY. The earliest mineral exploration centred on the immediate area around Naendip and Copper Mine Creek, where uneconomic deposits of manganese and copper were investigated by Blatchford (1926), Grey and Gleeson (1951) and Townley (1953). Heavy-mineral deposits at Cheyne Bay and Gordon Inlet were described by Baxter (1977). The Plantagenet Group sedimentary rocks of BREMER BAY were explored for oil shale by BHP Minerals in 1981. The Southdown magnetite deposit, to the west of Wellstead, was investigated by Portman Mining Ltd in 1987. The area from Cheyne Bay north to Boxwood Hill, and eastwards south of Devils Creek Road to the Fitzgerald River National Park, including Doubtful Island Bay, Dillon Bay and Wray Bay, was explored for heavy-mineral sands and drilled extensively in the late 1980s by Eucla Mining NL (1991a, b, c, d, e, f, 1992).

Regional geological reconnaissance of BREMER BAY began in the 1950s. Clarke *et al.* (1954) were the first to recognise differences in the structural trends within gneiss outcrop. Thom and Chin (1984) reviewed reports on the structure and geochronological studies of the area. An account of the structural geology, based on the synthesis of published works, geophysical data and field work, is described by Myers (1990a, b; 1995). An overview of the Bremer Basin sedimentary rocks is given by Hocking (1990).

The earliest recorded groundwater investigation is in a report by Maclaren (1912) on desert water supplies and gnamma holes in the Ongerup District. The first commissioned examination of groundwater conditions in the western portion of BREMER BAY was undertaken by Berliat (1951). Drought conditions in 1969 prompted the Western Australian Government to provide assistance in the search for underground water supplies in thirteen separate areas (Lord, 1971), including the South Stirling, Chillingup and Ongerup districts of BREMER BAY. The drought program of 1969 was a major contribution to the understanding of groundwater conditions in the district (Davidson, 1977). A synthesis of drought-relief drilling and interpretation on regional groundwater of the south coast is given by Laws (1982).

Additional hydrogeological data were obtained from unpublished reports by the GSWA on groundwater conditions at Bremer Bay (Smith, 1992, 1993). Following an investigation in 1969 by the Public Works Department (PWD) for a town water supply to service Bremer Bay (O'Driscoll, 1962), a borefield was established in the Gnornbup Swamp area. A request to meet increased demand for water supplies resulted in subsequent reports on the borefield by Bestow (1982) and Hirschberg (1983).

Surface-water salinity problems were reported after the turn of the century, and have become a major issue in recent times. Salinisation is now widespread in the southwest of Western Australia. The problem is particularly severe on the south coast and has driven the need to better understand the regional hydrogeology of the region. The National Landcare Program has provided funding for the Hydrogeological Mapping Project that has seen the publication of 1:250 000 hydrogeological series maps for Mount Barker–Albany (Smith, 1995), Esperance–Mondrain Island (Baddock, 1996) and Ravensthorpe (Johnson, 1996).

1.6 Map compilation

The hydrogeological map of Bremer Bay depicts aquifer distribution and type, watertable level and topographic contours in m AHD, groundwater salinity contours (isohalines), groundwater point data distribution and cadastral data. Contributing to compilation of the map were: topocadastral data from Department of Land Administration; geology from Geological Survey of Western Australia (Thom and Chin, 1984); bore data from the Water and Rivers Commission water point database (AQWABase), Agriculture Western Australia (AgWA) Albany Branch bore and piezometer data; and WAMEX and WAPEX mineral and petroleum exploration drilling data and reports from the Department of Minerals and Energy.

The Bremer Bay hydrogeological map is, at the 1:250 000 scale, a generalisation of the available digital data, which have been entered into a digital data base and stored as graphical layers of information at various scales. Documentation is included in Appendix 1 showing scales of capture for each graphical layer. The digital data can be augmented, and maps of catchments or specific areas can be reproduced at any scale for land and water resource management and planning. Most interpretation of the data was conducted at the 1:50 000 scale, and this should be considered when working with larger scales. The hydrogeological boundaries, watertable level contours, and groundwater isohalines are interpretive, and must be taken as approximate. The greater the bore density, the more confident the interpretation.

2 Geology

2.1 Regional setting

The geology of BREMER BAY has been described by Thom and Chin (1984) and the tectonic history by Myers (1990a, b, 1995). The stratigraphic sequence is summarised in Table 1.

The basement consists of Archaean granite and gneiss of the Yilgarn Craton and Proterozoic gneiss and metasedimentary rocks of the Albany–Fraser Orogen (Fig. 3). The basement rocks are partly covered by Cainozoic sedimentary rocks and a well-developed regolith. Isolated basement highs form monadnocks, which protrude through the sediments or lie just below the surface.

The Cainozoic sedimentary rocks consist of Tertiary sedimentary rocks of the Plantagenet Group of the Bremer Basin, and surficial sediments. The Plantagenet Group, in turn, comprises two distinct lithofacies; the Werillup Formation and the Pallinup Siltstone. The Werillup Formation infills Cretaceous to early Tertiary palaeodrainages formed during the continental break-up of Australia and Antarctica, and is overlain by horizontally bedded Pallinup Siltstone.

Epeirogenic uplift along the Jarrahwood axis, north of BREMER BAY, probably during the Oligocene, tilted the Tertiary sediments slightly to the south and rejuvenated south-trending drainage (Cope, 1975).

Cainozoic surficial deposits, which form a thin cover over most of the remainder of the sheet, are derived through erosion of the duricrust, Tertiary sediments and basement rock. The surficial deposits consist of eolian sand, colluvium, lacustrine deposits of thin clay and silt and, near the coast, shelly sandstone and coastal dune sand. To a lesser extent, a thin pisolitic laterite has also developed near the top of the Tertiary Plantagenet sediments.

2.2 Archaean

The northwest plateau of BREMER BAY is part of the Western Gneiss Terrane sub-division of the Yilgarn Craton, and is characterised by a mainly north-northwest structural trend, which swings east-northeast near the Albany–Fraser Orogen (Myers, 1990b). The oldest gneiss complexes were repeatedly deformed before two episodes of younger granite–greenstone emplacement, with the first granite–greenstones being deformed before the second episode (Myers, 1995).

Table 1. Stratigraphy

Age	*Formation*	*Maximum thickness intersected (m)*	*Lithology*
Quaternary	Alluvium *(Qa)*	12.5	Silt, clay and sand
	~~*unconformity*~~~~~		
	Coastal sediments *(Qs)*	40	Shelly sandstone, dune sand
	~~*unconformity*~~~~~		
Tertiary— Eocene	Plantagenet Group *(TPp/TPw)*		
	Pallinup Siltstone *(TPp)*	60	Siltstone, spongolite, minor sandstone.
	Werillup Formation *(TPw)*	60	Siltstone, sandstone, peat conglomerate
	~~*unconformity*~~~~~		
	Gnowangerup dyke swarm *(Pd)*	-	Dolerite
	~~*unconformity*~~~~~		
Proterozoic	Mount Barren Group		
	Kundip Quartzite *(PBk)*	-	Quartzite, micaceous sandstone
	Kybulup Schist *(PBy)*	-	Schist, phyllite, shale, and minor banded iron
	~~*unconformity*~~~~~		
	Albany–Fraser Orogen *(Pn)*	-	Gneiss, schist, metamorphic, clay
Archaean	Yilgarn Craton *(Ag/An)*	-	Granite/gneiss, metamorphic, greenstone, clayey sand,

Note: (-) thickness is not determined

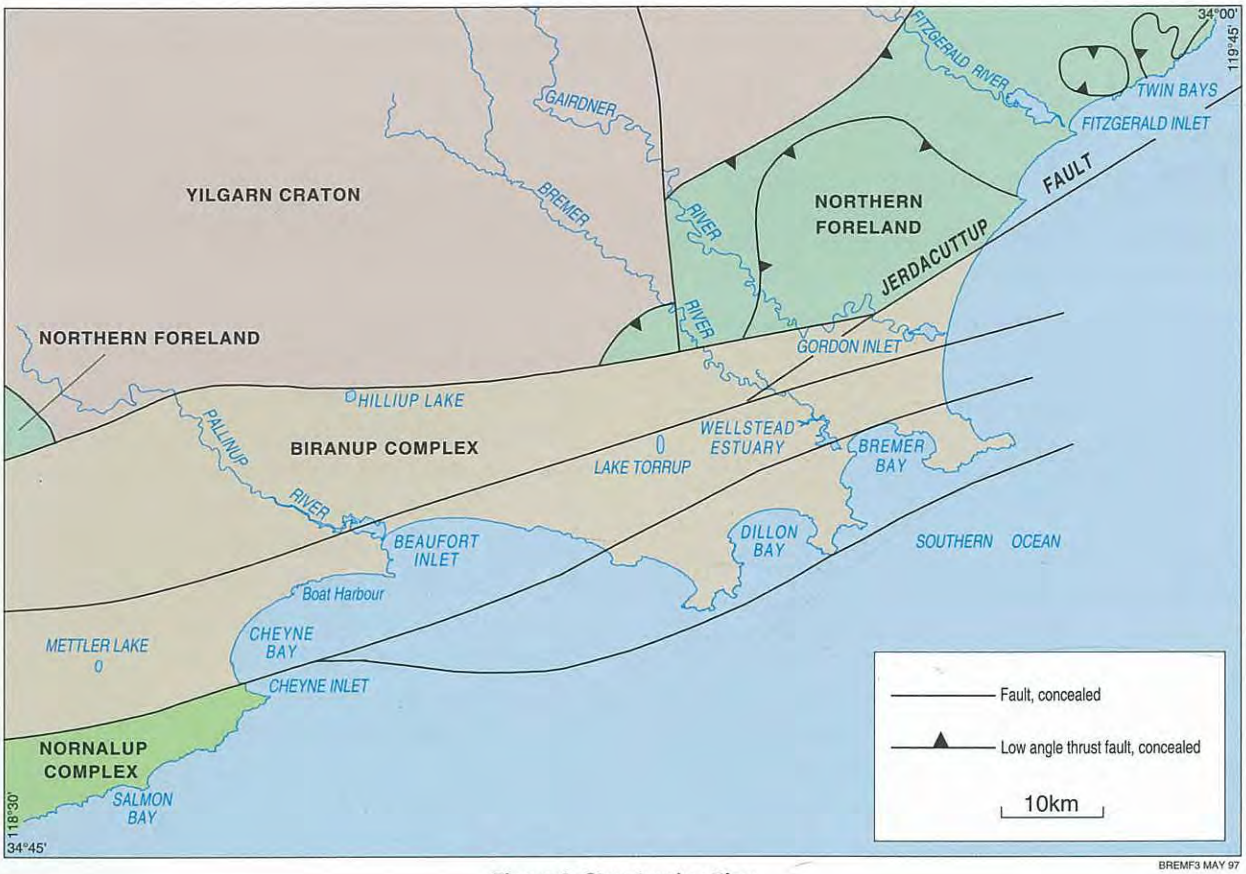

Figure 3. Structural setting

The gneissic rocks are granitic and adamellitic in composition. They comprise augen gneiss, paragneiss, orthogneiss, schist and metamorphosed agmatite. The granitic rocks consist mainly of medium- to coarse-grained granite, and an adamellite that are locally porphyritic. Archaean ultramafic rocks, metasedimentary gneiss, quartzite and metamorphosed banded iron occur locally northwest of Boxwood Hill.

