The geology and hydrogeology of the superficial formations between Cervantes and Lancelin, Western Australia

by

A. M. Kern

Abstract

From 1985 to 1987, drilling at 35 sites on the Swan Coastal Plain between Cervantes and Lancelin was undertaken to investigate the hydrogeology, assess the groundwater resources, and provide a network of bores for long-term monitoring. A total of 65 bores was drilled, with up to four monitoring bores at each site. The aggregate depth drilled was 2825 m and the deepest bore was 111 m.

The superficial formations in this area consist mainly of shallow-water marine and eolian sands and limestone, unconformably overlying Mesozoic formations. In the eastern part of the coastal plain, they range in thickness from about 50 m in the south to less than 10 m in the north. The thickness of these deposits is more variable in the Coastal Belt due to the rugged topography.

The superficial formations contain a predominantly unconfined regional groundwater flow system which receives recharge from rainfall over the whole area. Groundwater flows westwards from the Gingin Scarp to discharge along the coast. The aquifer is recharged mainly by direct infiltration of rainfall supplemented by both seepage from runoff and upward leakage from Mesozoic aquifers in the northeast and the coastal area. Groundwater discharge occurs along the shoreline above a saltwater wedge. There is also significant downward leakage to the Leederville Formation in the southeast.

Groundwater storage in the superficial formations and the annual outflow at the coast are estimated to be 10 x 10^9 m^3 and 100 x 10^6 m^3/year respectively. The major groundwater resources of the area lie west of Regans Ford where the salinity is less than 1000 mg/L (total dissolved solids) and where the saturated thickness of the unconfined superficial formations exceeds 40 m. There is also groundwater of low salinity (less than 500 mg/L) within the Tamala Limestone between Lancelin and Wedge Island. The groundwater in the northern part of the area and along the Gingin Scarp is generally brackish.

KEYWORDS: Groundwater, salinity, hydrogeology, Swan Coastal Plain, geology, stratigraphy, Perth Basin

Introduction

The area investigated extends over 1900 km^2 on the Swan Coastal Plain between Cervantes and Lancelin. The project was named the Cataby Project after a small settlement on the Brand Highway located approximately 170 km north of Perth (Fig. 1).

The project, carried out by the Geological Survey of Western Australia (GSWA), is a northward extension of the Salvado Project drilled in 1980 (Moncrieff and Tuckson, 1989). The objectives of the project were to investigate the geology of the superficial formations* and to identify the underlying Mesozoic formations, to investigate the hydrogeology and assess the groundwater resources of the area, and to provide a network of groundwater observation bores for long-term monitoring.

The project is part of a long-term program to evaluate the groundwater resources of the Perth Basin. Funding was initially jointly provided by the Commonwealth and State Governments under the National Water Resources Assessment Programme. From mid-1986, however, the State Government alone has financed the project.

* Superficial formations are Pliocene to Holocene sedimentary rocks which underlie the Swan Coastal Plain in the Perth Basin; despite the variability in lithologies, these formations form a single aquifer system (Allen, 1976).

About two-thirds of the project area (including the Nambung National Park and numerous nature reserves) is covered by native vegetation. Most of the clearing for agriculture has taken place in the sandy central area and along the Gingin Scarp. The largest towns in the area are Lancelin and Cervantes, and there are smaller coastal settlements at Wedge Island and Grey.

Previous work

The superficial formations of the coastal plain were mapped by Low (1972) and Lowry (1974). Exploration for oil and gas by West Australian Petroleum Pty (Wapet) provided the first information on the underlying Mesozoic formations (Moyes, 1970; Bird and Moyes, 1971) and led to the discovery of gas at Walyering, approximately 7 km northwest of Cataby. Prospecting for heavy minerals in the early 1970s along the foot of the Gingin Scarp in the project area resulted in the discovery of the Gingin and Munbinea Shorelines (Baxter, 1977). Commercial development of the mineral-sand deposit at Cooljarloo is under way.

Numerous exploratory drilling programs for coal were carried out in the late 1970s and early 1980s in the northern part of the project area where the Cattamarra Member of the Cockleshell Gully Formation underlies a veneer of Cainozoic sediments.

