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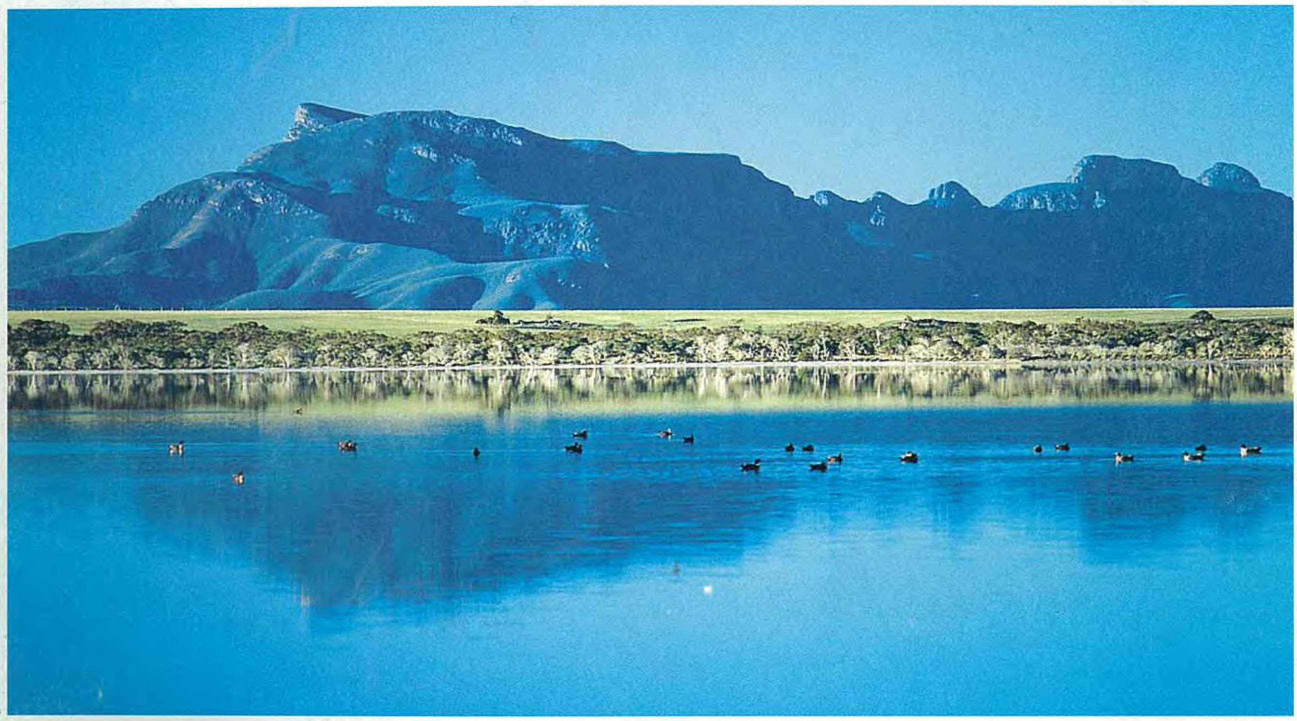
Hydrogeology of the Mount Barker–Albany 1:250 000 Sheet



Hydrogeological Map Explanatory Notes Series

Water and Rivers Commission Report HM 1

1997

Water and Rivers Commission

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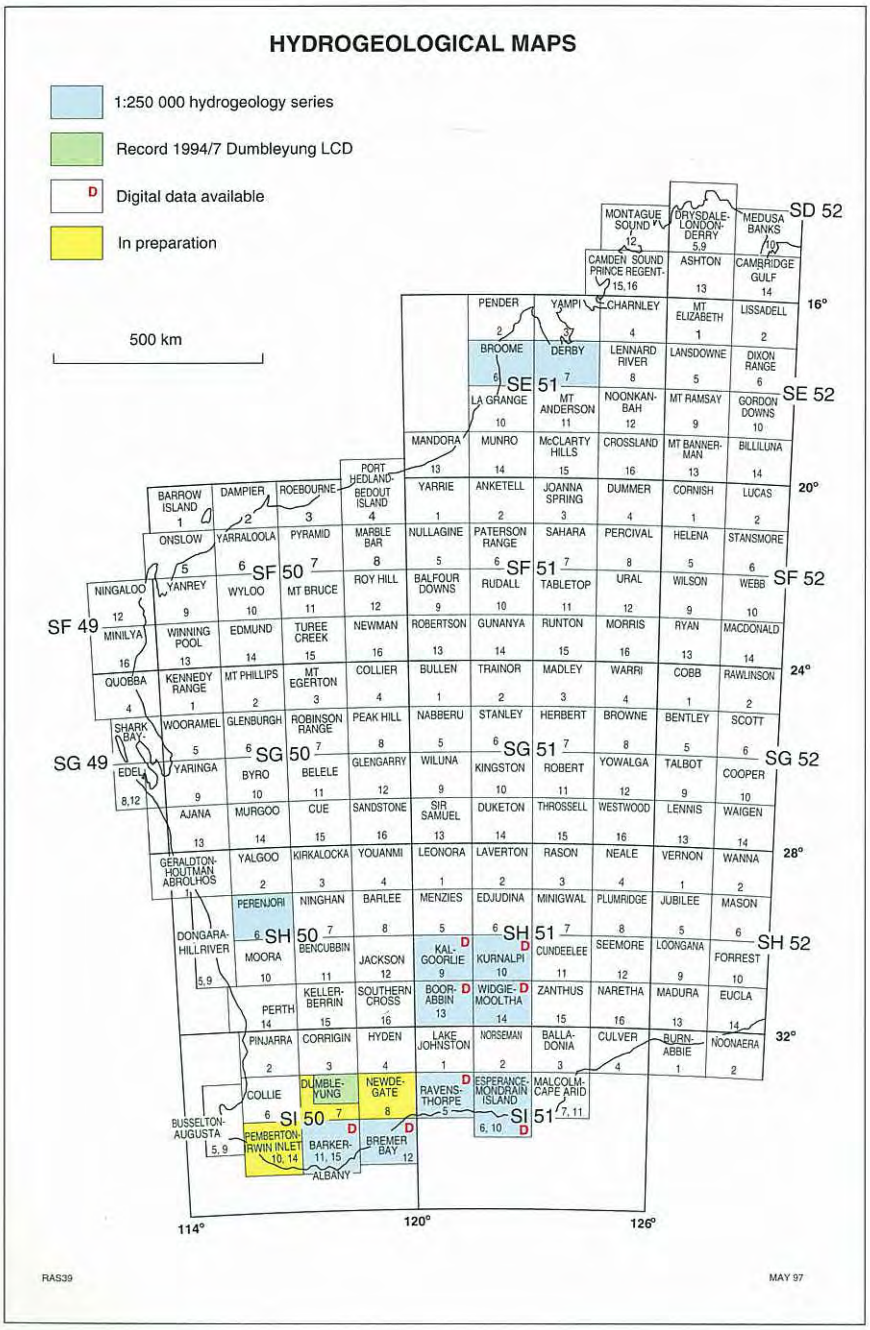

Cover Photograph: Bluff Knoll in the Stirling Ranges, centrepiece of MOUNT BARKER–ALBANY, viewed from the south.

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by

R. A. Smith

Water and Rivers Commission
Resource Investigation Division

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Hydrogeology of the Mount Barker–Albany 1:250 000 sheet

by

R. A. Smith

Abstract

The Mount Barker–Albany Hydrogeological Sheet covers parts of the Yilgarn–Southwest Groundwater Province, the Albany–Fraser Groundwater Province including most of the Stirling Range Formation, and the Bremer Basin. The area contains fractured, weathered, fissured, sedimentary, and unconsolidated aquifers.

The fresh groundwater resources in the area occur mainly in the surficial and sedimentary aquifers in the southeastern quarter of Mount Barker–Albany. Small, saline resources suitable for stock watering are site specific in the northern half of Mount Barker–Albany where most of the groundwater is saline to hypersaline.

Groundwater provides most of the water used for Albany, Kendenup, Mount Barker, and Narrikup, and is most intensively developed southwest of Albany between Princess Royal Harbour and Torbay.

Keywords: hydrogeological maps, hydrogeology, aquifers, groundwater resources, Albany, Mount Barker.

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Figure 1. Location map

1 Introduction

The MOUNT BARKER–ALBANY *Hydrogeological Sheet comprises the MOUNT BARKER sheet, SI 50-11, and part of the ALBANY sheet, SI 50–15, and is bounded by latitudes 34°00'S and 35°15'S and longitudes 117°00'E and 118°30'E. About 3% of MOUNT BARKER and 97% of ALBANY are occupied by the waters of the Southern Ocean (Fig. 1).

Most of the MOUNT BARKER–ALBANY area supports an assortment of rural land use encompassing agroforestry, crops, horticulture, stock, and viticulture. The Stirling Range National Park, Porongurup Range, coastal reserves, wildlife sanctuaries and State Forest form a significant but very small proportion of the area. Good road access is provided by the Albany Highway, Great Southern Highway, South Coast Highway, Muirs Highway, Chester Pass Road, Denmark–Mount Barker Road and a network of other sealed and gravel roads, fire control and four-wheel drive tracks.

The main town and port is Albany with a population of about 25 000, including suburbs which spread northeastward to Oyster Harbour and satellite suburbs located south towards Frenchman Bay. Rural towns in the area include Borden, Cranbrook, Denmark, Frankland, Kalgan, Kendenup, King River, Mount Barker, Rocky Gully, South Stirling, and Tambellup. Smaller settlements scattered throughout the area include Elleker, Karribank, Marbellup, Narrikup, Porongurup, Redmond, Stirling Range and Tenterden. Land use is primarily pasture and timber, with minor horticulture and viticulture. Industry in the region includes timber, agroforestry, dairy farming, crop and animal farming, horticulture, viticulture, shipping, fishing, mineral exploration, tourism and recreation, eco-tourism, and outdoor education. Mineral exploration activities have targeted coal, oil shale, oil, mineral sands, silica sands, and gold.

1.1 Climate

Most of the area has a Mediterranean-type climate with cool, wet winters and warm to hot, dry summers. However the coastal areas, and as far north as Mount Barker, also receive significant summer rainfall. Rainfall decreases sharply from the southwest to the northeast across MOUNT BARKER–ALBANY; the average annual rainfall is 1108 mm at Denmark, 813 mm at Albany, 744 mm at Mount Barker, and 385 mm at Borden. Rainfall reliability decreases in a similar pattern.

Most of the rain comes from fronts associated with low-pressure systems passing over, or to the south of the area. At Albany Airport, 8 km northwest of Albany, the pan evaporation rate is about 1200 mm per annum, and is less than rainfall in 4 to 5 months of the year. Average monthly minimum and maximum temperatures range between 14 and 26°C in summer and 7 and 16°C in winter.