Intensive weathering of the Archaean rocks in the Tertiary has produced a laterite profile consisting of a ferruginous duricrust overlying a pallid sandy clay and saprolite up to 30 m thick (Hocking and Cockbain, 1990). Rejuvenation of south-trending drainage, and erosion of the regolith has resulted in isolated laterite outcrops on hilltops and extensive exposure of massive gneiss and granite in the northwest of the sheet.

2.3 Proterozoic

The Proterozoic rocks of the Albany–Fraser Orogen lie south of the Yilgarn Craton and are divided into the Northern Foreland, the Biranup Complex, and the Nornalup Complex, by a series of east-northeast thrust faults. The Northern Foreland consists of metasedimentary rocks of the Stirling Range Formation and the Mount Barren Group, of which only the latter outcrops on BREMER BAY. The Biranup Complex and Nornalup Complex each consist of banded gneiss, which exhibits polyphase deformation, and are thrust northwards in steeply dipping tectonic slices 5 to 15 km thick (Myers, 1995). The Nornalup Complex lies to the west of Cape Riche on BREMER BAY, and is less intensely deformed.

2.3.1 Gneiss

Proterozoic gneissic rocks include augen gneiss, compositionally layered gneiss, strongly foliated granoblastic gneiss, mafic granulite and migmatitic granulite of admellitic and granitic composition (Thom and Chin, 1984). These rocks are exposed along the bed of the Pallinup River and at the coast, where they form steep-sided headlands.

The weathered gneiss profile varies considerably in thickness, ranging from only 3 m in ALB 9 to more than 30 m in ALB 10 (Johnson, 1995). The weathered profile is characterised by a clay horizon above partially decomposed gneiss, in which the original texture is preserved.

2.3.2 Mount Barren Group

The Mount Barren Group was defined by Thom and Chin (1984) as comprising three formations: the Steere Formation, Kybulup Schist and the Kundip Quartzite. The Steere Formation lies unconformably on the Archaean but does not crop out on Bremer Bay, and hence is not represented. The Mount Barren metasedimentary rocks extend throughout the Fitzgerald River National Park, except south of the Jerdacuttup Fault where the Biranup Complex is thrust northwards and abuts the metasedimentary rocks (Fig. 3).

Kybulup Schist

The Kybulup Schist consists of shale, sandstone, phyllite, schist and minor banded iron-formation. The schistose rocks comprise chlorite–quartz and muscovite–chlorite–quartz mineral assemblages with interbedded, finely layered quartz arenite (Thom and Chin, 1984). The formation, which is overlain by the Kundip Quartzite, is exposed at Woolbernup Hill and Thumb Peak in the far east. It is also exposed along the coast, and where rivers have cut down through the schist. Folding is most intense low in the sequence, where a series of south-dipping thrust sheets have been piled one over another, creating foliation, cleavage, lineation and fracturing in less-ductile matrix. The total thickness of the Kybulup Schist is unknown due to the intense folding.

The Kybulup Schist is variably weathered beneath the cover of Cainozoic sediments. The original texture of the weathered profile is well preserved in micaceous clay to depths of more than 15 m (Panasiewicz, *et al.*, 1996).

Kundip Quartzite

The Kundip Quartzite consists of partially or completely recrystallised quartz arenite and micaceous sandstone. Sedimentary bedding planes and cross-bedding sedimentary structures are well preserved, for example at Mount Maxwell. The formation strikes northeast and dips steeply to the southeast near West Mount Barren and Mount Bland. Farther east at Thumb Peak, the Kundip Quartzite forms a pile of low-angle thrust sheets that dip between 10 and 30^0 to the south (Witt, in press).

The quartzite is particularly resistant to weathering and hence well exposed in the rugged peaks of West Mount Barren, Mid Mount Barren, Mount Bland and Mount Maxwell within the Fitzgerald River National Park.

2.3.3 Gnowangerup dyke swarm

The Gnowangerup dyke swarm, emplaced in the southern Yilgarn Craton, is grouped within the Northern Foreland by Myers (1995). The dykes are not present in the Biranup Complex and hence they probably predate the Biranup Complex rocks (Myers, 1990a). The dykes are composed of dolerite to quartz dolerite. The major east-northeasterly trending dykes are of low metamorphic grade and have a fine-grained igneous texture. The dykes dip steeply to the south and vary from several metres to tens of metres in thickness. Northwesterly trending dykes occur randomly within Archaean granite and gneiss.

2.4 Cainozoic

2.4.1 Tertiary Werillup Formation

The Werillup Formation consists of dark-grey siltstone, sandstone, carbonaceous clay and lignite sands, with a minor limestone sequence, the Nanarup Limestone Member (Cockbain, 1968). The type section is between 17 and 59 m deep in Werillup 3 borehole, approximately 600 m southwest of Albany Prison. The formation is generally an upward-fining sequence, with the coarsest sediments encountered within palaeochannels. Generally, the thickness and extent of the Werillup Formation reduces northwards across Bremer Bay.

The Werillup Formation rests unconformably on the basement rocks, and is overlain conformably by the Pallinup Siltstone, or unconformably by Quaternary sediments where the Pallinup Siltstone has been eroded. The formation has limited exposure on Bremer Bay, occupying a chain of buried lakes interconnected by palaeodrainages beneath the Pallinup Siltstone; however, it is exposed along the Twertup and Susetta Creeks within the Fitzgerald River National Park (Cockbain and van de Graaff, 1973). The top of the Werillup Formation is at or below sea level at the coast and rises to more than 200 m AHD in the north of Mouny Barker–Albany (Smith, 1996).

2.4.2 Tertiary Pallinup Siltstone

The Pallinup Siltstone consists of multicoloured siltstone, spongolite and minor sandstone. The type section is exposed in a cliff on the north side of Beaufort Inlet, 1.6 km upstream from the mouth of the Pallinup River. The facies comprise brown, clayey siltstone, and fine-grained, clayey, glauconitic sandstone, which is commonly silicified. The basal beds are generally coarser grained and sandy (Cockbain, 1968). Spongolite overlies and interfingers with the siltstone, and is most prominent in the Fitzgerald River National Park and Ravensthorpe areas (Cockbain, 1968).

Three palaeo-shorelines, at slightly different elevations, marked by discrete beach sand units that pass laterally (seaward) into marine sediments, were identified during mineral-sand exploration (Eucla Mining NL, 1991a, b). The facies is poorly defined by discontinuous occurrences along Swamp Road and Devils Creek Road that probably represent eroded remnants of the three palaeo-shorelines: the elevation of the main shoreline ranged between 80 and 90 m AHD. A palaeo-shoreline was recognised on ESPERANCE–MONDRAIN ISLAND at approximately 90 m AHD (Baddock, L., 1995, pers. comm.). Another shoreline was intersected by AgWA drilling in 1995 at 50 m AHD near the intersection of Cape Road and the South Coast Highway.

The Pallinup Siltstone conformably overlies the Werillup Formation, and unconformably overlies basement rock where the Werillup Formation is absent. The maximum thickness of siltstone intersected on BREMER BAY is 65 m, within the Wellstead borefield, and the thickness and extent of the formation reduce to the north across the map sheet. The Pallinup Siltstone extends over approximately half of onshore BREMER BAY, and although generally covered by sand plain, it is exposed in breakaways over the Yilgarn Craton in the northwest.

In the east, the Pallinup Siltstone is exposed in deeply incised drainage of the Bremer and Gairdner Rivers and throughout the Fitzgerald River National Park as part of a dissected relict peneplain. Well-developed burrows are preserved in several levels and are associated with solution cavities, giving a karst-type appearance in outcrop. The Pallinup Siltstone is often capped by a thin (<1 m) ferricrete cover containing angular quartz grit.

2.4.3 Quaternary coastal sediments

Calcareous shelly sandstone, which crops out along the coast between gneissic headlands, is overlain by vegetated and active coastal dune sand. The sediments consist of predominantly fine- to medium-grained, well-sorted calcareous sand with shell fragments.

The thickness of the coastal sediments is unknown, particularly where access is difficult, but is likely to be highly variable. Shelly sandstone crops out along the east side of Cape Knob in steep-sided cliffs to 150 m AHD and rests unconformably over Precambrian basement. Mineral-sand exploration at Dillon Bay intersected up to 40 m of Quaternary quartz sand above the Pallinup Siltstone (Eucla Mining NL, 1991c). A fossil scarp within the Pallinup Siltstone, approximately 2.5 km north of Wray Bay, is overlain by 30 to 40 m of coastal sediments. Farther west the Pallinup Siltstone is completely eroded and the Quaternary sediments overlying the Werillup Formation are up to 60 m thick (Eucla Mining, 1991d).

2.4.4 Quaternary surficial sediments

The Quaternary surficial deposits, consisting of yellow to white sand with limonitic nodules and ferruginous pisoliths, cover two-thirds of onshore BREMER BAY. Colluvium, minor alluvium and the sandplain sediments are derived from, and overlie, the dissected peneplain of Tertiary sedimentary rocks and weathered profile of basement rocks. The pisoliths are derived from the erosion of the laterite capping over the Archaean basement and Pallinup Siltstone. The sediments generally form a thin veneer over the underlying rock.

3 Hydrogeology

3.1 Groundwater occurrence

Groundwater is contained within ten major rock units whose distribution is shown on BREMER BAY. The relationships between rock units are demonstrated schematically in Figure 4 and on the map sections A–B and C–D. The principal aquifer in the region is the Werillup Formation; however, there is a large variation in both potential yield and salinity within the aquifer.

BREMER BAY is underlain almost entirely by fractured and weathered Archaean and Proterozoic gneiss and granite. Fissured, fractured and weathered metasedimentary rocks of the Mount Barren Group occur in the east. These basement rocks, which are generally associated with complex hydrogeology, form relatively impermeable barriers to the movement of groundwater, and hence are considered aquitards.