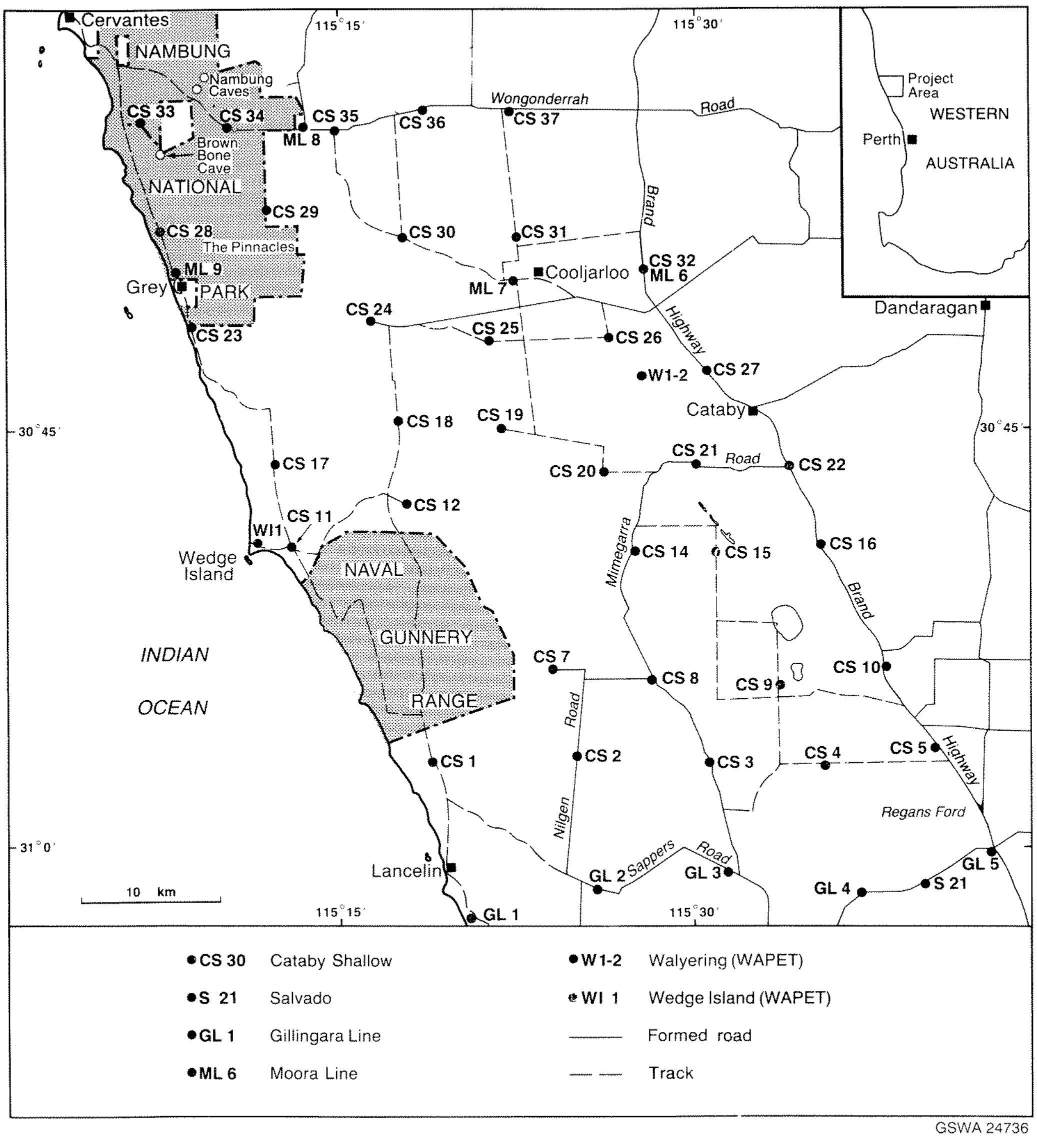


Figure 1. Bore location and access

In 1974, deep exploratory drilling for water along the Moora Line (ML) was carried out in the area by the GSWA (Briese, 1979). The Gillingarra Line (GL) was drilled along the southern boundary of the project area between 1982 and 1986 (Moncrieff, 1989).

The hydrogeology of the superficial formations south of Lancelin has been described by Moncrieff and Tuckson (1989). Details of the present project are given by Kern (1988a,b).

Climate

The region has a mediterranean climate characterized by hot, dry summers and mild, wet winters. The average annual rainfall decreases northward from about 630 mm at Lancelin to about 570 mm at Cervantes. Most of the rain falls during the winter months between April and October. The average annual evaporation is about 2000 mm and rainfall exceeds evaporation only during the winter months.

Physiography

Landform

The investigation area lies on the Swan Coastal Plain which is bounded to the east by the Gingin Scarp. The scarp was formed by marine erosion and separates the coastal plain from the Dandaragan Plateau in the southeast and the Arrowsmith Region in the northeast (Fig. 2).

The coastal plain is a low-lying, gently undulating area covered by Holocene and Pleistocene coastal dunes and shoreline deposits, with belts of alluvium and colluvium along the foot of the Gingin Scarp. The coastal plain may be subdivided into two main