1.2 Physiography

The generally well worn planar landscape of MOUNT BARKER–ALBANY is punctuated by the jagged peaks of the Stirling Range (Figs 1 and 2) with Bluff Knoll (1073 m), some 70 km east of Cranbrook, the highest point in the southern half of the state (Beard, 1981). Other peaks in the range are from 637 m (Donnelly Peak) to 1052 m (Toolbrunup) in elevation. To the west of the range the hills are more rounded, and range from 373 m (Sukey Hills) to 400 m (Geekabee Hill) in elevation.

The plains, south and southeast from the Stirling Range, contain numerous ranges and hills of exposed bedrock that tend to be lower near the coast. The better known of these are Porongurup and Green Range, and Mounts Melville, Clarence and Manypeaks.

The major rivers on MOUNT BARKER–ALBANY are seasonal and contained within four recognised surface basins (Australian Water Resources Council, 1982):

Basin 602	Albany Coast (includes Kalgan River, Pallinup River, other small rivers)
Basin 603	Denmark River (includes Hay River, other small rivers)
Basin 604	Kent River (includes other small rivers)
Basin 605	Frankland River (includes Gordon River, other small rivers)

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

Figure 2. Topography

The northern and northwestern third of Mount Barker–Albany is drained by the easterly flowing Pallinup River and westerly flowing Gordon, Frankland and upper Kent Rivers, apart from an area of internal drainage north of the Stirling Range that is characterised by saline lakes (Fig. 2). Short south-flowing rivers, such as the Kalgan, Hay and Denmark Rivers, drain the plains of the Albany coast. The southeast is poorly drained and dotted with numerous lakes and swamps. Coastal dunes up to 200 m high extend several kilometres inland and, with bedrock highs, outline coastal swamps and inlets.

The Pallinup, Frankland, Gordon and Kalgan Rivers are generally saline (>3000 mg/L), although the Kalgan is brackish (1500–3000 mg/L) near the coast. The Kent, Denmark and Hay Rivers are also brackish or marginal (500–1000 mg/L), although the Hay may be fresh toward the coast (<500 mg/L). The very short coastal rivers are generally fresh. Straddling the watershed between the Frankland and Kent Rivers is an area of generally saline lakes within a veneer of Quaternary sediments overlying Tertiary sediments. These Tertiary sediments have been described as a westward-trending palaeodrainage (Street, G. S., 1995, pers. comm.). With recent changes in the position of the divide between the Frankland and Kent Rivers, as a result of some uplift and then stream capture, salt stored in these sediments has been remobilised into the headwaters of these river systems. Clearing in the upper Kent River catchment has exacerbated salinization in the Kent River catchment.

1.3 Vegetation

The vegetation associations of the area are described by Beard (1981), although more than 95% of the area has been cleared for rural landuse. The western half of Mount Barker–Albany is within the Southern Jarrah Forest, which grades to Karri Forest in the higher rainfall, southwest corner, and to woodland of wandoo and yate northeast of Cranbrook and southwest of Tambellup. The remaining eastern part of the area is predominantly mallee (eucalypt shrubs), which is associated with heath in the south and with woodland in valleys in the north.

1.4 Previous investigations

The area was geologically mapped by Muhling and Brakel (1985), while Doepel (1975) summarised the early geological notes and publications on the area, including those by Darwin (1876). Forty-eight publications on aspects of groundwater within the Mount Barker–Albany area are indexed in bibliographies by Smith (1992, 1993).

Clarke and Tarton-Phillips (1953) provided a general account of the area, including some remarks on coastal geology and springs, and water supplies, while Berliat (1954) described the prospects for usable supplies of groundwater in large land-grant areas near the Stirling Range, Manypeaks, and Frankland as mostly unfavourable. Probert (1967c) reported that the area around Kendenup had mainly saline and stock-quality water although near the Kalgan River a few shallow, small domestic supplies were obtained from sand lenses or from weathered bedrock. Sanders (1968, 1969a,b) suggested that, southeast of Cranbrook, the quartzite of the Stirling Range and the Tertiary sediments to the south of the range, were potential aquifers. Subsequent drilling in the sediments provided a stock-watering bore, whereas two other bores were saline. Bestow (1969) sited several successful bores in the Kybelup Plain, 25 to 40 km east of Tambellup, and noted freshwater seepages about a kilometre from the Pallinup River. Many other unpublished reports of the Geological Survey of Western Australia (GSWA) describe groundwater prospects based on localised inspections in Mount Barker–Albany.

An extensive drought-relief drilling program was undertaken in the Ongerup, South Stirling, North Stirling, and Chillinup districts from 1969 to 1971 (Lord 1970, 1971). The success of the program in providing bores with water of less than 11 000 mg/L total dissolved solids (TDS) and with yields of more than 4.5 cubic metres per day (m^3/d) is reported by Davidson (1977).

A groundwater supply for Albany was proposed initially by Low (1957) and his work led to the establishment of the present borefield. More detailed assessments of the hydrogeology of the Albany area for town water supply, using geophysics, began with Rowston (1965) and Probert (1965), with drilling reported by Probert (1966, 1967a,b). Subsequently, Forth (1973a,b) made the earliest estimates of groundwater resources and the safe yields for borefields supplying Albany. Geophysical investigation continued (Rowston, 1976) and Hirschberg (1976) gave an account of the geology and hydrology of the Albany to Mount Barker area. The most recent geophysical investigation (Nowak, 1978) located groundwater prospects that were not drilled until 1994 (Smith, 1994). The performance of the borefield was subsequently reviewed by Australian Groundwater Consultants (1987), and later by Katsavounidis (1990).

Leech and Moncrieff (1976) selected sites for water bores near the Stirling Range, and Moncrieff (1977) outlined the geology and groundwater prospects, based on field notes for the Mount Barker–Albany Geological Map (Muhling *et al.*, 1978) and Explanatory Notes (Muhling and Brakel, 1985).

An overview of groundwater occurrence in the Bremer Basin was prepared by Allen (1991). Subsequent proposals by Moncrieff (1992) for further groundwater assessment were followed by drilling (Smith, 1994), geophysical surveys (Perry, 1994), and additional drilling in 1995 (Johnson, 1995).

Since surface-water salinity problems were detected at Cranbrook and other locations by Bleazby (1917), salinization has been widely reported, particularly by Agriculture Western Australia (McFarlane, 1991), and has been a rapidly expanding facet of groundwater investigation. Salinization of Lake Poorrarecup was assessed by Bestow (1979), and other published reports on salinity issues are listed by Smith (1993).

More recently, work on rising groundwater levels and salinity has focused on the Kent River catchment (Public Works Department, 1980; Geoterrex Pty Ltd, 1985; P and V Geophysical Services, 1985; Colman and Miers, 1986), the upper Denmark River catchment (Stokes and Ruprecht, 1986; Kern, 1990; Ferdowsian and Greenham, 1991, 1992; Ferdowsian, 1992), the North Stirling area (Appleyard,1994; Laws, 1986; Lewis 1992), and the Oyster Harbour catchment (Nixon, 1994).

In 1994 and 1995 significant additional exploratory drilling results in the Bremer Basin became available as a result of the GSWA Groundwater Exploration Initiative (Smith, 1994; Johnson, 1995). In this two-stage program, 12 bores with an aggregate depth of 989 m were drilled to the pre-Tertiary bedrock, and 23 bores drilled on the Kybelup Plain, 20 km west of Borden, to investigate low-salinity groundwater in a shallow Tertiary aquifer (Dodson, 1995).

Additional bore data were obtained from shallow drilling by Agriculture Western Australia, minor salinity investigations by the Geological Survey of Western Australia, and reports by mineral exploration companies, including two oil exploration wells in the Bremer Basin. These are Kendenup No.1 (Berven, 1974a) and Sunday Swamp No.1 (Berven, 1974b).

Mineral exploration (for coal, oil shale, mineral and silica sands) has included some drilling, although much of the drilling on road reserves has not been formally reported. Drilling for coal was undertaken north of the Stirling Range (Westblade, 1982) and reconnaissance for Permian and Triassic coal basins north of Frankland.

Reworked alluvial silica sands in a fluvial channel cut through granite, 9 km west of Narrikup, were investigated by Westralian Sands Limited (1984).

Exploration drilling for heavy mineral sands overlying Tertiary sediments and bedrock was carried out at Hassell Beach, in the southeast of MOUNT BARKER–ALBANY (Appleby, 1989, Eucla Mining NL, 1990), along drainages at Parry Inlet (Dendle, 1988), and south of the Stirling Range (McGoldrick, 1991a,b).

1.5 Data compilation

Data from more than 2300 bores and wells were used in the preparation of MOUNT BARKER–ALBANY. More than half of these, including the Albany town water supply bores, are located in the central third of the southern half of the sheet area. Drill logs from the drought-relief drilling program (Davidson, 1977) and from drilling for town water supply were reinterpreted and hydrogeological boundaries drawn in conjunction with the geological compilations of Muhling *et al.* (1978). All water-bore data are now entered in the extensive AQWABase held by the Water and Rivers Commission.

Layers of information used to compile MOUNT BARKER–ALBANY are available in digital form. These data were digitized at various scales and some data, simplified for presentation at 1:250 000 scale, are available at several scales. The digital data can be interrogated down to 1:25 000 scale for catchment management purposes.

The depth to the watertable is largely dependent on topography. The gridded side panel on MOUNT BARKER–ALBANY indicates the maximum depth at which water is likely to be obtained for a supply. It does not indicate the minimum depth of the watertable for predicting areas of potential waterlogging. The depth to water is greater in areas with lower rainfall (to the east) in the MOUNT BARKER–ALBANY area.

2 Geology

2.1 Regional setting

The northern third of MOUNT BARKER–ALBANY is underlain by mainly orthogneiss of the Yilgarn Craton (Myers, 1990a), together with deformed metamorphosed sandstone and shale of the bordering Stirling Range Formation in the south (Fig. 3). The bedrock of the southern half of MOUNT BARKER–ALBANY comprises gneiss, metamorphic rock and granitoid in the Biranup and Nornalup Complexes of the Albany–Fraser Orogen (Myers, 1990b). Sediments of the Bremer Basin (Hocking, 1990) form a discontinuous veneer over much of both the Yilgarn Craton and Albany–Fraser Orogen (Clarke, 1993, 1994). These flat-lying sediments are thickest in the southeast, reaching 138 m (Table 1) in ALB 1B (Smith, 1994). Quaternary sediments have formed in an erosive rather than depositional landscape and most, in drainage lines and near the coast, are less than 10 m thick. The thickest Quaternary deposits are calcarenite dunes which are up to 71 m thick in the borefields southwest of Albany. The dunes extend to elevations of more than 200 m above sea level and so are presumed thicker than 71 m in some locations. The rock types of the sheet area are described in detail by Muhling and Brakel (1985).