Dolerite dykes exhibit major east-northeasterly and minor northwesterly trends across the Archaean granites and gneisses of BREMER BAY. They tend to be igneous textured, typically appear to lack fractures, and generally impede groundwater flow. However, groundwater occurs within quartz veining associated with sheared dolerite along Toompup South Road (Laws, 1987).

The basement is overlain, in part, by sedimentary rocks of the Tertiary Plantagenet Group. Although these rocks have intergranular porosity, they are characterised by low permeability due to their silty or clayey nature. However, they are generally the most porous of the area and are thus considered the best aquifers. The aquifers occupy broad flat depressions, and locally lie within palaeochanels on the uneven basement palaeosurface.

Quaternary sediments, which overlie approximately 80% of BREMER BAY (Fig. 4), are generally unsaturated, except at the coast and within alluvium and lacustrine deposits. Potential for significant groundwater storage within the Quaternary sediments is limited to the coast, southwest of Bremer Bay, where potable groundwater exists.

A perched aquifer may be present within the Quaternary sand, particularly where this sand overlies relatively impermeable basement (Fig. 4). The extent of the perched aquifer is not shown on the map.

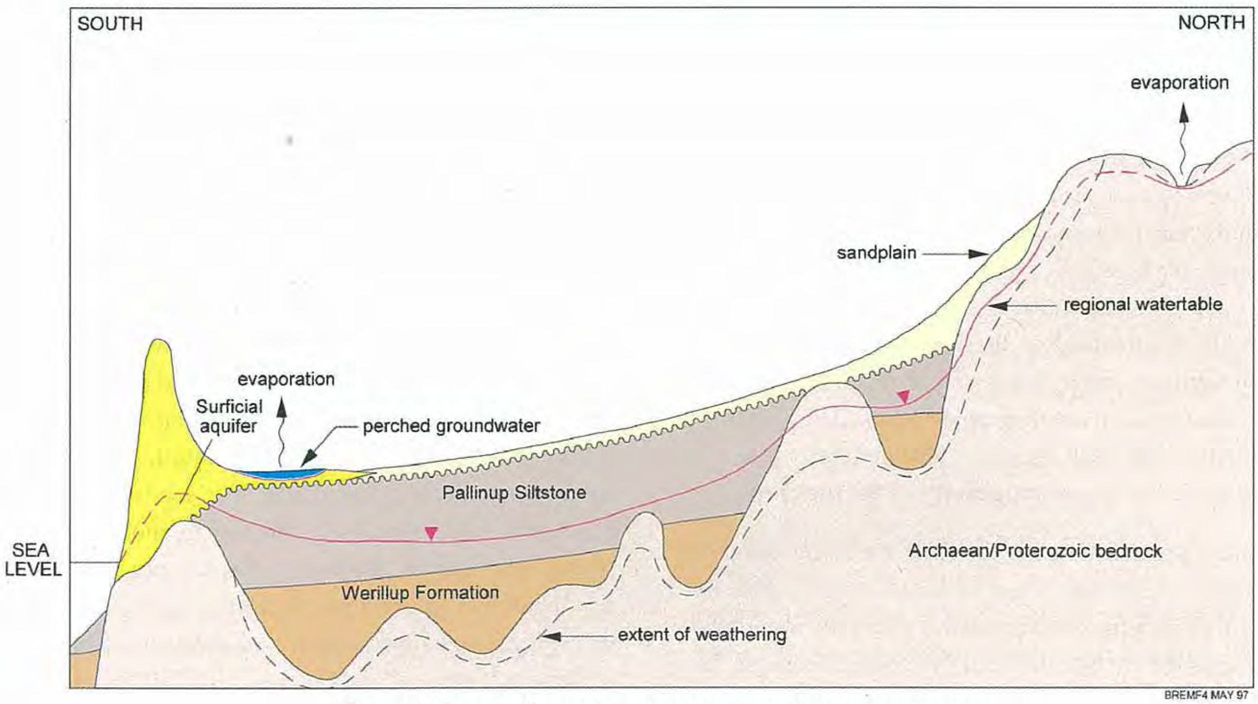

Figure 4. Schematic section showing groundwater occurrence

3.2 Regional watertable

The regional watertable represents the level below which all pore space and fractures within rocks are saturated. It generally forms a continuous surface throughout BREMER BAY, broken only by basement outcrop in the northwest. The depth to the watertable is dependant on rock type, topography, and groundwater recharge and discharge. The regional watertable is depicted on the map sheet by groundwater contours in metres Australian Height Datum (m AHD). The groundwater contours, which are interpreted from historical and recent bore water levels, including monitoring piezometers, are non-synoptic.

In the northwest, the watertable forms a subdued image of the topography, particularly where basement rocks are near the surface. Depth to groundwater is generally less than 5 m in valleys below ground surface, but may reach 20 m along topographic divides. In Tertiary sediments the watertable has a very low gradient and depths to groundwater range from 20 m near Swamp Road to 30 m or greater south of Bremer Bay Road. Anomalies in this trend may occur around isolated basement highs. Along the coast, depth to groundwater is poorly defined due to a lack of data and difficulty of access. A groundwater mound may exist within the Quaternary coastal sediments as a result of higher rainfall and limited surface runoff over coastal dune sand increasing recharge.

3.3 Groundwater flow and discharge

Groundwater flows in the direction of decreasing potential, from a maximum of about 300 m AHD in the northwest to near sea level at the coast. The volume of groundwater throughflow depends on the hydraulic gradient, the hydraulic conductivity, and the thickness and extent of the aquifer. Although the regional hydraulic gradient is low, there may be local variations in throughflow as a result of enhanced recharge or dramatic variation in topographic relief. The hydraulic conductivity of each aquifer is also generally low, but can vary due to the heterogeneity of the rock type.

Groundwater discharges at the coast and along drainage courses. Groundwater is also discharged by evapotranspiration, or evaporation where the watertable intersects the surface or is cut by incised drainage, for example along the Gairdner River.

3.3.1 Lakes

In the south west and central BREMER BAY where the Tertiary sedimentary cover is thickest, numerous lakes fill depressions on an essentially flat land surface that is internally drained. Three types of lakes have been recognised: broad and shallow, seasonal fresh water depressions and deeper sumps that are perched above the regional groundwater level; brackish sumps that are close to the regional groundwater level; and saline lakes and sumps that receive groundwater discharge (Ferdowsian *et al.*, 1996).

Deep depressions which intersect the watertable are characterised by steep-sided cliffs on their northwest side and a gentle rise to the southeast. These lakes are permanent, mainly brackish to saline, and groundwater discharges to the lake when the level of the regional watertable intersects the bed of the lake. However, when the level of the regional watertable falls below the bed of the lake, some recharge by downward leakage may occur.

Broad and shallow depressions and local deeper sumps generally have a base perched above the regional watertable. These depressions are seasonal and contain mainly fresh water. The depressions are characterised by eolian lunette dune sand on the east or southeast side of each depression, and generally overlie low-permeability siltstone. The depressions may contribute recharge to the groundwater system through slow vertical leakage.

3.4 Aquifers

3.4.1 Quaternary coastal sediments

The Quaternary coastal sediments (*Qs*) form an unconfined aquifer along the coast from Bremer Bay westwards to Beaufort Inlet, and is inferred to exist south of Cape Riche near Salmon Bay. Where the unit is shown on BREMER BAY it is interpreted as saturated. The aquifer consists of predominantly fine- to medium-grained, well-sorted, partly indurated, calcareous sandstone with shell fragments. The sandstone layers have intergranular porosity and may be moderately to highly permeable. However, limited bore data are available, and information about the aquifer is based on the logs from mineral-sand exploration using air core drilling technique (Eucla Mining NL, 1991c, d, e, f, 1992).

The Quaternary sediments are recharged by rainfall, with minimal surface runoff evident from eolian dune sand. Recharge is controlled by local conditions and is greatest where sandy sediments occur, where elevated gneiss outcrops give rise to appreciable runoff to surrounding sandy sediments, and where stream flow from clayey sediments crosses more permeable material (Bestow, 1982). Groundwater flow is local, with discharge to the Southern Ocean through streams that have developed at the contact with Proterozoic gneiss, as at Stream Beach. In the north, groundwater may discharge to swamps, such as Yenteyerrup, Qualinup, Cardiminup, Potato and Bitter Water Swamps north of the coastal dunes. However, discharge is more likely to take place via vertical leakage to the underlying Pallinup Siltstone, particularly where the more porous spongolite facies is present.

Aquifer parameters are unknown as no pumping test data are available. Saturated thickness of the aquifer is unknown, but is probably greatest southwest of Bremer Bay at Cape Knob, thinning westward towards Beaufort Inlet, and northward away from the coast. At Dillon Bay, the saturated thickness is highly variable owing to the uneven surface of coastal dune sand, and may be insignificant (1–2 m) in low-lying areas, such as along Bitter Water Creek (Eucla Mining NL, 1991c). North of Wray Bay, the saturated thickness is poorly documented and estimates of open-hole yields range from 20 to 40 m^3/day (Eucla Mining NL, 1991d). Along the coastline within the Fitzgerald River National Park, Quaternary sediments occur as a thin veneer over Tertiary sediments and no significant groundwater exists within the Quaternary sediments (Eucla Mining NL, 1991e, 1992).

Groundwater is generally brackish but potable water was sampled from discharge to Stream Beach. The stream water was analysed as 480 mg/L Total Dissolved Solids (TDS) in 1995, and salinity from a well south of Bremer Bay was recorded as 720 mg/L TDS. However, groundwater salinity is expected to be higher in the north away from the coast.

3.4.2. Quaternary surficial sediments

The surficial sediments *(Qa)*, which form an unconfined aquifer in the northeast of BREMER BAY, consist primarily of alluvium within modern drainage. This alluvium comprises predominantly reworked basement rock, sand, silt and clay, and is some 12 m thick. The aquifer created by the alluvium has been recognised through exploratory drilling of the Susetta Creek lignite beds (Cockbain and van de Graaff, 1973). The surficial sediments, recharged by rainfall and river flow, are recognised as a separate aquifer to the coastal surficial sediments owing to their lower permeability and low groundwater storage potential.

Elsewhere the surficial sediments occur as sandplain deposits forming a thin veneer over the underlying rocks, and sporadically as distinct dunes (e.g. south of Mettler Lake) and as lunette dunes on the east and southeast side of numerous swamps; they comprise fine- to medium-grained, well-sorted grey sand. Isolated perched water forms within the sand during winter, and may persist into summer in times of higher rainfall. The maximum saturated thickness rarely exceeds several metres. Groundwater flow is local, discharging along the margins of the dunes where soaks develop, and to the many swamps associated with the dunes. Groundwater is generally fresh to brackish. The sandplain is not delineated on BREMER BAY.