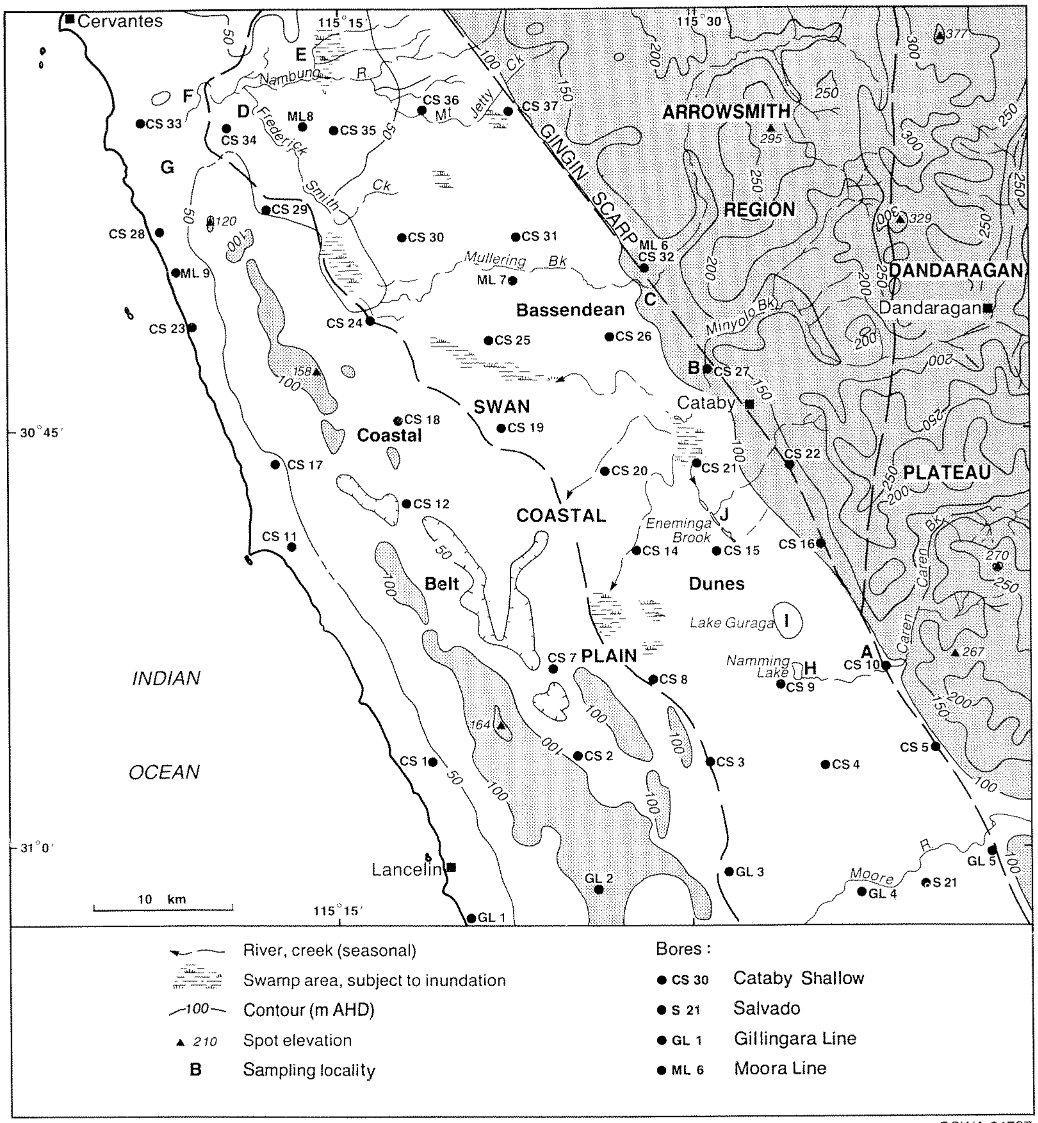


Figure 2. Physiography and drainage

geomorphic units; the Coastal Belt and the Bassendean Dunes.

The Coastal Belt consists of Quaternary shoreline deposits and the Quindalup and Spearwood Dunes. The Quindalup Dunes are composed of the Safety Bay Sand, which forms both stabilized and mobile dunes up to 150 m high. These overlap the Spearwood Dunes, which consist largely of lithified Pleistocene eolianite with leached quartz sand (Tamala Limestone), and form linear ridges rising to 164 m AHD and a low limestone plateau.

Well-developed cave systems occur in the limestone in a number of localities in the Nambung National Park. Limestone pinnacles are particularly well developed in the Tamala Limestone near Cervantes. The cylindrical columns of limestone represent strongly lithified fillings of solution pipes which formed in eolianite during an earlier erosion cycle.

The Bassendean Dunes occur in a zone about 15 km wide between the Coastal Belt and the Gingin Scarp. They consist of a belt of low dunes of leached quartz sand (Bassendean Sand) with numerous interdunal lakes and seasonal swamps.

Surface water

The area is drained by watercourses originating on the Dandaragan Plateau and Arrowsmith Region. All except the Moore River are seasonal streams terminating in large swamps or lakes in the Bassendean Dunes (Fig. 2). Surface drainage is absent in the Coastal Belt, but there are well-developed cave systems which allow extensive subsurface flow of water. When the Nambung River is active it flows through limestone caves towards the sea.

Stream salinity ranges from fresh to brackish with the highest salinities occurring in early winter when salinized