The rocks of the Yilgarn Craton are Archaean in age and are intruded by undeformed dolerite dykes of the Gnowangerup dyke swarm (Myers, 1990b). The Stirling Range Formation is Middle Proterozoic (Muhling and Brakel, 1985) or possibly Late Proterozoic (Cruse *et al.*, 1993) in age. Most Proterozoic rocks were deformed during the Albany–Fraser Orogeny. The Bremer Basin sedimentary rocks are Tertiary (Eocene) in age and have been weathered or lateritized. Quaternary sediments have formed by reworking of crystalline rocks and Tertiary sediments.

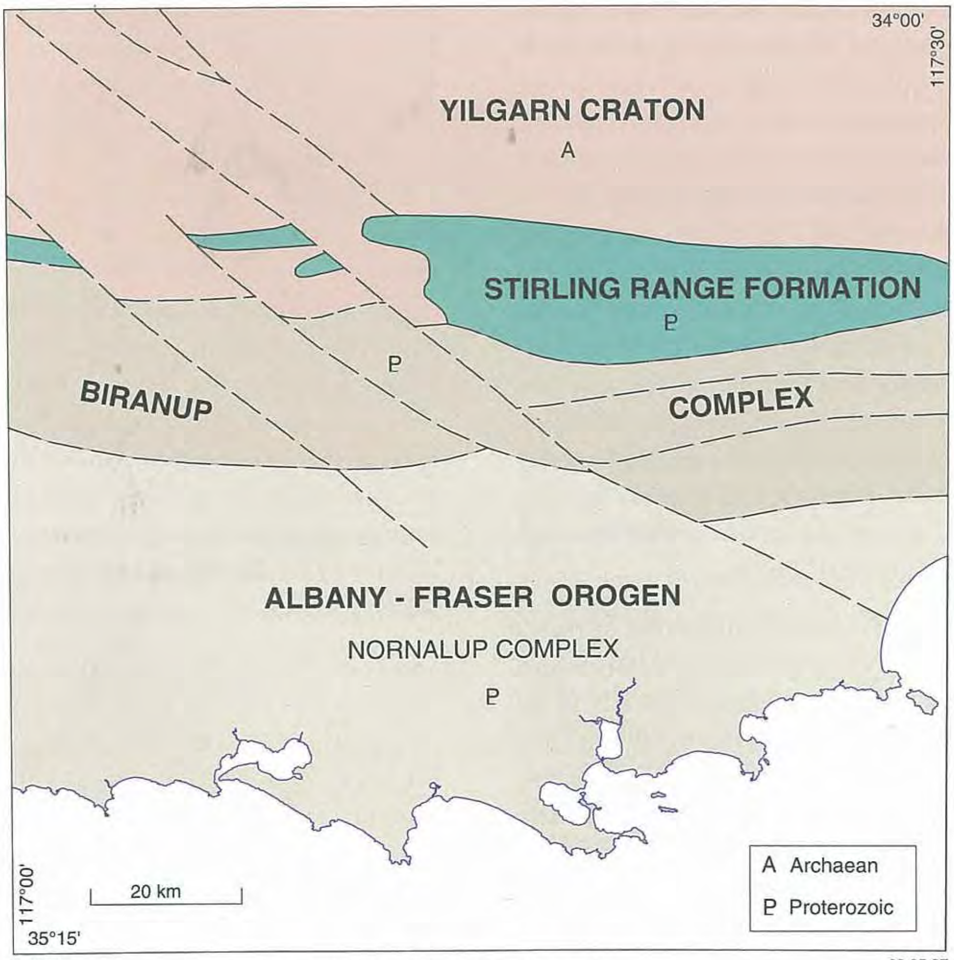

Figure 3. Structural setting

Table 1. Stratigraphy and aquifer potential

Age	*Code*	*Stratigraphic unit*	*Maximum thickness intersected (m)*	*Lithology*	*Aquifer potential*
Quaternary	*Qa, Cza*	surficial sediments	10 inland 71 coastal	Sand, limestone, silt, clay, minor gravel	Both minor
			~~ *Unconformity* ~~~		
	Tp	Plantagenet Group			
Tertiary–	*Tpp*	Pallinup Siltstone	87	Siltstone spongolite, minor sandstone	Minor
Eocene	*Tpwn*	Nanarup Limestone	27	Limestone	Minor
	Tpw	Werillup Formation	51	Siltstone, sandstone, peat, conglomerate	Major
			~~ *Unconformity* ~~~		
	Ꝑd	dykes	–	Dolerite	Very minor
	q	veins	–	Quartz	Minor
			~~ *Unconformity* ~~~		
Proterozoic	*Ꝑs*	Stirling Range Formation	41	Sandstone, quartzite, shale	Minor
			~~ *Unconformity* ~~~		
		Albany–Fraser Orogen	–		
	Ꝑn	Biranup Complex		Gneiss, metamorphic, quartzite, clay	Very minor
	Ꝑg	Nornalup Complex	–	Granitoid, clayey sand	Minor
Archaean	*Ag*	Yilgarn Craton	–	Granitoid, clayey sand	Minor
	An		–	Gneiss, migmatite, quartzite, schist, clay	Very minor

2.2 Structure

Interpretation of the structure is based on Muhling and Brakel (1985), who used Bouguer gravity anomaly and total-magnetic-intensity maps published by the Commonwealth Bureau of Mineral Resources (now the Australian Geological Survey Organisation), and on more recent commercial geophysical surveys (Fig. 3). The Yilgarn Craton contains several major southeasterly trending faults, paralleling the trend of this region. The rocks of the Albany–Fraser Orogen have an easterly trend, parallel to the Manjimup Fault which defines the northern boundary of the province, and are cut by a number of easterly trending faults. These are more evident in the northern Biranup Complex, which may contain reworked rocks from the Yilgarn Craton, than in the less deformed southern Nornalup Complex (Myers, 1990b).

The Stirling Range Formation, overlying or thrust against the Archaean Yilgarn Craton, is mildly folded and thrusted. The rocks strike mainly easterly in the Stirling Range with dips of 12° south (Muhling and Brakel, 1985). At the western end, folding and thrusting have been severe and the rocks are systematically jointed. West of the Stirling Range the formation is exposed in down-faulted blocks. The youthful appearance of the Stirling Range has prompted a suggestion of Cainozoic uplift (Myers, 1990b).

The flat-lying Tertiary sediments of the onshore Bremer Basin do not appear to be faulted. They are a fringing veneer to the offshore succession of the Bremer Basin. They are mildly diachronous and were deposited over an irregular surface of precambrian rocks, shaped by Late Palaeozoic continental glaciation and major Triassic–Cretaceous erosion of the craton. Pronounced northward and westward flowing drainages, which remain the dominant feature of the landscape across the southern Yilgarn Province, Bremer Basin, and Albany-Fraser Province (Hocking and Cockbain, 1990), were interrupted during sagging associated with the breakup between Australia and Antarctica in the Late Neocomian (Hocking, 1990). These major drainages were active in the Jurassic–Cretaceous, but had ceased activity by the Eocene and are now virtually entirely palaeo-features.

Late in the Tertiary, the present day southward drainage was activated with the post- breakup rebound of the margin, which lifted the Tertiary sediments to a present height of 300 m AHD (Hocking, 1990). This relatively short drainage pattern was rejuvenated by southward tilting (possibly in the Oligocene) which formed the Ravensthorpe Ramp (Cope, 1975).

3 Hydrogeology

Four hydrogeological divisions containing twelve hydrogeological units, including one with major groundwater potential and eight with minor groundwater potential, are recognised on MOUNT BARKER–ALBANY (Table 1). Overlying unsaturated units, usually Tertiary or Quaternary sediments, are not shown on the map. The aquifers contain unconfined and some confined groundwater resources and tend to drain southeasterly toward the coast. Groundwater movement is extremely slow and is controlled by topography with most groundwater discharging into dissecting drainages from local shallow flow systems.

The hydrogeology is described commencing with the younger stratigraphic units, which are the most significant.

3.1 Surficial sediments (*Qa* and *Cza*)

Surficial sediments containing groundwater are shown on MOUNT BARKER–ALBANY as Quaternary (*Qa*) and Cainozoic (*Cza*), including other units described by Muhling *et al.* (1978), and consist mainly of limestone (equivalent to the Tamala Limestone), sand, silt, and clay, with a small proportion of gravel and gypsum. They have mostly been derived from Tertiary sediments from which they are not readily distinguished, and occur along drainage lines, in inland depressions, and near the coast. Sea level changes in the Quaternary have resulted in coastal sands up to 15 m thick along substantial stretches of fossil coastline inland from the present coast (Appleby, 1989). They lie unconformably on all other units, though mainly on Tertiary sediments.

The coastal sediments are significant aquifers as they are thicker than sediments elsewhere and include limestone and sand. Lacustrine or alluvial silt, gypsum, and gravel in the inland depressions and drainages form an aquifer northwest of Cranbrook and between Kendenup, Frankland and Rocky Gully. Gravel forms an alluvial aquifer on drainages near Chester Pass within the Stirling Range, and on the lower Hay River.

The surficial sediments are generally less than 10 m thick within the inland depressions, thin or absent in the modern (erosive) drainages, but substantially thicker in coastal dunes. The maximum recorded thickness near the coast is 71 m at Albany Sandpatch No. 10; the lower 13 m were saturated and overlie 35 m of Tertiary sediments.

The surficial sediments are recharged by rainfall, river flow and occasional flooding, and from upward groundwater leakage from underlying aquifers. Groundwater flow is generally localised, discharging into surface water drainages or lakes, or at the coast, possibly over a saltwater interface. Artificial drains have been installed to discharge groundwater from low-lying agricultural areas behind some of the coastal dunes.

Groundwater salinity ranges from about 100 to about 100 000 mg/L and in most of the sheet areas is generally too high for stock use. Potable groundwater (<1500 mg/L) is present at Chester Pass and near the coast.

The aquifers with potential for exploitation are in coastal areas where the surficial sediments are generally sandier and bore yields of more than 10 m^3/d are possible; however, these sediments have very small saturated thicknesses. The best aquifers in coastal areas are formed where the underlying bedrock constrains groundwater flow and prevents discharge directly to the sea, e.g. southwest of Albany and northwest of Mount Gardner. The inland sediments are more clayey and have little potential for exploitation; bore yields are generally very small (<10 m^3/d).