3.4.3. Tertiary Pallinup Siltstone

The Pallinup Siltstone (*TPp*) forms an unconfined aquifer of horizontally bedded, variably consolidated siltstone, claystone, spongolite and minor sandstone. The formation was deposited by a transgressing sea in a low-energy environment, and despite its intergranular porosity, fine-grained lithology and cementation results in low permeability. As a result, bore yields from the siltstone range from negligible to 40 m^3/day in the north, and to greater than 100 m^3/day in the south.

The Pallinup Siltstone is recharged by rainfall and downward leakage from overlying Quaternary sediments. The saturated thickness varies considerably, depending on the thickness of the Pallinup Siltstone, which inturn is governed by the uneven palaeosurface of the basement rocks. The potential for groundwater storage within the aquifer diminishes rapidly northwards across BREMER BAY. Generally, only the lower portion of the sequence is saturated. Groundwater discharges by evapotranspiration, by slow vertical leakage to the underlying Werillup Formation, and by throughflow to the Southern Ocean or along the incised drainages of the Pallinup, Bremer, Gairdner and Fitzgerald Rivers.

The spongolite facies is generally unsaturated on BREMER BAY, as the average depth to the watertable is greater than 20 m below the surface within Tertiary sediments. The exception is near the coast where the Pallinup Siltstone underlies Quaternary sediments southwest of Bremer Bay. Here the saturated thickness is greater, bore yields range from 70 to 450 m^3/day from pumping tests at the Bremer Bay town water supply borefield. Higher rainfall and overlying Quaternary coastal sediments enhance recharge by leakage to the Pallinup Siltstone.

Groundwater has not been reported within the 80 to 90 m AHD shoreline facies in the north along Swamp Road or Devils Creek Road, and the facies is interpreted as largely unsaturated. Several bores south of Swamp Road indicate that a shoreline facies at approximately 50 to 55 m AHD is below the regional watertable (AgWA, 1990). No bore yields are recorded; however, field conductivity measurements of a bore water sample indicated the groundwater contained more than 12 000 mg/L TDS.

Groundwater salinity within the Pallinup Siltstone ranges from less than 1000 mg/L TDS in the Bremer Bay town water supply borefield to about 12 000 mg/L in bores near Swamp Road. The salinity distribution reflects reduced rainfall and increased evaporation northwards across BREMER BAY. The exception is along Murray Road where groundwater salinity within the Pallinup Siltstone is generally less than 7000 mg/L (Baddock *et al.*, 1996). Groundwater beneath surface water divides is generally less than 7000 mg/L within isolated outcrops of Pallinup Siltstone in the northwest and groundwater seeps commonly occur at the contact between the Pallinup Siltstone and granitic basement (such as near Naunerup Creek).

3.4.4. Tertiary Werillup Formation

The Werillup Formation (*TPw*) is a heterogeneous and anisotropic aquifer underlain by weathered and fractured basement and overlain, in general, by the Pallinup Siltstone. It consists largely of unconsolidated quartz sand, silt, clay and lignite of fluvial or lacustrine origin, ranging from clay particles to rounded quartz pebbles. The Werillup Formation is upwards fining, the coarsest sediment being confined to discrete palaeochannels. Its extent on BREMER BAY has been extrapolated between boreholes, and hence is largely inferred. The top of the Werillup Formation rises steadily from the coast to 200 m AHD (Fig. 5.), however it is extensively eroded, exposing the underlying basement.

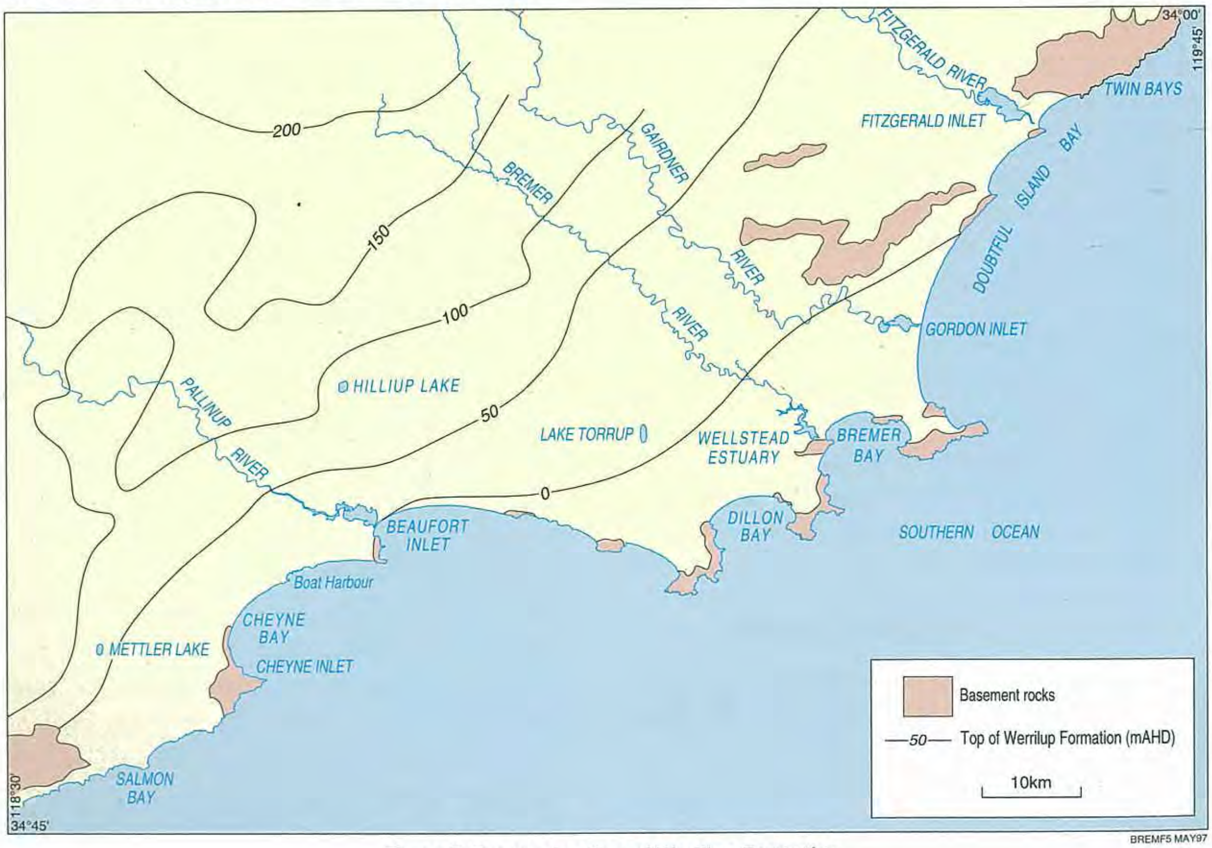

Figure 5. Pre-erosion Top of Werillup Formation

The Werillup Formation is generally 30 to 40 m thick but is highly variable and 61 m was intersected in one oil exploration hole. Where it abuts basement highs and the Pallinup Siltstone has been eroded, the aquifer is unconfined or semi-confined by the carbonaceous clay layers. Where the aquifer is confined beneath the Pallinup Siltstone it is recharged by slow downward leakage. Where it is unconfined, it is recharged from rainfall and possibly upward discharge from weathered basement.

The Werillup Formation is considered to be the major aquifer on BREMER BAY. Bores ALB10 and ALB11 drilled during the Albany Stage 2 program were airlifted at 170 and 330 m³/day respectively (Johnson, 1995), and bores drilled during the recent South Coast drilling program produced airlift bore yields greater than 150 m³/day (Koomberi, 1996). Although no aquifer parameters or pumping test data are available for BREMER BAY, hydraulic conductivity is anticipated to be similar to that of the Wollubar Sandstone documented by Commander *et al.* (1992), i.e. between 20 to 70 m/day.

Groundwater is usually saline, increasing from 12 000 to 20 000 mg/L TDS with depth. Brackish groundwater has been intersected in isolated instances where the Werillup Formation abuts basement highs and is unconfined. This lower salinity is probably due to increased local recharge from surface runoff from basement outcrop.

3.4.5. Proterozoic Mount Barren Group

The Mount Barren Group, which outcrops only in the east of BREMER BAY, consists of the Kundip Quartzite (*PBk*) fissured rock overlying the Kybulup Schist (*PBy*) fractured and weathered rock. As there are no bores within the quartzite, it is not known if the quartzite contains groundwater. However, it is shown on BREMER BAY wherever outcrop occurs and includes deformed quartzitic breccia and oligomictic conglomerate derived from the Kundip Quartzite.

The Kybulup Schist is characterised by metamorphosed, fine-grained, fissile rocks. The Cowerdup Sill of altered dolerite, which lies east of Thumb Peak, is grouped with the Kybulup Schist. The schist is a heterogeneous, fractured rock aquifer, generally low in permeability. However, secondary porosity due to faults and fracturing has enhanced groundwater storage. The schist has a thin weathered zone with the original rock texture preserved, and groundwater may be found at the base of the weathering profile. Bore yields within the schist are highly variable, ranging from negligible to greater than 100 m³/day (Smith, 1994a).

The fractured-rock aquifer is recharged by rainfall. Groundwater flow is radial from topographic highs and may discharge into overlying Tertiary sediments. Groundwater is brackish to saline, ranging from 2300 mg/L TDS in a fracture zone west of Mount Maxwell to 20 000 mg/L between the Bremer and Gairdner Rivers (Panasiewicz *et al.*, 1996).

3.4.6. Archaean granite

Archaean granite rocks (*Ag*) form localised fractured and weathered rock aquifers. The granite is widely exposed in the northwest of BREMER BAY as massive outcrop with minor foliation or jointing. In general, the granite has a low permeability, although fractured basement aquifers are characterised by secondary permeability resulting from tectonic fracturing and jointing. Weathering, exfoliation and chemical dissolution increase secondary permeability along fractures.

The granite may be covered by a weathered profile up to 30 m thick, consisting essentially of saprolite clay beneath a massive ferruginous duricrust. Groundwater is commonly located with the saprolite zone and in fractures within the uppermost 5 to 10 m of fresh rock. Groundwater is recharged by rainfall and flows to the southeast, and discharges to overlying Tertiary sediments, along valley slopes, or is lost through evapotranspiration. Bore yields from the weathered and fractured rock are generally low (<10 m³/day), but greater yields may be obtained where groundwater storage is increased by fracturing or enhanced local recharge (Smith, 1994b).