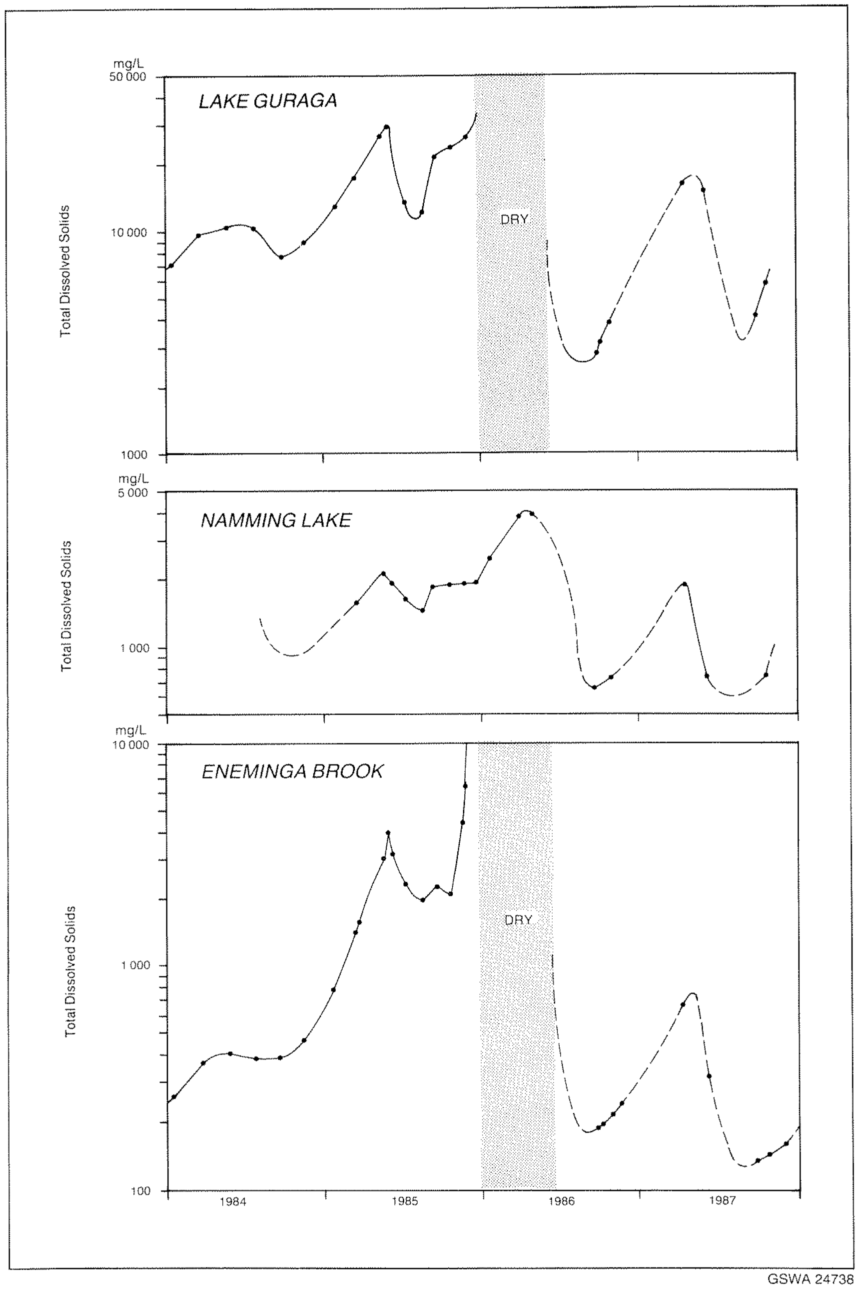


Figure 3. Wetland salinity

areas are flushed by heavy rainfall (Kern, 1988a). The salinity of the Nambung River decreases downstream owing to dilution by tributaries with lower salinities. It is lowest where it enters the caves in the Tamala Limestone.

A number of permanent and seasonal lakes and swamps occur in interdunal depressions in the Bassendean Dunes. They occupy about 100 km^2 and usually fill with water at the end of winter when chains of swamps and lakes connect to form broad streams which flow northwest toward the Nambung River.

Major lakes are generally permanent and in hydraulic connection with the unconfined aquifer. The lake levels are highest at the end of winter (September) and lowest at the end of summer (May). They were extremely low during the 1985/86 summer following below-average winter rainfall, and some lakes were completely dry (Fig. 3).

Three wetlands in the project area were closely monitored during the period 1985–1987 (Figs 2 and 3). Two of these, Namming Lake and Eneminga Brook, contain fresh to brackish water, whereas the third wetland, Lake Guraga, contains brackish to saline water. Monitoring shows that the salinities are highest when waterlevels are lowest.

Investigation techniques

Drilling and bore construction

The project commenced in February 1985 and was completed in July 1987. Drilling was carried out at thirty-five sites located in seven easterly trending lines across the coastal plain. Sixty-five bores (prefixed CS) were drilled to a maximum depth of 111 m; 60 bores were cased and completed (Table 1). The remaining bores were abandoned due to drilling or construction difficulties. The aggregate depth drilled by the Mines Department Drilling Branch was 2825 m.

At each site, a deep bore was first drilled to about 10 m into the Mesozoic strata underlying the superficial formations. Where the superficial formations were thin, drilling was continued to a total depth of about 50 m. Following lithological and geophysical logging, the bore was cased to the appropriate depth and a second, shallower bore drilled alongside. Where required, a third bore was drilled and, very rarely, a fourth. The shallowest bores were generally completed at about 10 m below the watertable.

The observation bores were cased with PVC or polyethylene pipes (slotted over the selected interval) with a protective steel casing at the surface. Steel casing was used throughout where PVC was impractical. The casing diameter in cored holes is either 35 mm or 50 mm internal diameter and generally 100 mm in rotary-drilled holes. The annulus between the casing and the borehole was packed with graded sand.

Sampling, logging, and testing

In the bores drilled using the Jacro rotary rig, samples were taken at 3 m intervals and at any change in lithology. Continuous cores were obtained with the wireline-drilling technique used by the Edson rig, and sludge samples were collected only when core recovery was uncertain. The wireline-drilling technique provided good core recovery commonly varying between 30% and 80%.

On completion of drilling, a suite of geophysical logs was generally run. Natural gamma, normals resistivity, point resistance, and caliper logs were run in rotary-drilled holes. Neutron logs were run through drillpipe in a few of the cored holes. Sidewall cores for palynological and lithological determinations were collected at five sites after completion of the geophysical logging.

All the bores were developed by air-lifting and water samples were submitted to the Chemistry Centre (W.A.) for chemical analysis.

All observation bores were levelled to the Australian Height Datum (AHD) by the Surveys and Mapping Division of the Department of Mines. Monitoring of waterlevels in the observation bores was carried out at the end of winter and of summer when waterlevels are respectively at their highest and lowest. Some sites were monitored over two years until October 1987.

Geology

Setting

The Cataby area is located in the central part of the Perth Basin where two structural subdivisions are recognized: the Dandaragan Trough and the Beagle Ridge (Playford et al., 1976). The Dandaragan Trough contains as much as 15 000 m of Phanerozoic sediments, mostly of Permian and Mesozoic age. The Beagle Ridge is a narrow mid-basin ridge of relatively shallow basement between the Dandaragan Trough and the Abrolhos Sub-basin.

Sediments of Triassic to Quaternary age were intersected during drilling (Table 2). The Tertiary and Quaternary units together are referred to as the superficial formations (Fig. 4).

Structure

The Perth Basin is characterized by normal faulting, with minor folding (Fig. 5). Three major faults with a north-northwesterly to northerly trend occur in the project area. These are the Beagle, Lesueur and Warradarge Faults. A strongly faulted anticline is developed between the Lesueur and Warradarge Faults. A syncline occurs in the southern part of the project area and is referred to as the Yanchep Syncline.

The erosion surface on which the Cainozoic sediments were deposited slopes towards the coast from about 120 m AHD at Cataby to about 25 m below sea level between Wedge Island and Lancelin (Fig. 5). The gradient is steep along the Gingin Scarp and near the coast between Cervantes and Wedge Island.

The Cainozoic sediments are generally flat lying and range in thickness from a maximum of about 170 m in the Coastal Belt to less than 10 m along the northern boundary of the project area (Fig. 6).

Stratigraphy

Only those formations encountered in the drilling program are described and these are listed, in order, from oldest to youngest.