3.2 Plantagenet Group (*Tp*, *Tpp* and *Tpw*)

3.2.1 Lithologies

The Eocene Plantagenet Group (*Tp*) comprises the Werillup Formation (*Tpw*) and the overlying Pallinup Siltstone (*Tpp*). The Werillup Formation consists of a discontinuous basal gravel, coarse sands, lignite ('black shale'), and clay, and locally near the top includes the Nanarup Limestone Member (*Tpwn*). The Pallinup Siltstone comprises very fine sandstone, multicoloured siltstone and clay, and minor lignite layers near the base. The Plantagenet Group occurs throughout south and southeast of MOUNT BARKER–ALBANY, covering about one third of the sheet area, and is most extensive in the

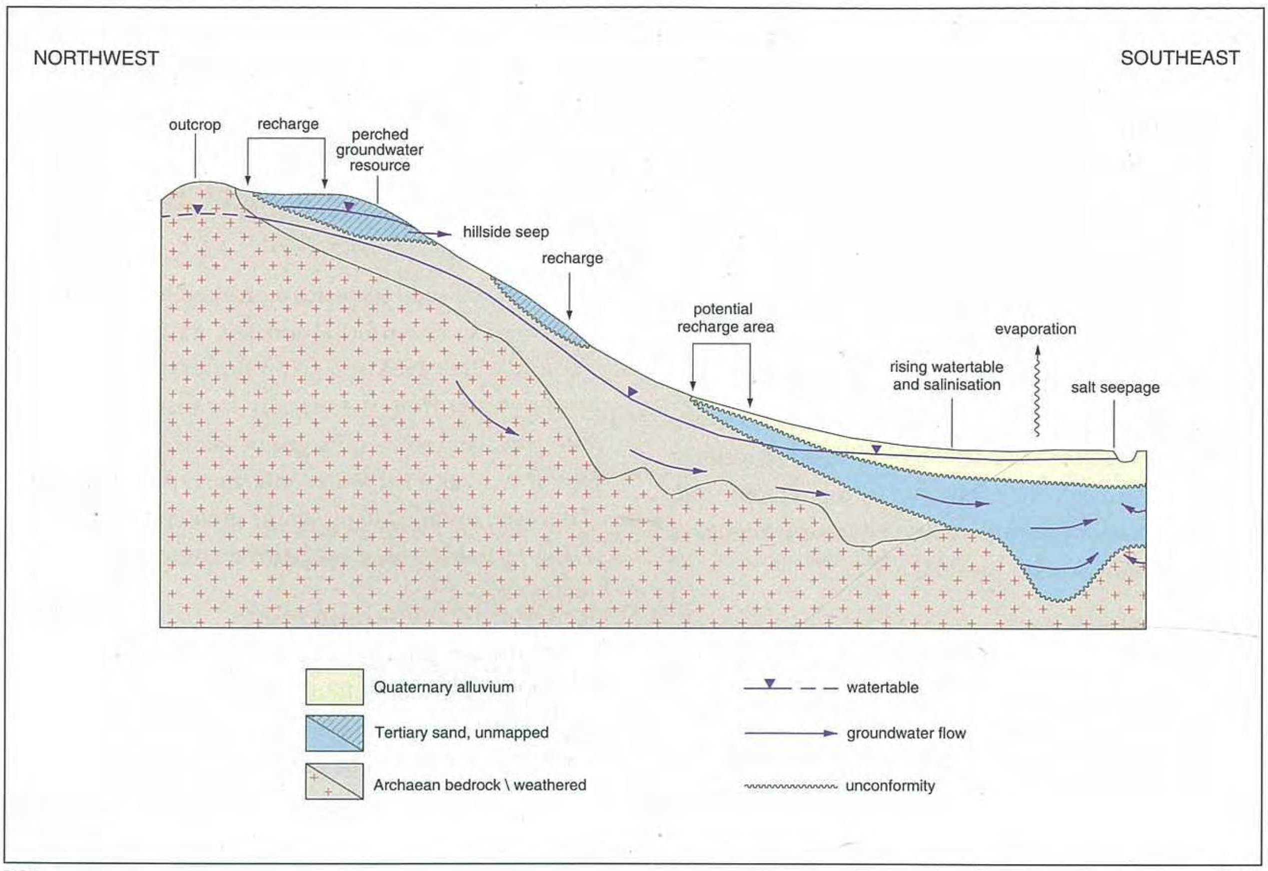

Figure 4. Diagrammatic section to show groundwater occurrence and flow northwest of Mount Barker

southeast (where it defines the onshore extent of the Bremer Basin). Large boulders occur north and south of the Stirling Range where the base of the Werillup Formation appears to be exposed. Down-cutting streams have left isolated remnants of Tertiary sediments in place, especially in the north and west, at elevations up to 270 m AHD. Elsewhere they are preserved in broad depressions, such as north of the Stirling Range, and as almost complete veneers in the southeast third of MOUNT BARKER–ALBANY. The elevation of these sediments falls below sea level near the coast.

The Werillup Formation is mainly a fluvial, non-marine to marginal marine infill of palaeochannels and pre-Tertiary drainage depressions, which bear little resemblance to the modern south-flowing rivers. The unit subcrops in a wide range of modern topographic positions (Fig. 4). The Pallinup Siltstone is marine and outcrops extensively in the southeast half of MOUNT BARKER–ALBANY. Usually the Plantagenet Group sediments are lateritized at the surface. The Nanarup Limestone Member, which formed in the Middle Eocene (McGowran, 1989) as an irregular fringing bryozoan limestone around bedrock islands, is revealed in small outcrops, particularly near Nanarup.

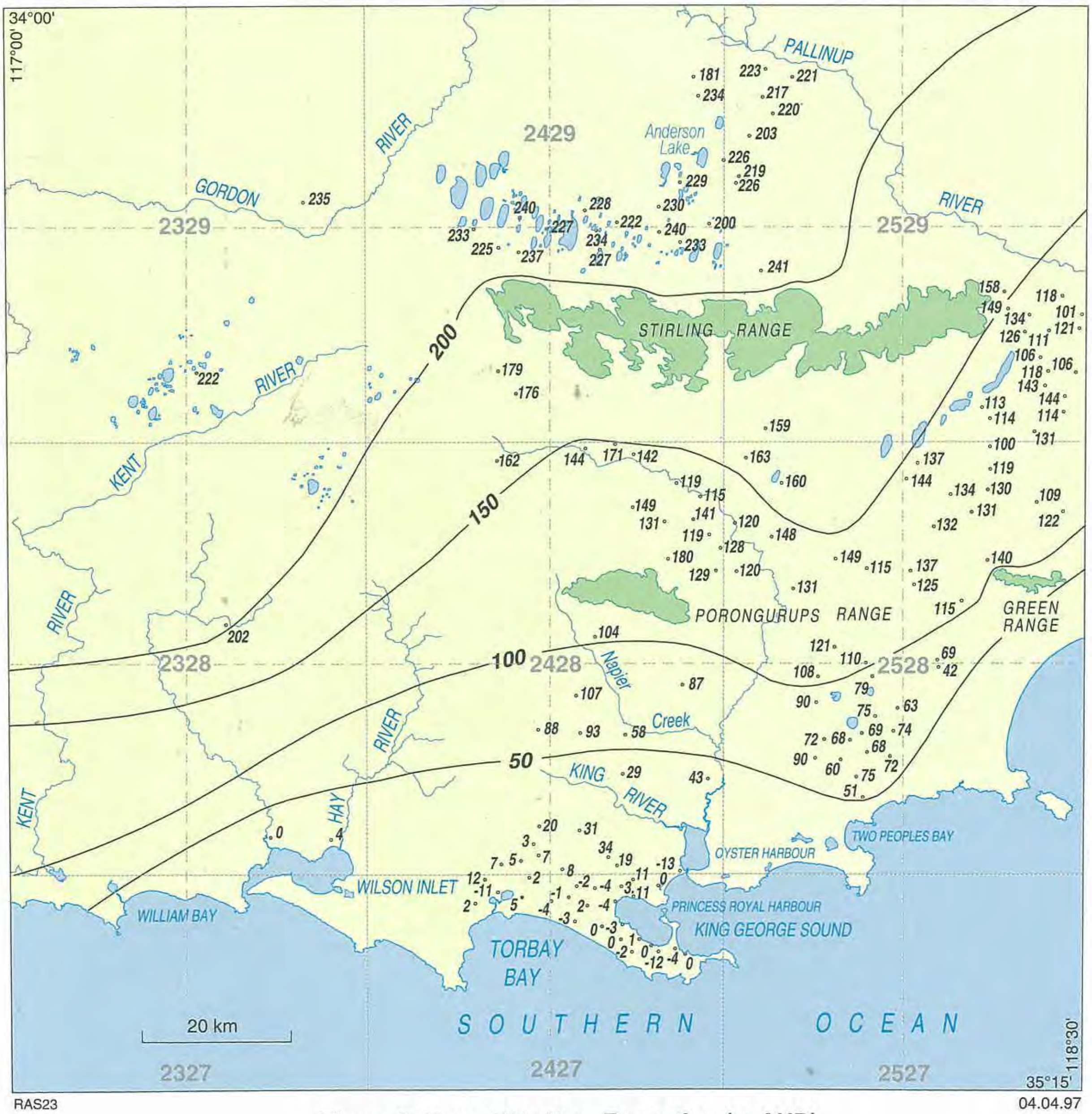

Figure 5. Top of Werillup Formation (m AHD)