Groundwater is typically saline to hypersaline, although it may be brackish in fractures near surface catchment divides in the northwest of BREMER BAY.

3.4.7. Archaean and Proterozoic gneiss

Archaean gneiss (*An*) is well exposed in the northwest of BREMER BAY, while Proterozoic gneiss (*Pn*) is exposed along the Pallinup River and at the coast. The gneisses appear massive in outcrop, are strongly foliated and metamorphosed due to multiple phase deformation, and are very low in permeability. Local quartz veins or fractures may contain small supplies of groundwater.

Gneissic rock may be covered by a weathered profile up to 30 m thick, consisting essentially of saprolite clay beneath a massive laterite. Groundwater is commonly located within the saprolite zone directly above fresh rock and in fractures within the uppermost 5 to 10 m of fresh rock. Groundwater is recharged by rainfall and flows to the southeast, and discharges to overlying Tertiary sediments, along valley slopes, or is lost through evapotranspiration. No bores in the weathered and fractured gneiss are recorded as bore yields are generally negligible. Groundwater quality is generally saline to hypersaline.

3.5. Groundwater quality

3.5.1. Regional groundwater salinity

Groundwater salinity is represented on BREMER BAY by isohalines in mg/L TDS. The data used to interpret the isohalines have been derived from bore water samples collected over a long period of time, and hence are non-synoptic. The isohalines represent groundwater salinity obtained from a pumping bore, and not necessarily the salinity at the watertable, as a thin layer of lower salinity groundwater, reflecting recharge, may be present immediately at and below the watertable.

On BREMER BAY the groundwater is predominantly saline, ranging from less than 1000 mg/L TDS in the Quaternary coastal sediments, to more than 35 000 mg/L in weathered and fractured basement aquifers. Groundwater salinity increases to the north and east across the sheet area as rainfall decreases.

Owing to higher rainfall and greater recharge, more potable groundwater (<1000 mg/L) occurs within Quaternary coastal sediments and the Pallinup Siltstone in near coastal environs, than elsewhere on BREMER BAY. Small quantities of potable groundwater may also exist where a perched watertable forms within the Quaternary sandplain above less permeable strata.

Brackish to stock-quality groundwater (1000 to 7000 mg/L) is generally restricted to the southern third of BREMER BAY, south of the South Coast Highway, west of the Pallinup River and near Bremer Bay Road in the east, as rainfall reliability decreases to the north and eastwards. Brackish groundwater from granitic saprolite has been reported near surface-water divides in the northwest and adjacent to basement monadnocks where excess runoff enhances local recharge, as at Wiriup Hill (Davidson, 1977). Near Murray Road, groundwater throughflow towards the incised drainage of the Bremer and Gairdner Rivers keeps salinity within the Plantagenet Group below 7000 mg/L (Panasiewicz *et al.*, 1996).

Groundwater of salinity exceeding 7000 mg/L is reported over most of BREMER BAY within the Tertiary sedimentary rock aquifers and the fractured basement aquifers. Salinity within the Pallinup Siltstone between Swamp Road and Bremer Bay Road generally exceeds 7000 mg/L and reaches 15 000 mg/L at the base of the siltstone. Groundwater salinity in the Werillup Formation is greater than 12 000 mg/L, and increases to 20 000 mg/L south of Bremer Bay Road (Koomberi, 1996).

Salinity of groundwater within basement rock is typically greater than 15 000 mg/L, even within several hundred metres of surface-water divides. However, the Kybulup Schist contains groundwater with highly variable salinities depending on proximity to local recharge (as at Mount Maxwell) and the presence of fractures. Most bores in the schist record a groundwater salinity in excess of 20 000 mg/L (Panasiewicz *et al.*, 1996).

Local variations

As a rule, groundwater salinity increases with depth, due to stratification within the aquifer, and with distance along the direction of groundwater flow. Local variations in unconfined groundwater salinity may arise due to factors governing recharge, such as surface runoff from basement outcrop, or evaporation of surface water creating saline plumes down-gradient from a lake. Recharge may be greater in certain areas of permeable surface sands or sandy aquifers, such as dune sand at the coast. Facies changes within sedimentary rocks may also affect groundwater quality, particularly in an unconfined aquifer.

There may be variations in salinity within fractured rock aquifers where open fractures allow preferred groundwater flow. The saprolite of weathered granitic rock may contain groundwater with a range of salinity due to local variations in grain size or fracture frequency.

3.5.2. Hydrochemistry

Chemical analysis of groundwater samples from the Bremer Bay townwater supply production bores, the Albany Stage 2 drilling program, and additional bore, swamp and stream samples are presented in Table 2. The major ions are plotted on a Piper trilinear diagram as a percentage of their total milli-equivalents per litre concentration (Fig. 6).

Representative groundwater samples are not available for all of the aquifers. However sodium and chloride are the most dominant ions in groundwater, regardless of the aquifer type. The source of sodium and chloride is likely to be from the cumulative effect of cyclic salts carried by rainfall. In the southwest of Western Australia, winter rainfall is associated with strong westerly winds which carry moisture derived from the ocean, and this, combined with the subdued topography, favours the transport of salt inland (Hingston and Gailitis, 1976).

In coastal areas groundwater may contain significant calcium and bi-carbonate type groundwater, due to dissolution of calcium carbonate in the Quaternary coastal sediments. Chemical analysis of shallow-cased bores from the town water supply borefield, such as Production Bore 6/84 and the Golf course bore, reflect recharge from the coastal aquifer to the Pallinup Siltstone.

The pH of the groundwater ranges from 6 to 8.4 within the available data. Nitrate levels are low, except for the Stream Beach sample at 53 mg/L, which is nevertheless within the Australian Drinking Water Guidelines for consumption by adults and children over 3 months of age. However, this is a relatively high level and may indicate contamination of the stream water or the aquifer.

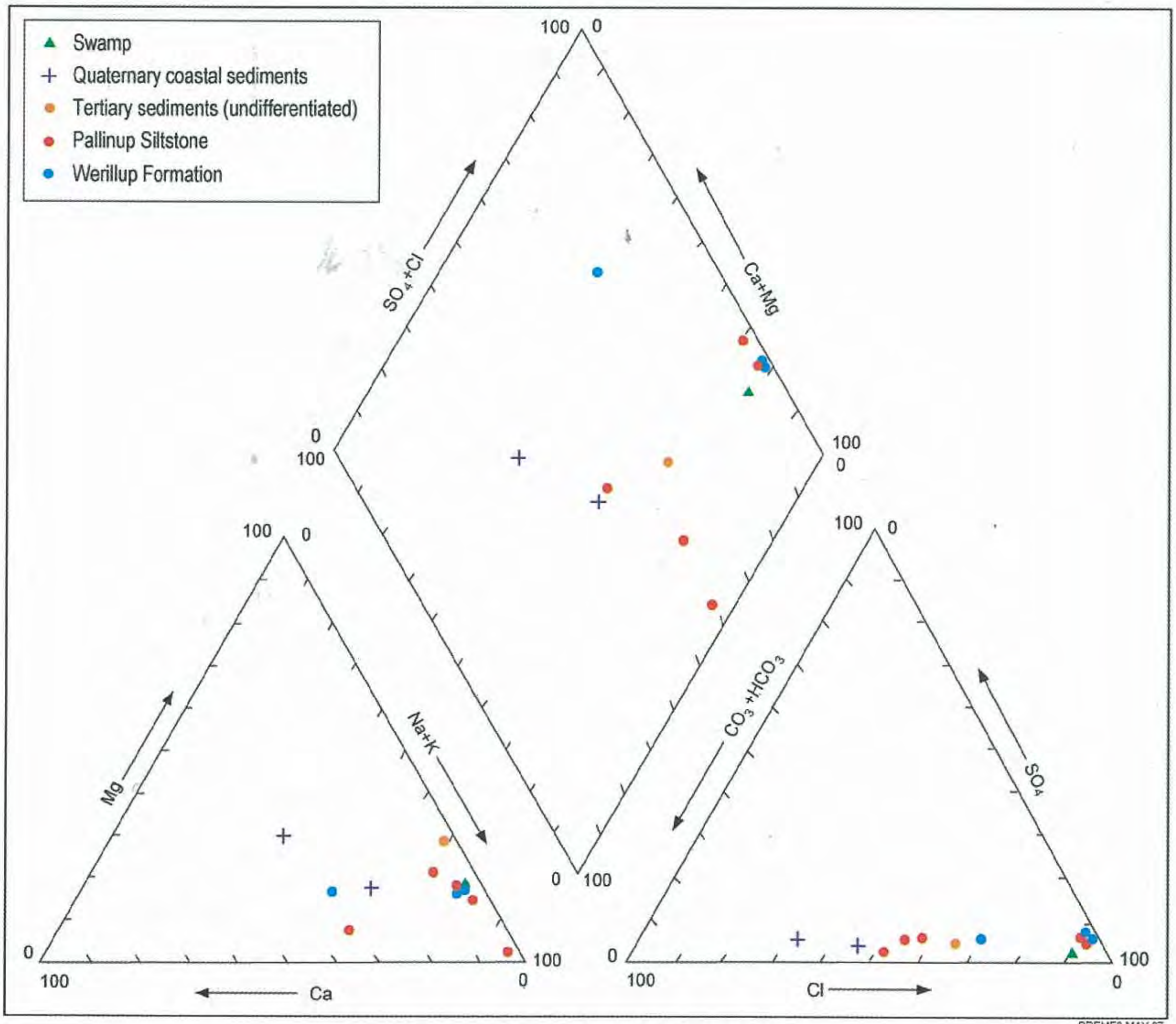

Figure 6. Piper trilinear diagram of selected analyses

Table 2. Summary of chemical analysis of groundwater

Bore	Easting/Northing	pH	TDS	Ca	Mg	K	Na	Fe	HCO_3	CO_3	SO_4	Cl	SiO_2	NO_3	Total hard.	Total alkal.
			mg/L TDS													
Surface water																
Swamp (Loc. 1511)	685000mE6200450mN	7.6	5 320	105	180	27	1 480	-	390	<1	165	2 890	-	4.2	1 000	320
Quaternary coastal																
Golf Course	719740mE6190270mN	8.4	730	60	24	5.3	165	-	385	10	24	215	-	6.8	250	335
Stream Beach	708800mE6181050mN	8.2	480	55	32	1.6	67	-	305	<1	24	91	-	53	270	250
Pallinup Siltstone																
5/69	716332mE6191306mN	7.4		3	6	11	361	-	416	0	41	326	61	0	32	341
6/84	716986mE6190890mN	7.5		30	5	4	58	-	127	0	6	84	55	2	96	105
9/84	716752mE6190710mN	7.8		9	25	11	241	-	295	0	36	268	80	6	125	242
1/82	716689mE6191298mN	8.4		9	35	12	316	-	321	5	51	375	68	3	167	271
3/83	716991mE6191075mN	6		7	4	5	59	13.7	-	-	-	85	52	-	34	37
ALB 9	647800mE6182200mN	7.8	5 180	130	225	81	1 360	-	170	<1	270	2 770	-	<.2	1 250	140
ALB 12	691950mE6194700mN	7.2	13 450	210	500	105	3 920	-	355	<1	860	7 160	-	<.2	2 580	290
Werillup Formation																
ALB 8[1]	608550mE6140550mN	8.3	1 430	160	47	7.1	290	-	370	<1	73	595	-	0.9	595	300
ALB 10	720800mE6198300mN	7.6	5 430	105	180	39	1 540	-	135	<1	390	2 750	-	<.2	1 000	110
ALB 11	708050mE6193150mN	7.5	12 350	190	410	99	3 380	-	220	<1	840	6 350	-	<.2	2 160	180