Kockatea Shale

The Kockatea Shale was intersected at shallow depth at three sites on the Beagle Ridge where it is overlain

Table 1. Bore data

Bore	Grid ref. AMG Zone 50	Drilling Comm.	Drilling Compl.	Elevation (m AHD) Surface	Elevation (m AHD) Top casing	Total depth (m)	Top of Mesozoic (m AHD)	Casing size (mm)	Slotted/screened interval (m bns)	Aquifer	Head (m AHD) (26.5.87)	Salinity TDS (mg/L)	Status
CS1D	392E/747N	14.04.86	21.04.86	25.126	26.124	59.0	-22	35	44.0 – 46.0	Tamala	0.6	650	obs
CS2A	489E/753N	04.12.85	12.12.85			90.5	-1	103					abd
CS2B	489E/753N	05.02.86	13.02.86			91.5	-1	152					abd
CS2C	489E/753N	11.03.86	20.03.86			66.0	-1	155					abd
CS2D	489E/757N	21.03.86	14.04.86	79.725	80.128	111.0	-1	103	1.0 – 77.0	Tamala	20.9	580	obs
CS3S	577E/752N	12.05.86	12.05.86	65.925	66.698	19.0	11	35	12.0 – 18.0	Guildford	48.7		obs
CS3D	577E/752N	07.05.86	12.05.86	5.905	66.730	68.3	11	35	48.0 – 54.0	Guildford/Ascot	48.6	220	obs
CS4D	654E/751N	23.05.86	23.05.86	77.990	78.857	19.0	10	35	11.0 – 17.0	Guildford	73.1	700	obs
CS4S	654E/751N	13.05.86	23.05.86	77.961	78.731	77.5	10	35	33.5 – 39.5	Guildford	68.0	1 040	obs
CS5I	727E/754N	28.02.85	06.03.85	89.816	90.826	60.5	60	100	21.0 – 26.0	Guildford	80.3	1 220	obs
CS7D	471E/754N	22.04.85	29.04.86	80.462	81.576	87.3	1	35	73.5 – 79.5	Tamala	19.7	950	obs
CS8S	538E/805N	06.05.86	06.05.86	57.585	58.542	12.0	10	35	6.0 – 12.0	Guildford	49.4		obs
CS8I	538E/805N	01.05.86	06.05.86	57.594	58.563	32.4	10	35	26.5 – 32.5	Guildford	49.4	4 420	obs
CS8D	538E/804N	30.04.86	01.05.86	57.622	58.456	50.8	10	35	41.5 – 46.5	Ascot	49.4	2 820	obs
CS9S	623E/804N	03.04.85	03.04.85	80.135	81.112	15.5	19	100	8.0 – 14.0	Guildford	73.9	700	obs
CS9M	623E/804N	02.04.85	04.04.85	80.172	81.139	50.0	19	100	42.0 – 48.0	Ascot	68.5	1 860	obs
CS9D	623E/804N	01.04.85	02.04.85	80.172	81.187	71.0	19	100	56.0 – 62.0	Ascot	68.5	2 030	obs
CS10S	691E/814N	25.02.85	26.02.85	97.622	98.564	20.0	76	100	13.0 – 19.0	Guildford	81.5		obs
CS10D	691E/814N	21.02.85	25.02.85	97.524	98.529	45.0	76	100	31.5 – 35.5	Leederville	78.6	1 570	obs
CS11S	296E/889N	18.06.87	19.06.87	28.735	29.090	45.2	-14	50	33.0 – 45.0	Tamala	0.2	910	obs
CS11D	296E/889N	10.06.87	18.06.87	28.750	29.110	107.3	-14	50	86.0 – 102.0	Yarragadee	0.1	22 300	obs
CS12D	371E/918N	22.06.87	26.06.87	45.229	45.656	66.0	1	50	30.0 – 42.0	Tamala	16.8	530	obs
CS14S	524E/891N	18.03.85	19.03.85	63.242	64.215	9.0	15	100	2.0 – 8.0	Guildford	61.7	390	obs
CS14M1	524E/891N	15.03.85	18.03.85	63.398	64.329	28.0	15	100	21.0 – 27.0	Ascot	59.6	810	obs
CS14M2	524E/891N	14.03.85	15.03.85	63.423	64.397	43.0	15	100	36.0 – 42.0	Ascot	59.4	920	obs
CS14D	524E/891N	11.03.85	13.03.85	63.345	64.394	63.0	15	100	51.0 – 57.0	Leederville	59.4	940	obs
CS15S	579E/891N	27.03.85	28.03.85	77.124	78.040	16.0	19	100	9.0 – 15.0	Guildford	71.6	860	obs
CS15M	579E/891N	26.03.85	28.03.85	77.046	78.030	37.0	19	100	30.0 – 36.0	Ascot	64.8	820	obs
CS15D1	579E/891N	20.03.85	23.05.85			65.0	19						abd
CS15D2	579E/891N	25.03.85	28.03.85	77.124	78.040	61.0	19	100	51.0 – 57.0	Ascot	64.8	680	obs
CS16D	647E/897N	19.02.85	20.02.85	117.527	118.559	39.0	72	100	28.0 – 36.0	Guildford			abd
CS16DA	647E/897N	19.11.86	24.11.86	117.618	118.784	50.7	72	35	34.0 – 40.0	Guildford	86.5		obs
CS17D	283E/943N	22.05.87	09.06.87	35.982	36.525	54.2	2	50	36.2 – 54.2	Lesueur	8.5	460	obs
CS18D	364E/973N	04.12.86	05.12.86	44.739	45.595	59.9	8	35	28.0 – 36.0	Tamala	32.2	600	obs
CS19D	452E/968N	10.12.86	11.12.86	59.823	60.908	48.0	13	35	35.0 – 45.0	Ascot	45.1	770	obs
CS20S	403E/942N	02.12.86	02.12.86	70.312	71.291	19.0	19	35	9.0 – 18.0	Guildford	59.2	810	obs
CS20D	503E/942N	26.11.86	01.12.86	70.282	71.277	80.8	19	35	37.0 – 46.0	Ascot	58.9	940	obs
CS21D	564E/949N	06.03.85	08.03.85	85.361	86.379	31.0	25	100	25.5 – 30.0	Guildford	72.2	620	obs
CS22D	627E/948N	14.02.85	18.02.85	136.959	137.837	26.0	116	100	15.5 – 19.5	Guildford			abd
CS22DA	627E/948N	24.11.86	25.11.86	136.949	137.828	53.8	116	35	29.0 – 35.0	Yarragadee	100.1		obs
CS23D	225E/035N	01.09.86	09.09.86	7.424	8.526	17.5	- 4	35	3.0 – 11.0	Guildford	0.1	430	obs
CS24D	345E/040N	03.12.86	04.12.86	44.875	45.755	30.8	28	35	8.0 – 16.0	Guildford	44.0		obs
CS25S	426E/027N	18.08.86	19.08.86	64.520	65.194	25.0	20	35	17.0 – 23.0	Yarragadee	50.3	930	obs