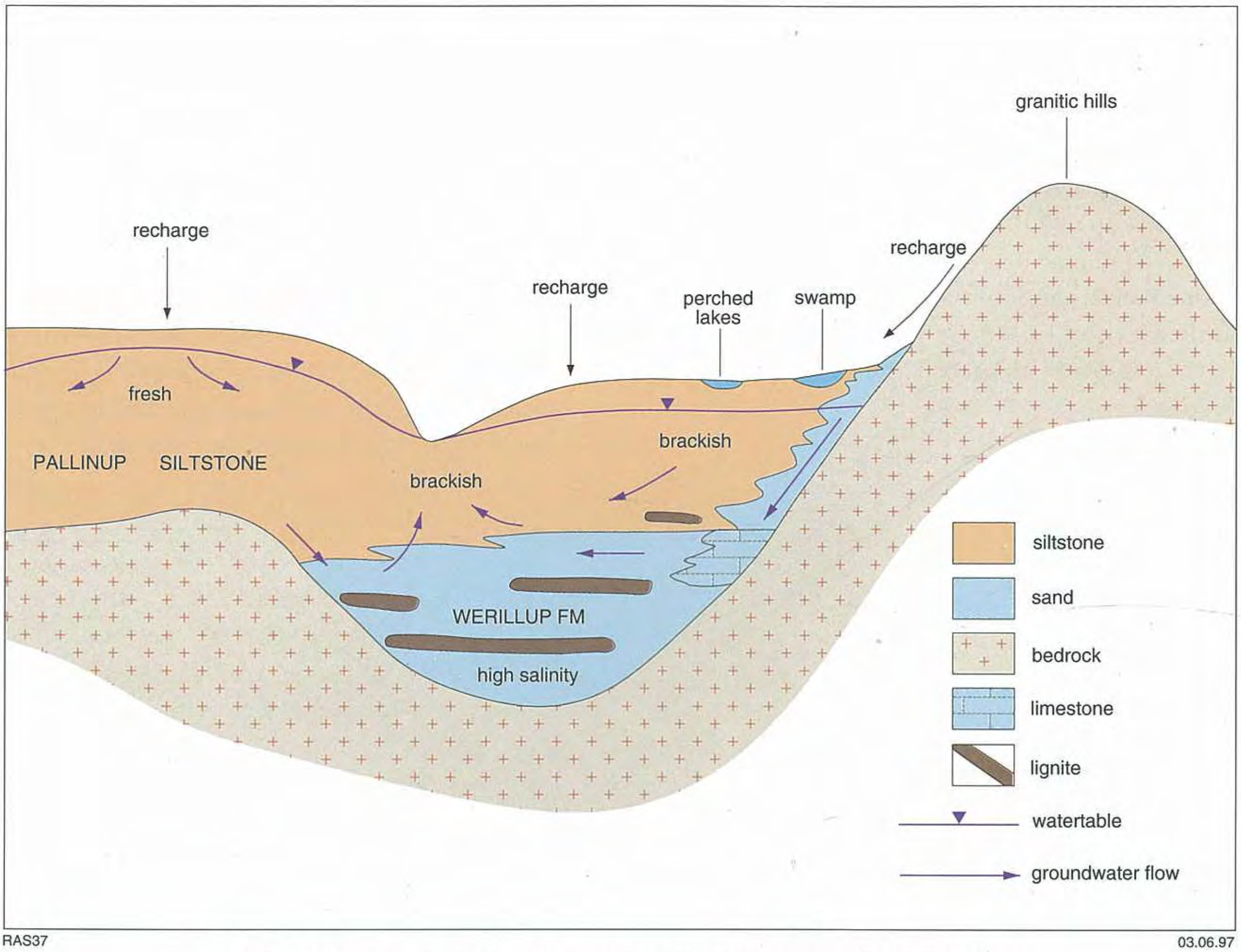

Figure 6. Diagrammatic section to show groundwater flow in the Plantagenet Group

3.2.2 Thicknesses

The maximum drilled thicknesses of the Werillup Formation and Pallinup Siltstone are about 87 and 51 m respectively in ALB 1B (Smith, 1994) near Sunday Swamp No.1 (Table 1), but similar thicknesses occur in the area west from Sunday Swamp to the Albany Aerodrome, townsite, and borefields (Fig. 1). The Werillup Formation type section, in Werillup No. 3 bore, is 40 m thick (Playford *et al.*, 1975). Twenty-seven metres of interbedded limestone and siltstone of the Nanarup Limestone Member was intersected in ALB 2B (Smith, 1994), of which the upper 4.5 m was the type section described by Cockbain (1968). The additional 22.5 m of this member below the type section, which is at the gradation from Werillup Formation to Pallinup Siltstone, indicates that the Nanarup Limestone Member largely preceded the deposition of the Pallinup Siltstone. The contact between the Werillup Formation and the Pallinup Siltstone is diachronous (becoming progressively younger inland) and falls south and east in steps between bedrock depressions to be at, or just below, sea level near the coast (Fig. 5). Here the Pallinup Siltstone has been extensively eroded and the coastal limestone rests on Werillup Formation (Section A-B of MOUNT BARKER–ALBANY). Thus both units are unconformably overlain by surficial sediments and, because the Pallinup Siltstone onlaps the Werillup Formation and the bedrock is uneven, both rest unconformably on bedrock.

3.2.3 Groundwater

The Tertiary sediments on MOUNT BARKER–ALBANY are shown as Werillup Formation because this is the main aquifer, although it is extensively overlain by Pallinup Siltstone. The Pallinup Siltstone also has a wider distribution, overlying Precambrian bedrock in places. The Pallinup Siltstone and Werillup Formation are recharged by rainfall, leakage from overlying Quaternary sediments and leakage from bedrock. Recharge to the Werillup Formation may be enhanced where there are coarser sediments flanking hills of granite bedrock. Groundwater movement is generally to the east or southeast, but flow may be constrained by irregular bedrock topography, incised drainages, and lateral differences in hydraulic conductivity. Some groundwater discharges to salt lakes.

3.2.4 Salinities and bore yields

Near the coast both units contain fresh to saline water, but farther inland groundwater is generally stock quality (generally less than 8000 mg/L, but in places up to 11 000 mg/L) to hypersaline water (up to about 100 000 mg/L). Both units have potential to provide additional small to moderate supplies of fresh to stock-quality water near the coast and in the southeast of MOUNT BARKER–ALBANY.

Very fine sand layers of the Pallinup Siltstone provide small, fresh to stock-quality farm water supplies of at least 4.5 m^3/d at less than 11 000 mg/L (Davidson, 1977). The Pallinup Siltstone is finer grained than the Werillup Formation and bore yields are very much lower. Coarse sand of the Werillup Formation is a more attractive target for groundwater exploration, but because the aquifer is generally thin, discontinuous, or contains interbedded clay, bore yields of more than 30 m^3/d, with a salinity less than 1500 mg/L TDS, are rare and have mainly been obtained southwest of Albany. Within the Albany South Coast Scheme borefields, yields from production bores in these aquifers range from about 400 to 1600 m^3/d. In contrast, investigation bore ALB 5 north of Albany was airlifted at 54 m^3/d (Smith, 1994).

The groundwater salinity increases sharply with depth in the Werillup Formation. The more saline water at the base of the formation may be the result of a combination of density flow, greater horizontal than vertical hydraulic conductivity, and lack of a discharge path for deep groundwater flow. These, together or separately, result in lower salinity water circulating only in the upper part of the aquifer and discharging to nearby drainages (Fig. 6). As in the Goldfields region (Commander *et al.*, 1994) saltfall fully accounts for the accumulation of salt in groundwater.

3.3 Stirling Range Formation (*Ps*)

The Stirling Range Formation (*Ps*) comprises sandstone, quartzite and shale, and extends discontinuously east–west across MOUNT BARKER–ALBANY, mainly east of Cranbrook where it forms the Stirling Range. It is thrust against, or rests unconformably on, Archaean bedrock to the north (Myers, 1990b) and is faulted against Proterozoic rocks to the south (Muhling and Brakel, 1985). These rocks were deformed at about 1150 Ma, the same time as the emplacement (Myers, 1990b) of plutons in the Albany–Fraser Orogen (Muhling and Brakel, 1985). In Chester Pass the formation is abutted by Tertiary sedimentary rocks and overlain unconformably by minor Quaternary sediments. The formation outcrops over relatively small areas (the peaks) with larger intervening areas of colluvium, comprising scree from the peaks.

The rocks are substantially faulted and form a fractured rock aquifer recharged by rainfall and runoff from ephemeral streams. Groundwater flows north and south from the Stirling Range, and probably discharges into overlying (mainly Tertiary) sediments. Sanders (1968, 1969a,b) suggested that, near Cranbrook, flow was to the south, owing to the dip and fracturing of the rock units.

The deepest bore drilled in the formation, to 41 m at Sukey Hill, did not obtain a supply and the aquifer is little utilised as it lies mainly within the Stirling Range National Park. Groundwater within the formation is probably fresh near the groundwater divide extending east and west through Red Gum and Chester Passes, but is saline near the northern and southern margins. TDS levels ranging from 2900 to 9000 mg/L have been recorded in bores. There is potential for fresh water to occur at low elevations near the groundwater divide, such as at Chester Pass.

3.4 Igneous and metamorphic rocks (*An*, *Ag*, *Pg*, *Pn*, *Pd* and *q*)

The Archaean and Proterozoic bedrock comprises mixed gneissic and metamorphic rocks (*An*, *Pn*) and granitoid rocks (*Ag*, *Pg*). These four bedrock groupings are made on the basis of age, and on the potential for aquifers within the weathered profiles of the numerous bedrock types. Bedrock outcrop on MOUNT BARKER–ALBANY is distinguished by an overprint symbol, where the overlying weathered profile is generally less than 5 m thick, and may include laterite at the surface. The bedrock is cut by regional faults and local joints, and by quartz veins and dolerite dykes. It has an irregular surface, shaped by Late Palaeozoic continental glaciation and major Triassic–Cretaceous erosion including pronounced northern and westward flowing drainages. The bedrock is unconformably overlain by the younger rocks described above and is mostly obscured by Tertiary sediments in the south.

In areas of laterized bedrock, the weathered profile is up to 10–20 m thick. Weathered granitoid rocks are the most prospective for minor local aquifers, as a grit zone is generally developed at the base of the profile. The gneissic rocks, however, generally weather to clay, and form poor aquifers. The quartz veins (*q*) also form fractured rock aquifers and can transmit groundwater along the fractured zones; however, the dolerite dykes (*Pd*) are generally impermeable or weather to an impermeable clay. Where they are perpendicular to groundwater flow they can form barriers, contributing to rising watertables and land salinization upgradient of the dyke.

Groundwater is recharged from rainfall and runoff. Groundwater flow is very slow, except locally where there are preferred flow paths provided by fractures. Generally groundwater flow discharges from seeps into drainages, or into Tertiary sediments (Fig. 4). The northwest trending Tenterden and Boyup Brook Faults (Myers, 1989) are open fracture systems containing groundwater. These faults are marked by lake strings in the northwest of MOUNT BARKER–ALBANY (Myers, J. S., 1995, pers. comm.), but the easterly trending faults including the Pemberton and Northcliffe Faults are annealed and do not contain groundwater.

Groundwater in the igneous and metamorphic bedrock is predominantly saline, with some poor quality stock water (3000–10 000 mg/L). Fresh to brackish groundwater is limited and localised, and restricted to higher ground along groundwater divides.

The bedrock is prospective for only small, local supplies from saturated gritty layers in the weathered profile above fresh granitoid rocks, and from open fractures. Both are very site specific, and locating the latter usually involves detailed investigation drilling. Substantial drilling of carefully selected sites in weathered and shallow bedrock during the Drought Relief Drilling Program (Davidson, 1977) located 91 successful bores in the Ongerup, North and South Stirling areas, mostly on MOUNT BARKER–ALBANY. Salinities ranged from 660 to 11 600 mg/L. Supplies ranged from 5 to 131 m^3/d, with 25 m^3/d typical for weathered granitoid rocks. Some of the higher yielding sites occur low in the landscape, and may have intersected unrecognised Tertiary sediments rather than weathered granitoid rocks.