[1] ALB 8 is located on Mount Barker–Albany and is included for comparison with higher rainfall zone (800mm/a)

4 Rising watertable and land salinisation

The clearing of native vegetation for agricultural production has resulted in an imbalance in the natural groundwater systems of the southwest of Western Australia. Annual and perennial crops and pasture, collectively transpire less of the infiltrating rainfall than the native perennial vegetation they have replaced. The resulting increase in rainfall infiltration has caused an increase in groundwater storage in areas where the groundwater flow rates are low, since discharge is less than the increase in recharge. Increased groundwater storage results in a rise in watertable levels.

Land salinisation occurs where the groundwater is brackish to saline and the watertable has risen to, or is within one to two metres of the surface. In these areas capillary action draws the groundwater to the surface where it evaporates and salts accumulate in the soil. Increased soil salinity results in reduced agricultural production in mild cases and salt scalding at the ground surface in severe cases. Pasture and vegetation in valley floors, particularly where the basement is at shallow depths, such as Devils Creek, is destroyed by salinization.

A rise in watertable level to near surface can also cause waterlogging which will reduce agricultural production, and increased periods of inundation may destroy native vegetation around swamps.

A rising watertable will also dissolve stored salt within the soil, with salinity increasing at the capillary zone due to the effects of evapotranspiration. The clearing of native vegetation has enabled stored salt in the unsaturated zone that was previously fixed by vegetation to be dissolved and contribute to increased groundwater salinity. Similarly, as intermittent swamps become perennial, their salinity may increase due to the concentration of salts by evaporation.

Groundwater salinity may also be reduced as a result of the increase in infiltration of rainwater having a diluting effect as a greater amount of rainfall becomes recharge near the watertable. However, vertical stratification within aquifers caused by groundwater migrating downwards under gravity, generally results in the oldest, and hence most saline groundwater, settling at the base of an aquifer.

The rate of rise in the watertable has been monitored since 1989 by a series of piezometer nests installed by the Albany Office of AgWA within the Jerramungup Shire. Southwest of the Pallinup River, a detailed study of rises in groundwater level in Tertiary sediments adjacent to the Pallinup River has measured average rises of 0.1 m/year since 1992 (Ferdowsian *et al.*, 1996). However, groundwater discharge to the river keeps this rate down. Where groundwater flow paths are longer or interrupted by basement outcrop, rates of groundwater level rise in Tertiary sediments may be greater.

Piezometer nests installed in the weathered profiles of Archaean granites and gneisses and the Kybelup Schist in the Jerramungup Land Conservation District have indicated that groundwater is rising at rates as high as 0.3 m/year, with an average of 0.2 m/year since 1989 (Martin, 1992).

5 Groundwater development

5.1. Town water supplies

The water supply for Bremer Bay town is derived entirely from groundwater. The borefield consists of 27 bores, six of which are equipped as production bores, while two additional bores are available for future use. The six production bores provided 55 500 m³/year of groundwater in 1993/1994, from the Tertiary sediments (Table 3). The currently defined aquifer is capable of supplying 60 000 m³/year, and demand is not expected to exceed this figure before the year 2000 (Holmes, 1995).

Groundwater quality within the aquifer is highly variable depending on local recharge and the local presence of alternating clay, silt and spongolite layers of the Pallinup Siltstone. Of the 27 bores drilled within the borefield only 10 bores have a recorded salinity lower than 1000 mg/L TDS with sodium and chloride being the dominant ions. Conductivity measurements from production bores in operation indicate that salinities range from 195 to 1300 mg/L, the mixing of which results in a supply of less than 1000 mg/L (Holmes, 1995). Extraction of groundwater within the borefield at high pumping rates has invariably led to greater salinity, and a maximum rate of 100 m³/day for each production bore was recommended by Hirschberg (1983).

Dissolved iron concentrations have increased within some production bores and reduced in others after pumping. This indicates local flow directions have changed as a result of groundwater abstraction. Several bores contain very high dissolved iron concentrations, and the groundwater is treated by aeration and chlorination and, where necessary, by sand filter.

5.2. Potential groundwater resources

The potential for groundwater resources is highest to the south and west of BREMER BAY. Elsewhere the potential for groundwater resources is limited by a lack of major aquifer systems and by the predominantly saline groundwater. Of 389 bores recorded within AQWABase as at 1995, only 4% yield in excess of 50 m³/day.

The highest yielding aquifer within BREMER BAY is contained within the Werillup Formation which, however, contains mostly saline groundwater unsuitable for human or stock consumption. Only in the area west of the Pallinup River and south of the South Coast Highway is groundwater of stock quality generally available. Large supplies usually occur beneath the carbonaceous clay at depths of between 45 and 60 m (Sanders, 1971). East of Boxwood Hill, groundwater of stock quality has been intersected within the Werillup Formation near basement outcrops, which direct appreciable surface runoff over sandy colluvium, thus increasing recharge to the Werillup Formation. Groundwater salinity increases sharply with distance from the basement outcrop. Southwest of Yellilup

Table 3. Summary of Bremer Bay town water supply production bores

Bore	*Aquifer*	*Casing interval (mbtoc)*	*Screen (mbns)*	*Depth yield*	*Airlift (m³/day)*	*Salinity (mg/L TDS)*
3/69	Pallinup Siltstone	200mm prod well	14.94–28.86	30.5	149	NR [1]
5/69	Pallinup Siltstone	200mm prod well		45.7	458	910
1/82	Plantagenet Group (undifferentiated)	195mm ID Class 12 PVC	22.14–40.39	74.4	836	1250
3/83	Plantagenet Group (undifferentiated)	195mm ID Class 12 PVC	15.70–39.50 15.70–39.50	56.0 56.0	198 198	370 370
6/84	Pallinup Siltstone	142mm ID Class 9 PVC	15.04–33.30	34.0	120	446
9/84	Pallinup Siltstone	142mm ID Class 9 PVC	15.64–33.90	34.8	NR	630

[1] NR = not recorded

Swamp groundwater within the Werillup Formation is brackish, which may be due to local seasonal recharge from the swamp.

Brackish groundwater has been located within the Werillup Formation, near Murray Road, approximately 55 m below the surface (Bertoli, F., 1995, pers. comm.) and in a nearby AgWA bore (Ferdowsian, R., 1995, pers. comm.). In this area, the Werillup Formation may infill a discrete palaeochannel as two further bores to basement drilled in 1995 failed to intersect the formation (Baddock *et al.*, 1996). Brackish groundwater also occurs in the Pallinup Siltstone, but airlifted bore yields were generally less than 40 m^3/day (Panasiewicz *et al.*, 1996). Where the top of the Werillup Formation is below mean sea level, south of the 0 m AHD contour on Figure 5, the Pallinup Siltstone has a greater saturated thickness and, depending on whether the spongolite facies is present, higher yielding bores may provide a stock-water supply.

The potential for potable groundwater resources is generally restricted to the near coastal environs where there is higher rainfall and Quaternary sandy sediments, as at Gnornbup Swamp. Potable groundwater exists as a result of the above conditions allowing for greater recharge. Conditions similar to Gnornbup Swamp may apply between Mount Remarkable and Warramurrup Hill, with potential for potable groundwater supplies. Potable water is also reported from Stream Beach at Cape Knob where groundwater discharges from the Quaternary sediments that rest unconformably on gneissic basement and at Hunter River within the Fitzgerald River National Park.

Small groundwater resources are found within the weathered saprolite of granitic rocks in the northwest of the sheet, such as at Chimney Creek, or within fractures in basement rock. No records exist of a successful bore within the gneiss.

Groundwater seeps often occur at the margins of dune sand after winter rainfall, and in the northwest of BREMER BAY where Tertiary sediments, mainly Pallinup Siltstone, overlie impermeable basement, as along Cowalellup Road north of Corackerup Nature Reserve. These seeps commonly provide fresh to brackish groundwater.

The many intermittent lakes associated with the sandplain on BREMER BAY contain fresh to brackish water, and are used to supplement dam supplies and to water stock.