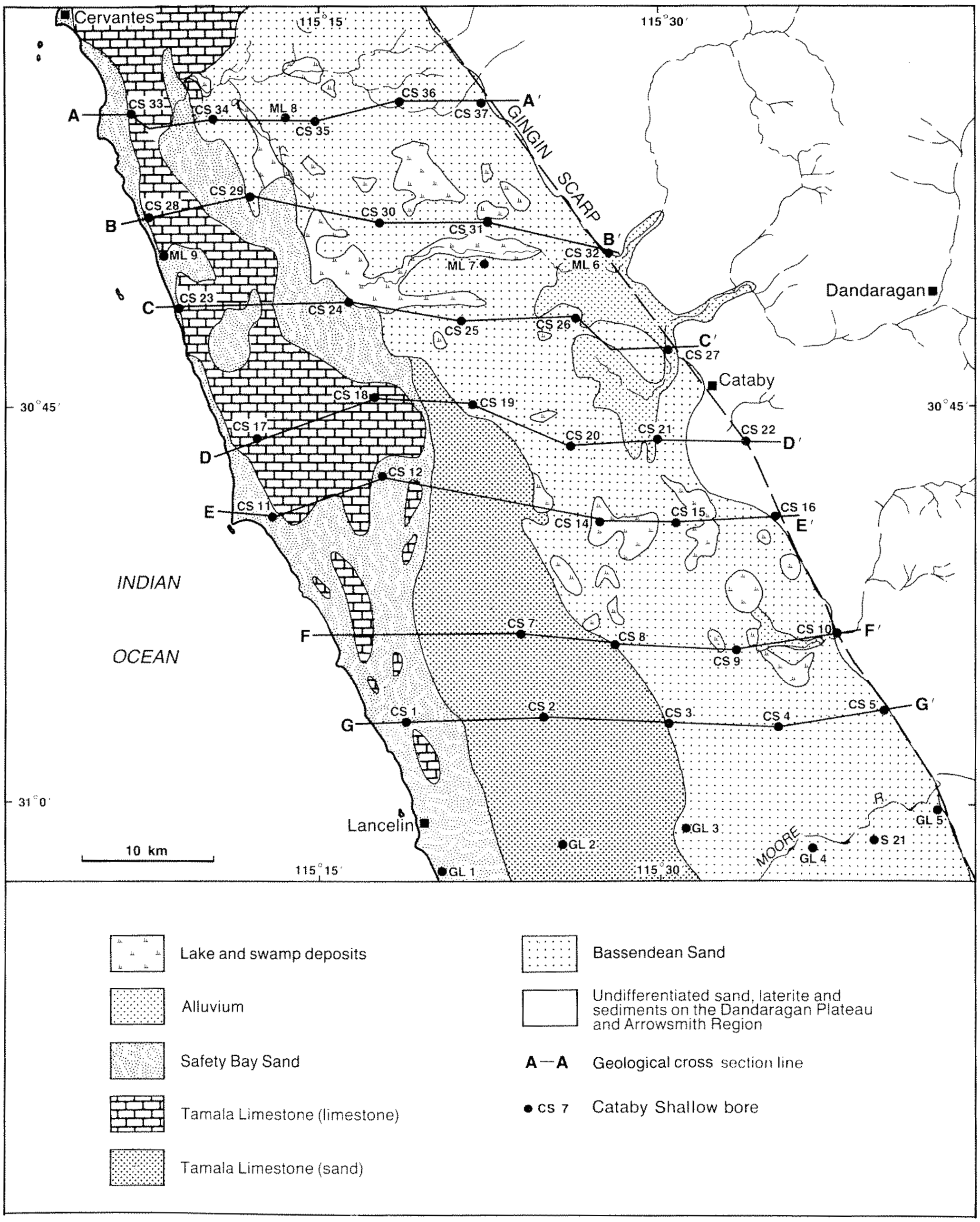
Table 1. *(continued)*

Bore	*Grid ref. AMG Zone 50*	*Drilling* Comm.	*Drilling* Compl.	*Elevation (m AHD)* Surface	*Elevation (m AHD)* Top casing	*Total depth (m)*	*Top of Mesozoic (m AHD)*	*Casing size (mm)*	*Slotted/screened interval (m bns)*	*Aquifer*	*Head (m AHD) (26.5.87)*	*Salinity TDS (mg/L)*	*Status*
CS25D	426E/027N	13.08.86	14.08.86	64.522	65.178	80.5	20	35	68.0 – 74.5	Guildford	50.6	1 220	obs
CS26S	505E/031N	13.08.86	13.08.86	87.151	88.007	14.0	32	35	6.0 – 12.0	Guildford	81.4	240	obs
CS26D	505E/031N	08.08.86	12.08.86	87.183	87.853	56.6	32	35	47.0 – 53.0	Ascot	81.4	560	obs
CS27D	571E/011N	12.02.85	14.02.85	106.171	107.181	30.6	81	100	19.0 – 24.0	Guildford	97.2	1 180	obs
CS28D	203E/095N	28.08.86	28.08.86	2.301	3.132	14.4	-7	35	4.5 – 8.0	Tamala	0.1	2 170	obs
CS29S	275E/112N	23.06.86	24.06.86	41.669	42.797	12.0	33	35	5.0 – 11.0	Tamala/Lesueur	37.2	350	obs
CS29D	275E/112N	19.06.86	23.06.86	41.667	42.526	50.5	33	35	41.0 – 47.0	Lesueur	37.2	690	obs
CS30S	356E/096N	16.07.86	16.07.86	51.999	52.746	10.0	28	35	4.0 – 9.0	Guildford	47.9	2 740	obs
CS30D	560E/096N	14.07.86	16.07.86	51.974	52.746	50.0	28	35	42.9 – 48.5	Yarragadee	47.8	7 510	obs
CS31S	441E/097N	21.08.86	22.08.86	67.348	68.127	15.0	33	35	8.0 – 14.0	Guildford	65.6	1 170	obs
CS31D	441E/097N	19.08.86	20.08.86	67.369	68.075	38.6	33	35	28.0 – 34.0	Guildford	64.8	880	obs
CS32D	528E/077N	07.02.85	11.02.85	112.135	113.054	25.8	109	100	7.5 – 12.5	Yarragadee	106.4	2 370	obs
CS33D	188E/167N	27.08.86	28.08.86	2.787	3.884	17.5	-10	35	4.0 – 11.0	Tamala	0.1	760	obs
CS34S	248E/166N	17.06.86	18.06.86	36.424	37.153	24.0	23	35	17.0 – 23.0	Guildford	22.7	780	obs
CS34D	248E/166N	12.06.86	17.06.86	36.356	37.071	50.5	23	35	43.0 – 48.0	Lesueur	22.7	1 020	obs
CS35S	320E/166N	01.07.86	01.07.86	45.415	46.113	15.0	38	35	10.0 – 14.0	Cockleshell Gully	40.8	530	obs
CS35D	320E/166N	25.06.86	30.06.86	45.365	46.098	47.5	38	35	36.8 – 42.8	Cockleshell Gully	40.6	1 450	obs
CS36S	378E/182N	09.07.86	09.07.86	55.541	56.301	9.5	47	35	2.0 – 8.5	Guildford	53.4	3 820	obs
CS36D	378E/182N	01.07.86	09.07.86			50.5	47	35					abd
CS37S	434E/182N	24.07.86	25.07.86	88.450	89.172	11.0	86	35	4.0 – 10.0	Yarragadee	84.3	360	obs
CS37D	434E/182N	17.07.86	24.07.86	88.435	89.168	50.5	86	35	41.6 – 47.6	Yarragadee	84.6	260	obs