4 Groundwater quality

4.1 Salinity

Groundwater salinity distribution (Fig. 7) is shown as a side panel on the Mount Barker–Albany Hydrogeological Sheet. Salinity is mostly more than 7000 mg/L TDS in the northern third (Appleyard, 1994) but generally less than 1000 mg/L TDS in the southern third. A less evident trend is an increase in groundwater salinity to the east and north across the sheet area, corresponding to lower rainfall. Topographic variation also contributes to the salinity pattern and several small areas of low salinity, such as west of Tambellup, west of Borden, and in the Stirling Range, correspond with groundwater-flow divides. Fresh groundwater also occurs locally around monadnocks near the coast (Allen, 1991) where runoff from the exposed bedrock enhances groundwater recharge and outflow. Very high groundwater salinity is associated with salt lakes to the north and south of the Stirling Range. North of the Stirling Range salinity increased from 7000 mg/L at the watertable to 180 000 mg/L at depth (Appleyard, 1994).

The reliability of the groundwater salinity map is limited by the uneven data distribution, shown by the bore density side panel on Mount Barker–Albany. The salinity is necessarily generalised, and in some areas groundwater salinity can differ substantially over short distances. The map also reflects groundwater salinity at or close to the watertable, below which salinity may increase substantially with depth.

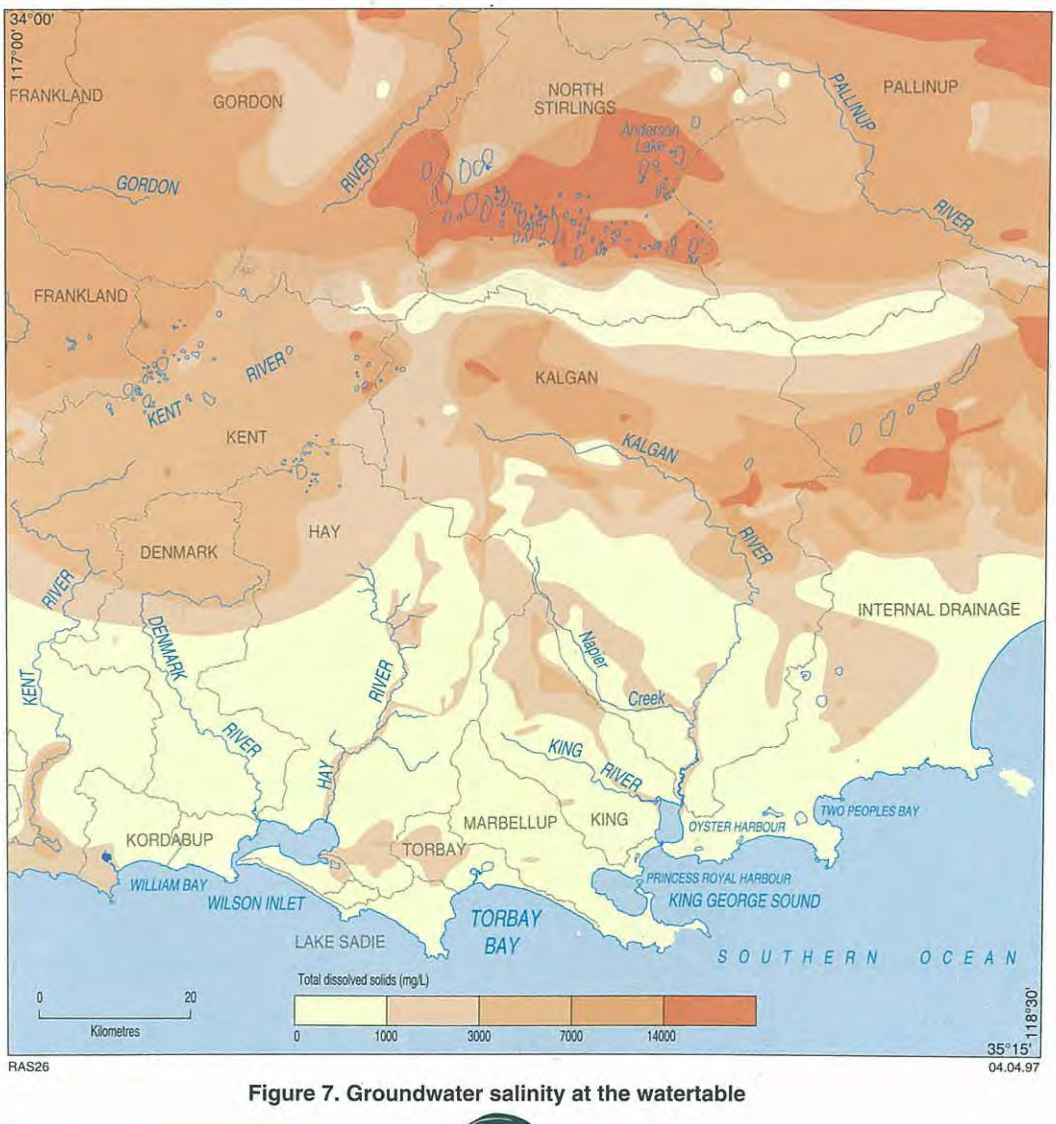

Figure 7. Groundwater salinity at the watertable

4.2 Hydrochemistry

Most waters are a sodium–chloride type (Fig. 8) irrespective of the aquifer, and reflect atmospheric saltfall. A selection of chemical analyses of groundwater are shown in Table 2. In both the coastal limestone and the Werillup Formation a proportion of the analyses contain significant calcium and bicarbonate concentrations. This reflects groundwater recharge from the limestone into the deeper Werillup Formation aquifer in the Albany South Coast Scheme (ASCS) borefields. The pH generally ranges from 3.2 to 8.5 with about 50% of samples falling in the range 7 to 8 and about 25% in the range 6 to 7.

Nitrate levels are generally very low and mostly below 10 mg/L, although a few areas have groundwater with nitrate levels up to 21 mg/L, which may indicate contamination. Fluoride, identified in a few samples, ranged from 0.1 to 1.0 mg/L (Table 2), while soluble iron was detected in only four water samples with concentrations up to 16 mg/L. The occurrence of boron from 2 to 7 mg/L was noted in a few samples.