6 References

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Appendix 1

BREMER BAY 1:250 000 hydrogeological series digital data reference files and documentation

Design file	Levels	Description	Scale of capture (where applicable)
Bremgeo.*dgn*	L1	hydrogeological boundary unconformity (x-section only)	
	L2	hydrogeological boundary, interpreted; extent of weathering boundary (x-section only)	
	L21	creek names and lead lines in x-section	
	L22	bore labels and lead lines in x-section	
	L37	watertable (x-section only)	
	L40	geological labels and leaders	
	L41	section lines and labels	
	L42*	geological labels and lead lines: hidden	
	L45	AMG grid, topographic information in x-section	
	L49	Kundip Quartzite overprint	1:50 000
	L50	Schist overprint	1:50 000
	L52	Granite overprint	1:50 000
	L53	Gneiss overprint	1:50 000
	L60	format information, legend text, black layer	
	L63*	latitude and longitude grid	
Bremtopo.*dgn*	L1	highway with national route, formed roads	
	L2	tracks	
	L11	waterholes, pools	
	L20	watercourse, intermittent	
	L21	watercourse, perennial	
	L26	bathymetric contours and heights	
	L27	coastline, islands, swamps	
	L29	sand dunes	
	L30	topographic contours and heights	
	L38	rocks, submerged reef	
	L41	beaches	
	L42	text for road, destinations	
	L43	landmarks	
	L44	localities, towns	
	L45	national parks, reserve boundaries and text	
Brembores.dgn	L1*	map border	
	L2	bores >50m^3/day	
	L3	abandoned bores >50m^3/day	
	L4	bores <50m^3/day	
	L5	abandoned <50m^3/day	
	L6	dry bores	
	L7	monitoring bores	
	L8	mineral exploration drillholes	
	L9	soaks	
	L10	wells	
	L11	abandoned wells	
	L17	refuse sites	
	L18	rising watertable - land salinization	
	L20*	coastline	

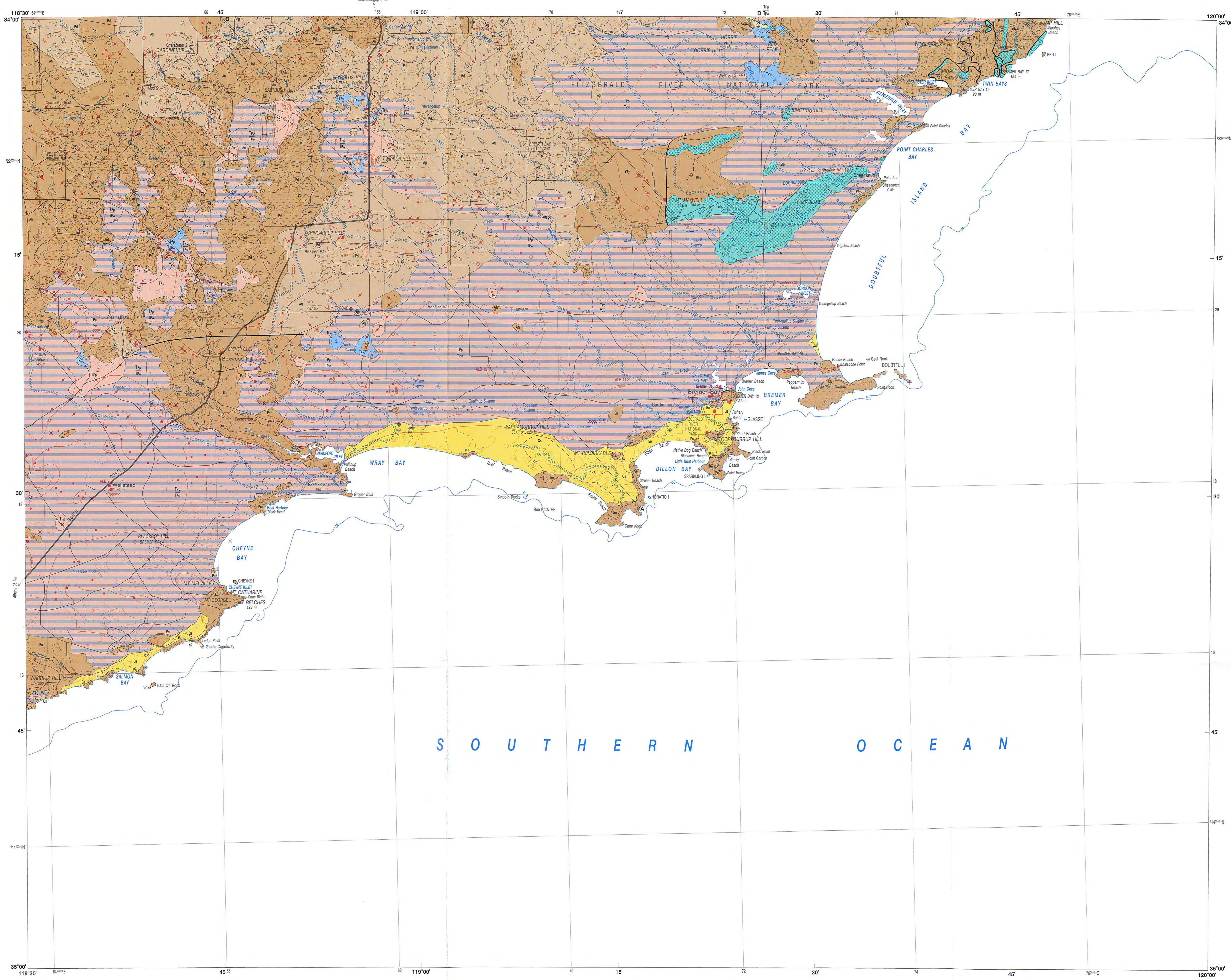
Design file	Levels	Description	Scale of capture (where applicable)
	L22	text for bore names appearing on map	
	L38	water reserve protection area, well field, numerous bores	
	L45*	AMG grid	
	L50*	dates	
	L51*	salinity	
	L52*	total depth	
	L53*	supply	
	L54*	standing water levels	
Bremsal.*dgn*	L1*	map border	
	L1	14 000 contour line	1:100 000
	L2	7000 contour line	1:100 000
	L3	3000 contour line	1:100 000
	L10	14 000 contour value	1:100 000
	L11	7000 contour value	1:100 000
	L12	3000 contour value	1:100 000
	L27*	coastline	
	L45*	AMG grid	
	L63*	latitude and longitude ticks	
Bremwc.*dgn*	L2*	20m contour line and value	
	L3	40m contour line and value	
	L4*	60m contour line and value	
	L5	80m contour line and value	
	L6*	100m contour line and value	
	L7	120m contour line and value	1:50 000
	L8*	140m contour line and value	1:50 000
	L9	160m contour line and value	1:50 000
	L10*	180m contour line and value	1:50 000
	L11	200m contour line and value	1:50 000
	L12*	220m contour line and value	1:50 000
	L13	240m contour line and value	1:50 000
	L14*	260m contour line and value	1:50 000
	L15	280m contour line and value	1:50 000
	L16*	300m contour line and value	1:50 000
	L20	groundwater seepage areas	
	L21	springs	
	L27*	coastline	
	L30*	depth to watertable contour line and value 5	1:50 000
	L31*	depth to watertable contour line and value 20	1:50 000
	L42	water catchment divide	
	L43	water catchment divide, approximate	
	L44*	water catchment divide, minor	
	L45*	AMG grid	
	L50	groundwater flow direction arrows	
	L51*	groundwater divide area	
	L60*	latitude and longitude grid ticks	1:50 000
Brempan.*dgn*	L1	black linework	
	L2	pribar –registration bar for negatives	
	L5	faults, structural geology	
	L10	yellow – registration point	
	L11	pms159 – registration point	

Design file	Levels	Description	Scale of capture (where applicable)
	L12	green – registration point	
	L13	pms139 – registration point	
	L14	pms266 – registration point	
	L15	pms151 – registration point	
	L17	pms430 – registration point	
	L18	pms140 – registration point	
	L20	coastline, pms300 – registration point	
	L21	blue line work, blue text	
	L22	bore density, red layer, pms192 – registration point	
	L23	sand	
	L40	labels for geological structure map	
	L42*	hidden labels	
	L45	AMG grid for side diagrams	
	L46	panel borders	
	L40	sheet boundary trim marks	
	L53-59	logos	
	L60	format information	
Bremply.*dgn*	L1	Qa	1:50 000
	L2	Qs	1:50 000
	L3	TPp/TPw	1:50 000
	L4	TPp	1:50 000
	L5	TPw	1:50 000
	L6	Pb	1:50 000
	L7	PBk	1:50 000
	L9	Pn	1:50 000
	L10	Ag	1:50 000
	L11	An	1:50 000
	L12	Ago	1:50 000
	L13	Ano	1:50 000
	L14	PByo	1:50 000
	L15	PBy	1:50 000
	L16	Pno	1:50 000
	L17	inlets	
	L20	depth of water 0–5	1:50 000
	L21	depth of water 5–20	1:50 000
	L22	depth of water >20	1:50 000
	L24	salinity 0–3000	1:100 000
	L25	salinity 3000–7000	1:100 000
	L26	salinity 7000–14 000	1:100 000
	L27	salinity >14 000	1:100 000
	L30	geological structure Ag	1:50 000
	L31	geological structure Ps	1:50 000
	L32	geological structure Pn	1:50 000
	L33	geological structure Pb	1:50 000
	L34	landmass, evaporation	
	L35	Bremer Bay index sheet area	
	L36	rainfall at Bremer	
	L40	base for map	

* Note: information not shown on printed map

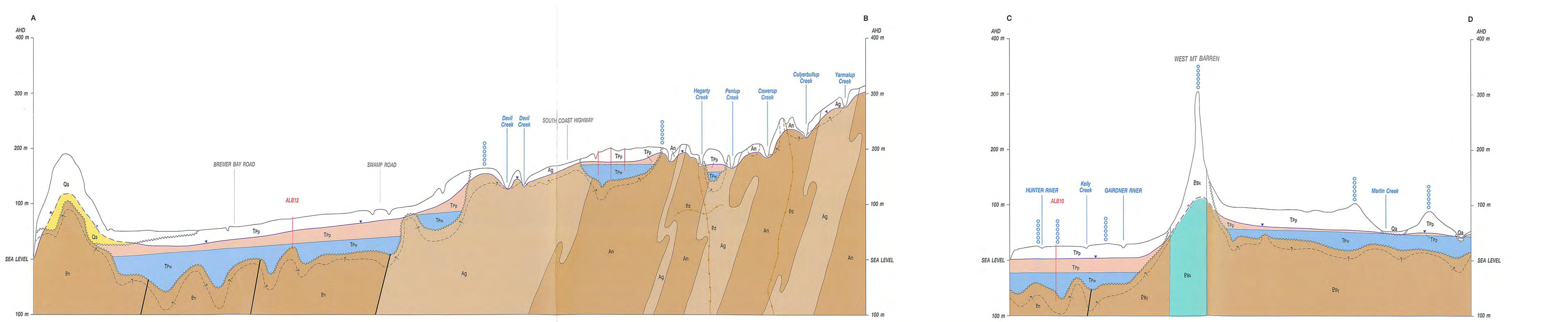
BREMER BAY

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA — WATER AND RIVERS COMMISSION



DIAGRAMMATIC SECTIONS

(Bores projected onto section line)
Vertical exaggeration x 50



REFERENCE

AQUIFER CHARACTERISTICS

- Surficial aquifer—local aquifers, probable sedimentary aquifer beneath, minor groundwater resources
- Surficial aquifer—local aquifers, probable sedimentary aquifer beneath, minor groundwater resources
- Sedimentary aquifer with intergranular porosity—extensive aquifers, significant groundwater resources
- Sedimentary aquicludes and local aquifers—minor or no groundwater resources
- Sedimentary aquifer, overlain by sedimentary aquiclude—probable extensive aquifer, groundwater resources
- Fissured aquifer, locally fractured and jointed—minor groundwater resources
- Fractured and weathered rocks—local aquifers, minor groundwater resources
- Fractured and weathered rocks—local aquifers, very minor or no groundwater resources