NOTES: AHD: Australian height datum TDS: total dissolved solids obs: observation bore abd: abandoned

Table 2. Stratigraphic succession

Age: System	Age: Series	Formation	Maximum thickness penetrated (m)	Lithology
QUATERNARY	Holocene	Alluvial, colluvial and swamp deposits	23	sand, clay
		Safety Bay Sand	3	sand
	Late Pleistocene	Bassendean Sand	2	sand
		Tamala Limestone	81	sand, limestone, clay
	Pleistocene	Guildford Formation	53	sand, clay
TERTIARY	Pliocene	Yoganup Formation	20	sand, clay
		Ascot Formation	29	limestone, sand
		~~UNCONFORMITY~~~		
CRETACEOUS	Early–Late	Coolyena Group		
		Lancelin Formation	-	marl
		Osborne Formation	-	shale, siltstone, sandstone
		~~UNCONFORMITY~~~		
	Early	Leederville Formation	20	sandstone, siltstone, shale
		South Perth Shale	-	shale
		~~UNCONFORMITY~~~		
JURASSIC	Middle–Late	Yarragadee Formation	46	sandstone, siltstone
	Middle	Cadda Formation	-	shale, siltstone, sandstone
	Early	Cockleshell Gully Formation		
		Cattamarra Member	42	sandstone, siltstone, shale
		Eneabba Member	40	sandstone, siltstone, shale
TRIASSIC	Middle–Late	Lesueur Sandstone	42	sandstone
	Early	Woodada Formation	-	sandstone, siltstone, shale
		Kockatea Shale	7	siltstone



GSWA 24739

Figure 4. Surface geology

by Quaternary sediments. The formation is characterized by micaceous siltstone and shale. Spores and pollen indicate a marine depositional environment of Griesbachian to Dienerian age (all dating in this paper is based on the work of J. Backhouse, quoted in Kern (1988a)).

Lesueur Sandstone

The Lesueur Sandstone is present in the westernmost part of the Dandaragan Trough. It was intersected under a thin cover of Quaternary sediments at three sites, and is characterized by ferruginous sandstone. The sandstone is mottled yellow and red, and composed of coarse to medium, angular to subangular, well-sorted quartz grains with a variable amount of feldspar and mica. A massive ferruginous 'coffee rock' is developed at the watertable. The microflora of the Lesueur Sandstone indicate a late Middle to Late Triassic age for the unit.

Cockleshell Gully Formation

The Cockleshell Gully Formation consists of two members: the Eneabba and Cattamarra Members. The basal Eneabba Member was intersected at site CS35 and consists of fine- to coarse-grained sandstone with