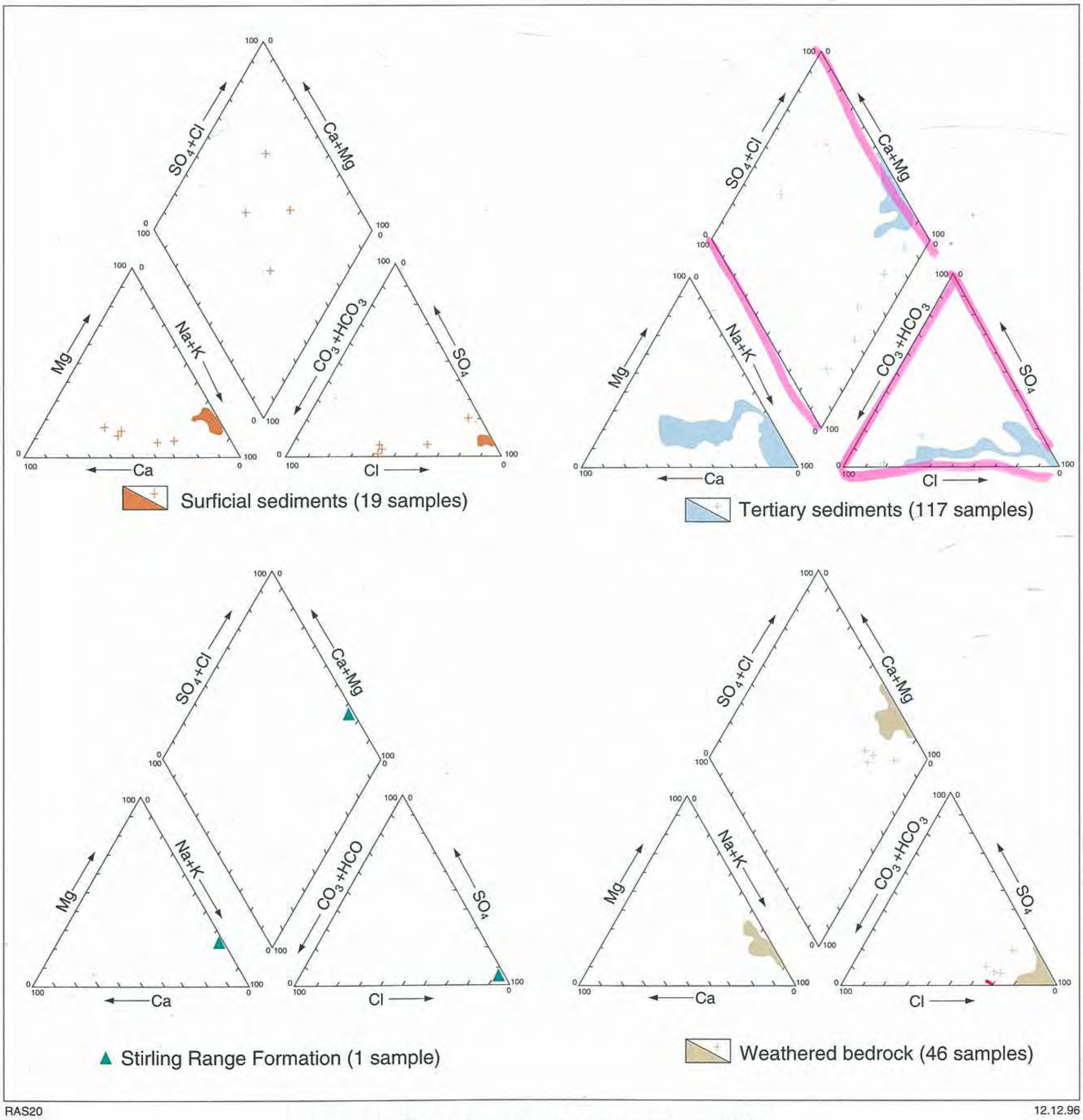

Figure 8. Piper diagram of chemical composition

Table 2. Selected groundwater analyses

Bore Record No.	Sample	pH	E.C. (mS/m)	TDS	Total hardness	Total alkalinity	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	SiO_2	F
				(mg/L)												
Surficial sediments																
2327-1-NE-0028	38445	5.7	1170	740	83	30	7	16	168	23	37	300	24	1	12	0
2427-1-NE-0009	8763	7.4	980	650	348	302	108	19	96	3	364	169	23	1	21	
2428-2-SW-0018	38456	4.5	360	210	40	0	3	8	46	4	0	93	13	1	6	
2429-2-NE-0002	88333	7.7	3330		5080	236	238	1090	5970	83	288	12000	1400	–	28	1
Pallinup Siltstone																
2428-1-NW-0009	26936	4.3	16000	10800	2613		120	562	2890	61		5750	817	3	33	
2428-2-SW-0098	43682	5.1	1040	550	91	5	7	18	156	3	6	282	30	1	8	0.1
2528-1-SW-0019	26902	4.9	4020	2590	549	–	40	109	740	16	–	1400	193	1	58	
2528-4-NW 0036	48206	6.8	14500	8330	3202	265	173	672	1950	41	323	4670	592	1	43	0.1
Weillup Formation																
2328-2-SE-0007	43683	5.2	870	470	79	10	7	15	130	3	12	225	36	–	29	0.1
2427-1-NE-0005	8768	5.4	770	460	150	5	32	17	83	2	6	142	123	1	2	
2428-2-SW-0088	43680	6.3	3360	1960	447	88	24	94	501	20	107	1030	21	1	20	0.2
2429-1-NE-0010	16916	7.2	1560	960	133	32	9	27	297	7	40	489	63	–	13	
2528-1-NW-0048	48207	6.1	16600	9910	3544	60	346	651	2350	92	73	5520	843	1	56	0.1
2528-2-NW-0001	15815		1580	1120	67	122	27	–	322	15	9	352	158	2	44	0.6
2528-3-NW-0010	41208	8.4	810	430	73	60	21	5	124	4	61	194	13	1	22	0.1
2529-3-NW-0009	88342	7.4	2950		3260	256	135	712	5870	59	312	10200	1190	–	28	0.2
Stirling Range Formation																
2529-3-NW-0004	26836	6.9	13000	8130	1740	138	80	275	2380	40	168	4500	490	4	27	
Weathered crystalline bedrock																
2327-1-NE-0012	38444	5.8	2010	1320	185	22	18	34	294	24	27	570	27	1	6	0
2328-4-NW-0008	1635	6.4	9690	6150	1930	85	160	371	1480	20	104	3430	243	1	53	
2329-1-NE-0013	26840	7.8	13900	8240	1400	5	8	336	2780	16	6	4930	484	13	19	
2428-3-NW-0006	43675	5.4	570	400	64	12	11	9	73	2	15	148	3	1	1	0.2
2429-2-NE-0006	88327	7.6	2310		2630	524	76	594	4260	153	639	7790	805	–	29	1
2529-4-NW-0026	16914	7.3	2330	1420	1	82	10	41	40	13	101	730	53	–	16	

E.C. = Electrical Conductivity (Ms/m @ 25°C); TDS = Total Dissolved Solids; – = Not detected.

5 Groundwater resources

The Werillup Formation within the southern two-thirds of the eastern half of Mount Barker–Albany contains the most significant groundwater resources in the area (Fig. 9, Table 3). The Archaean and Proterozoic bedrock does not provide significant groundwater supplies, and the Stirling Range Formation is largely unexplored. The groundwater flow systems are not known in sufficient detail to quantify the resources (Moncrieff, 1992).

Fresh groundwater occurs in about a quarter to a third of Mount Barker–Albany, however the most important fresh groundwater resources are found near the coast west and southwest of Albany. The Werillup Formation, Pallinup Siltstone, and coastal limestone contain most of the potable (fresh to brackish) water in the area. Groundwater elsewhere in the Werillup Formation is generally saline and suitable only for stock watering.

Minor groundwater resources are known in the Pallinup Siltstone in the southeast of Mount Barker–Albany, where fresh water commonly overlies stock-quality water. The value of these for a future town water supply is greatly limited by lateral and vertical variations in salinity within this aquifer. These reflect groundwater flow interpreted from drilling (Smith, 1994).

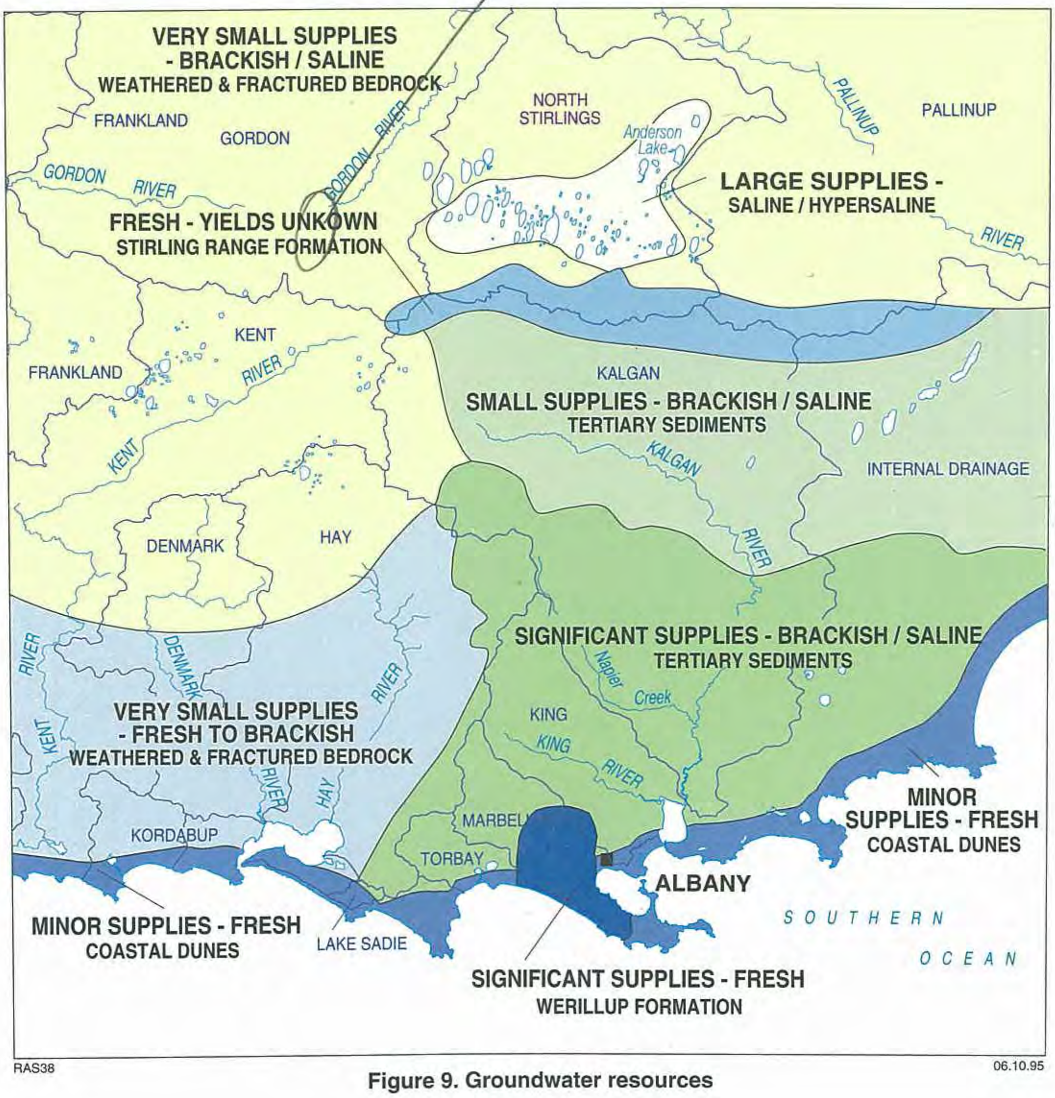

Figure 9. Groundwater resources

Table 3. Groundwater resource estimates

Aquifer	*Specific yield*	*Storage (10^6 m^3)*	*Recharge as % of rainfall*	*Recharge 10^6 m^3/a (approx.)*
Surficial sediments	0.2	300	20	60
Pallinup Siltstone	0.1	1000	10	190
Werillup Formation	0.1	10000	1	24
Stirling Range Formation	0.01	80	5	20

Note: Recharge estimates are based on a variety of factors including rainfall, amount of outcrop, and groundwater salinity. The approximate recharge (in 10^6m^3/a) is very high in relation to storage bvecause the aquifers are thin and discontinuous, and generally the groundwater discharges a short distance (and in a relatively short time) from where it recharges. No estimates are made for areas of granite and gneiss.

Fresh to saline groundwater resources also occur in local aquifers in outliers of the Plantagenet Group in the southwest and northwest of MOUNT BARKER–ALBANY.

Fresh groundwater resources may occur in the Stirling Range Formation in the Stirling Range National Park but as yet are unproven, while stock supplies have been obtained from the northwestern edge of the Stirling Range (Muhling and Brakel, 1985).

Small fresh groundwater resources occur in the coastal sand and limestone, while fresh to saline groundwater is present in local aquifers formed where alluvial deposits in coastal wetlands, in some drainage depressions, and along a few of the rivers are saturated.

Minor local aquifers within saturated, weathered granitoid bedrock and open fractured bedrock contain mainly saline water.

6 Groundwater development

6.1 Town water supply

The only major groundwater development in MOUNT BARKER–ALBANY is on the peninsula southwest of Albany (Fig. 10) where three borefields known as Sandpatch, Prison, and Racecourse (Katsavounidis, 1990) supply water to the Albany South Coast Scheme (ASCS). The intense groundwater development in, and near, the ASCS borefields has led to the proclamation of the encompassing Albany Groundwater Area (partly shown on Fig. 10) for water allocation by licence. The South West Water Reserve, and the Marbellup Water Reserve to the northwest, are for the protection of water quality in the public water supply area and Marbellup catchment respectively.

Groundwater abstraction from ASCS borefields in 1989–90 was 1.93 x 106 m3/a from forty-one production bores within the three borefields (Table 4) and projected demand to the year 2001 is not expected to exceed the estimated safe yield of 3.4 x 106 m3/a (Appleyard, 1989; Katsavounidis, 1990). Borefield abstraction for the ASCS is also augmented by up to 2 x 106 m3/a from several surface-water sources.