HYDROGEOLOGY

PHANEROZOIC – CAINOZOIC – QUATERNARY		Qa	Alluvium, minor colluvium—gravel, sand, silt, and clay	Minor local aquifers; fresh to brackish	
PHANEROZOIC – CAINOZOIC – QUATERNARY		Qs	Shallow marine, estuarine, lagoonal, and coastal eolian deposits—sand, clay, and limestone	Minor local aquifers; fresh to saline	
PHANEROZOIC – CAINOZOIC – TERTIARY	Plantagenet Group	Tpp	PALLINUP SILTSTONE—multicoloured (predominantly red and white) siltstone, spongolite, and minor sandstone	Minor local aquifers; fresh to saline	BREMER BASIN
PHANEROZOIC – CAINOZOIC – TERTIARY	Plantagenet Group	Tpw	WERILLUP FORMATION—bryozoan limestone, siltstone, sandstone, peat, shale, and basal conglomerate	Major aquifers; fresh to saline	BREMER BASIN
PROTEROZOIC		Ed	Dolerite dyke	Very minor local aquifers; brackish to saline	
PROTEROZOIC	Mount Barren Group	EBy	KYBULUP SCHIST—shale, sandstone, phyllite and schist; minor banded iron-formation; Cowerdup Sill altered dolerite: outcrop (indicated by overprint); subsurface weathered to clay	Minor local aquifers; brackish to saline	ALBANY–FRASER OROGEN
PROTEROZOIC	Mount Barren Group	EBk	KUNDIP QUARTZITE—quartz arenite and micaceous sandstone, minor deformed quartzitic breccia and conglomerate: outcrop (indicated by overprint)	Minor local aquifers; fresh to saline	ALBANY–FRASER OROGEN
PROTEROZOIC		En	Granitoid gneiss, augen gneiss, minor metaconglomerate: outcrop (indicated by overprint); subsurface weathered to clay	Aquiclude and very minor local aquifers; saline	ALBANY–FRASER OROGEN
ARCHAEAN		Ag	Granitoid rock, porphyritic and even-grained: outcrop (indicated by overprint); subsurface weathered to sandy clay	Minor local aquifers; fresh to saline	YILGARN CRATON
ARCHAEAN		An	Granitoid gneiss, foliated, minor migmatite, schist and amphibolite: outcrop (indicated by overprint); subsurface weathered to clay	Aquiclude and very minor local aquifers; saline	YILGARN CRATON

SYMBOLS

GEOLOGY

- hydrogeological boundary; position uncertain
- unconformity (section only)
- fault
- thrust fault
- extent of weathering (section only)

SURFACE WATER FEATURES

- drainage; permanent, intermittent; pool
- lake; permanent, intermittent; swamp
- surface water divide; position uncertain
- RH, WH: rockhole; waterhole
- (PD): position doubtful

GROUNDWATER FEATURES

- spring; seepage area
- 40: watertable contour (m AHD); position uncertain
- watertable; position uncertain (section only)
- direction of groundwater flow
- 3000: isohaline (mg/L TDS); position uncertain

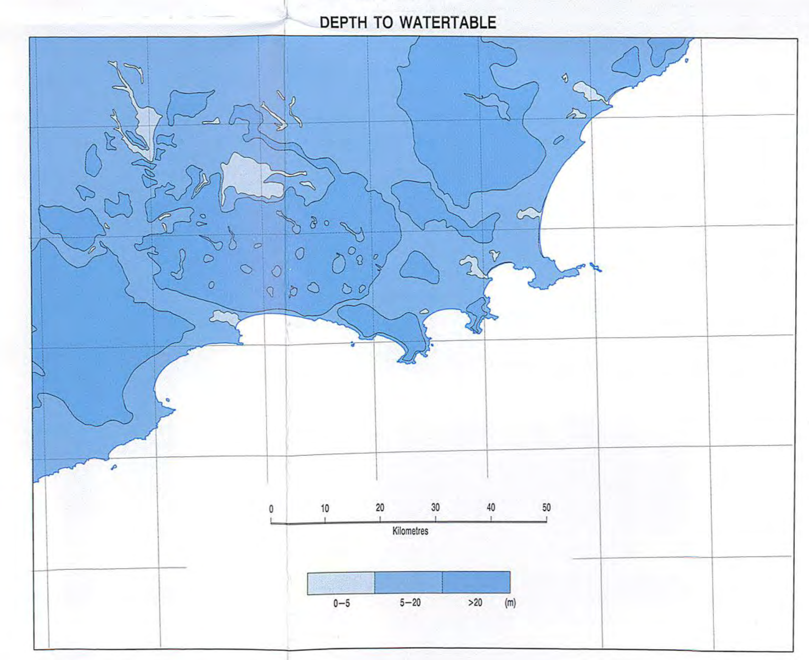
ARTIFICIAL FEATURES

- water bore: yield <50 m^3/day; ≥ 50 m^3/day; monitoring
- water bore abandoned: yield <50 m^3/day; ≥ 50 m^3/day; dry
- well; abandoned
- excavated soak for stock watering
- area with numerous bores, well field, town water supply
- boundary of groundwater control area
- landfill waste disposal site
- rising watertable, land salinization
- mineral exploration drillhole

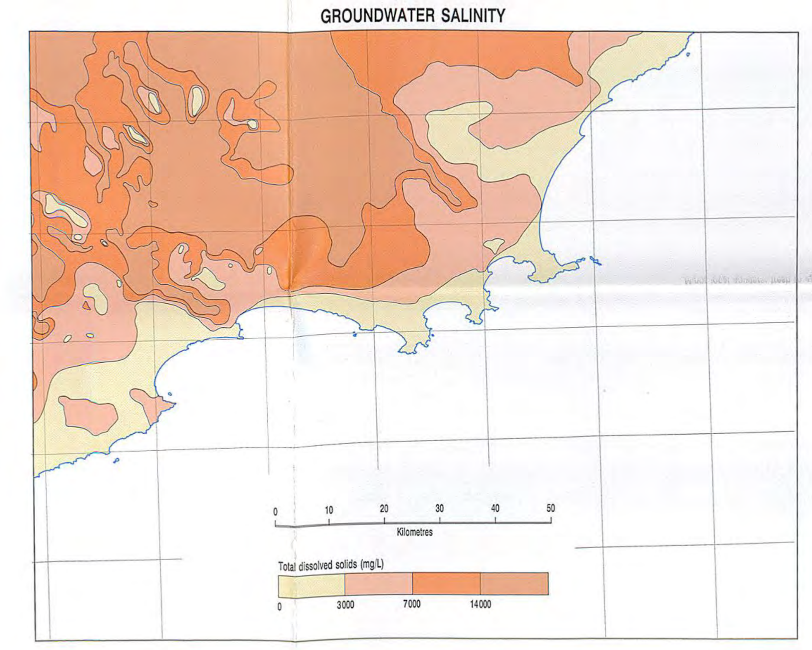
TOPOCADASTRAL INFORMATION

- highway with national route marker
- formed road
- track
- Bremer Bay: townsite, population less than 1 000
- Ramshead: locality
- rock; awash, submerged
- 100: topographic contour, 50 metre interval (AHD)
- sand dune
- horizontal control; major, minor (AHD)
- national park boundary
- 50: bathymetric contour (m)

DEPTH TO WATERTABLE



GROUNDWATER SALINITY



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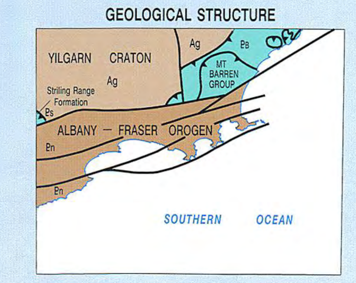

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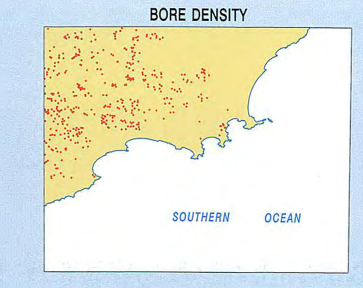
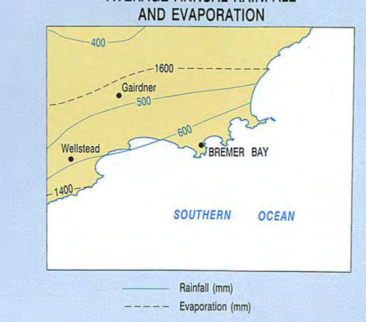
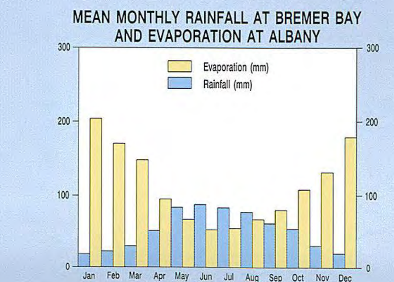


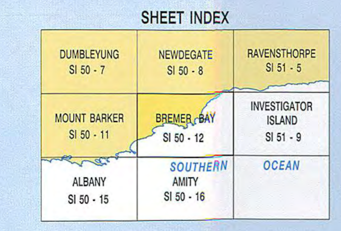
AVERAGE ANNUAL RAINFALL AND EVAPORATION



MEAN MONTHLY RAINFALL AT BREMER BAY AND EVAPORATION AT ALBANY



SHEET INDEX



Hydrogeology by W. Dodson, 1996
Geology by R.Thom and R.J. Chin, 1984
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Published jointly by the Geological Survey of Western Australia and the Water and Rivers Commission.
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SCALE 1:250 000

Metres 5000 0 5 10 15 20 25 30 Kilometres

TRANSVERSE MERCATOR PROJECTION

Grid lines indicate 20000 metre interval of the Australian Map Grid Zone 50

GOVERNMENT OF WESTERN AUSTRALIA
HON. PETER FOSS, Q.C., M.L.C.
MINISTER FOR THE ENVIRONMENT

WATER AND RIVERS COMMISSION
R. PAYNE, CHIEF EXECUTIVE OFFICER

DEPARTMENT OF MINERALS AND ENERGY
K.R. PERRY, DIRECTOR GENERAL

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
PIETRO GUJ, DIRECTOR

1:250 000 HYDROGEOLOGICAL SERIES

BREMER BAY

SHEET SI 50-12