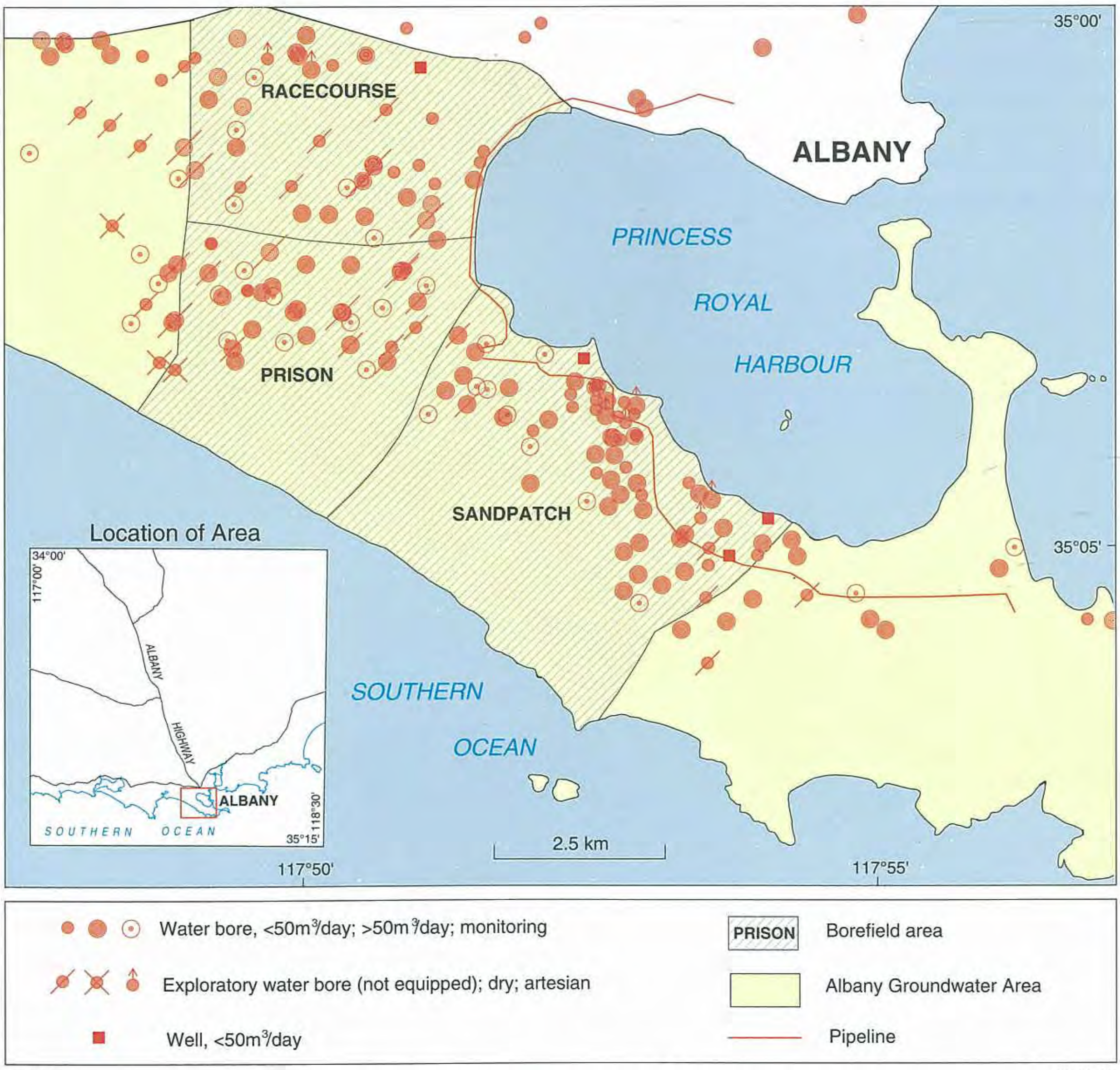

Figure 10. Albany groundwater area and bore locations

Table 4. Groundwater abstraction estimates

Borefield	*No. of bores*	*No. of monitoring bores*	*Abstraction 1989-1990 (10^6 m^3)*	*Estimated recharge (10^6 m^3/a)*	*Safe yield (10^6 m^3/a)*
Sandpatch	16	9	0.86	2.2	1.55
Prison	13	11	0.66	1.7	1.17
Racecourse	12	4	0.41	1.0	0.70
Total	41	24	1.93	4.9	3.42

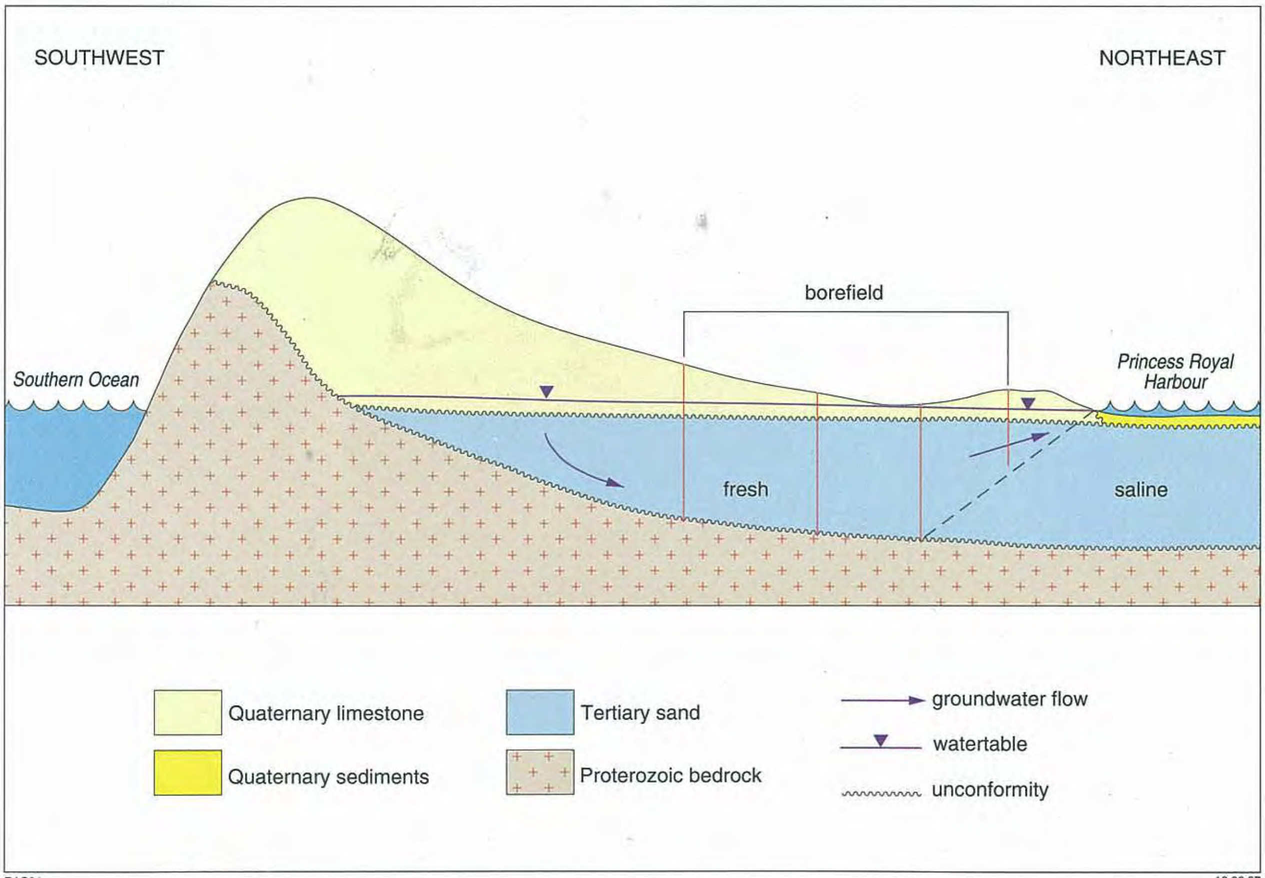

Figure 11. Diagrammatic section through the Albany Sandpatch borefield (Fig.10)

The borefields obtain water from an unconfined aquifer in Quaternary sand and from a confined aquifer in the Werillup Formation (Fig. 11). Monitoring carried out since 1969 confirms that the borefields have been overpumped both periodically and seasonally. When abstraction lowers the waterlevel to below sea level for several months during summer, saltwater intrusion occurs, particularly in the bores near Princess Royal Harbour.

The groundwater from the two aquifers has a moderately high content of calcium and bicarbonate, is alkaline, and coloured. Prior to reticulation in the ASCS the water is treated for colour, the pH is reduced, and the water chlorinated. For industrial users the water is softened to reduce the calcium and bicarbonate content. Some bores yield water with high iron concentrations.

Water is reticulated to the towns of Albany, Kendenup, Mount Barker, Narrikup, and Porongurup via the Albany South Coast Scheme (ASCS). Denmark is supplied from the Quickup and Denmark Dams and Scotsdale Weir. Borden, Cranbrook and Tambellup are part of the Lower Great Southern Water Supply (LGSWS) scheme, supplied from the Harris Dam near Collie. Local catchments and storages supply Frankland, and Rocky Gully, and also augment Borden and Cranbrook (Moncrieff, 1992).

Potential groundwater sources have been identified by Moncrieff (1992), based on geological mapping (Muhling *et al.*, 1978), and groundwater census information from the Albany to Mount Barker (Hirschberg, 1976) and Stirling Range areas (Moncrieff, 1977).

6.2 Domestic and stock

Groundwater use for domestic and stock purposes is limited by high salinity. Consequently there is a high dependence on farm dams throughout the MOUNT BARKER–ALBANY area. Small areas north of the Stirling Range contain fresh groundwater resources, the result of local recharge to a suitable rock type on groundwater divides such as in the Kybelup Plain area (Dodson, 1995).

7 Land salinization and rising watertables

Increased groundwater recharge after clearing of native vegetation and replacement by annual crops and pastures has resulted in groundwater levels continuously rising, by 0.1 to 0.4 m/year (McFarlane, D. J., 1994, pers. comm.). Cyclic salts accumulated in the regolith over thousands of years (Commander *et al.*, 1994) have been remobilised by the rising waterlevels and saline seeps appear where the watertable reaches the surface. Groundwater levels are rising most rapidly in areas with high rainfall and inadequate drainage. However areas with low rainfall develop similar severe salt problems, but over a longer period.

High rainfall areas with good drainage have accumulated less salt in the regolith, and the risk of salinization is generally low in the southwest of Mount Barker–Albany (Schofield *et al.*, 1989).

Areas of poor drainage, where the regolith is thick and clayey as in the upper Kent and the Denmark River catchments, or silty as in the North Stirlings, have accumulated the most salt. The inland North Stirling area has limited external drainage, and land and water salinisation has resulted in the development of extensive salt lakes. Areas with poor drainage and a predominately silty regolith, such as in the Tertiary sediments in the southeast of Mount Barker–Albany, have also accumulated saltfall and exhibit rising watertables and salinization.

Detailed studies on salinization along the western South Coast have been carried out by Agriculture Western Australia (George and Nulsen, 1985; George *et al.*, 1991; McFarlane, 1991; Lennard *et al.*, 1991; Ferdowsian and Greenham, 1992; Lewis 1992). Ferdowsian and Greenham (1992) showed that shear zones in basement rocks were affecting groundwater discharge. Lewis (1992) and Appleyard (1994) documented the severe salinity problem faced in the North Stirling Basin.

Detailed mapping of landform patterns on Mount Barker for Agriculture Western Australia has enabled hydrological systems to be defined (Ferdowsian, R., 1995, pers. comm.). Each system has a particular depth to groundwater, salt storage, groundwater salinity, and soil salinity and waterlogging hazards. Similar classifications are in progress for the Bremer Bay sheet and for north of the Stirling Range.

Airborne geophysical techniques have been employed over an area of 100 000 hectares in the Kent and Frankland River catchments to better define the geological controls on groundwater flow and salt storage (Anderson *et al.*, 1996). Agriculture Western Australia and CSIRO have developed a salinization prediction model for the upper Kent catchment based on topographic contours and Landsat Thematic Mapper data. This model is being extended to surrounding areas.

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