Table 3. Chemical analyses

Bore	Sample no.	Date sampled	pH	Conduct. mS/m (at 25 °C)	TDS mg/L (Calc at 180° C)	Total hardness (as $CaCO_3$)	Total alkalinity (as $CaCO_3$)	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	SiO_2	B	F
								mg/L											
CS2D	82564	29.05.86	8.3	108	580	234	210	69	15	122	4	3	250	213	8	1	22	0.60	0.2
CS3D	82636	14.05.86	7.1	42	220	53	32	8	8	56	4	2	39	98	11	1	16	0.05	0.1
CS4S	82562	27.05.86	7.5	121	700	141	110	17	24	204	5	2	134	234	117	2	33	0.05	0.2
CS4D	82563	26.05.86	8.3	189	1 040	354	280	89	32	244	8	3	335	440	12	1	45	0.05	0.3
CS5D	82604	06.03.85	7.5	231	1 220	205	33	8	45	375	6	2	40	636	65	1	62	0.07	0.3
CS7D	82639	15.05.86	8.6	178	950	281	260	73	24	247	10	9	299	389	26	1	20	0.06	0.3
CS81	82638	08.05.86	8.4	703	4 420	1 550	218	346	166	958	21	6	254	1 760	1 000	1	34	0.05	0.2
CS8D	82637	08.05.86	8.5	463	2 820	948	235	184	119	628	21	6	275	938	742	2	42	0.05	0.3
CS9S	82622	04.04.86	7.2	135	700	170	60	22	28	198	8	2	73	369	14	1	27	0.15	0.1
CS91	82621	04.04.86	7.5	335	1 860	476	250	105	52	154	14	2	305	900	74	1	48	0.34	0.3
CS9D	82620	03.04.86	7.5	370	2 030	527	248	114	59	556	16	2	302	1 000	77	1	53	0.25	0.2
CS10D	82603	25.02.86	7.4	295	1 570	281	45	12	61	486	8	2	55	850	83	1	41	0.22	0.2
CS11S	82594	29.06.87	7.4	169	910	327	214	80	31	223	4	2	261	385	41	1	11	0.04	0.4
CS11D	82593	30.06.87	7.2	3 330	22 300	5 170	168	717	822	6 480	154	2	205	12 300	1 670	1	12	0.40	0.1
CS12D	82592	10.04.85	7.3	91	530	186	235	58	10	136	3	2	287	146	18	1	16	0.02	0.3
CS14S	82616	10.04.85	7.7	63	390	69	162	16	7	119	5	2	198	84	35	1	24	0.18	0.1
CS14M1	82615	10.04.85	8.4	150	810	257	198	62	25	201	8	6	229	324	37	1	30	0.37	0.1
CS14M2	82614	10.04.85	8.4	172	920	296	205	71	29	229	9	9	232	380	43	1	35	0.38	0.2
CS14D	82613	28.03.85	8.1	171	940	289	207	68	29	232	10	21	253	402	39	1	35	0.28	0.2
CS15S	82619	28.03.85	11.0	166	860	65	55	26	1	275	32	12	2	420	65	1	31	(a)1.00	0.1
CS15M	82618	28.03.85	9.6	157	820	56	30	16	4	271	27	6	24	420	57	1	10	(a)1.40	0.1
CS15D	82617	28.03.85	8.0	121	680	203	198	40	25	158	33	2	241	239	36	1	24	0.11	0.2
CS17D	82591	29.05.85	7.8	84	460	235	202	53	25	84	3	2	247	133	25	3	11	0.05	0.5
CS18D	82589	10.12.86	7.9	100	600	187	265	52	14	178	3	2	323	143	29	1	19	0.03	<0.1
CS19D	82590	11.12.86	8.0	139	770	280	216	81	19	173	5	2	64	303	29	1	28	0.01	0.2
CS20S	82584	02.12.86	7.0	143	810	173	128	20	30	278	7	2	256	346	31	1	23	0.01	0.3
CS20D	82583	02.12.86	8.5	168	940	246	213	51	29	257	16	2	250	388	48	1	30	0.04	0.2
CS21D	82601	08.03.85	8.2	106	620	160	155	33	19	155	11	2	189	222	35	1	45	0.05	0.2
CS23D	82580	11.09.86	7.8	81	430	252	209	63	23	64	2	2	255	118	18	5	9	0.08	0.4
CS25S	82579	08.03.85	7.8	181	930	217	169	44	26	264	6	2	206	426	38	1	20	0.05	0.3
CS25D	82578	11.09.86	7.3	229	1 200	320	254	79	30	50	6	2	310	542	36	1	23	0.11	0.1
CS26S	82568	11.09.86	6.8	42	240	26	38	2	5	75	2	2	46	99	8	1	22	0.05	0.1
CS26D	82567	11.09.86	6.9	99	560	26	91	4	4	200	2	2	111	238	27	1	26	0.12	0.1
CS27D	82502	11.09.86	7.2	207	1 080	203	28	9	44	324	9	2	34	582	48	1	50	0.08	0.2
CS28D	82575	14.02.86	7.6	399	2 170	519	295	105	77	590	16	2	360	1 040	140	6	12	0.28	0.4
CS29S	82586	29.08.86	7.9	62	350	214	154	61	15	36	4	2	188	83	20	12	22	0.04	0.4
CS29D	82585	27.09.86	8.0	128	690	248	220	60	24	162	7	2	269	249	25	6	20	0.11	0.4
CS30S	82574	27.09.86	8.0	500	2 740	801	285	115	125	735	20	2	348	1 410	127	1	30	0.17	0.3
CS30D	82573	23.07.86	7.7	1 300	7 510	1 340	361	148	236	2 380	84	2	441	4 020	402	5	14	0.31	0.3
CS31S	82582	23.07.86	6.5	213	1 170	274	22	24	52	312	13	2	27	476	246	1	36	0.04	0.1
CS31D	82581	25.11.86	6.6	164	880	153	52	15	28	266	10	2	64	431	68	1	27	0.03	0.1
CS32D	82605	25.11.86	6.5	467	2 370	218	502	43	27	1 310	11	2	613	170	500	1	3	0.52	0.5

Table 3. *(continued)*

Bore	Sample no.	Date sampled	pH	Conduct. mS/m (at 25 °C)	TDS mg/L (Calc at 180° C)	Total hardness (as $CaCO_3$)	Total alkalinity (as $CaCO_3$)	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	SiO_2	B	F
								mg/L											
CS33D	82572	21.02.85	8.0	148	760	272	185	68	25	181	5	2	226	325	33	3	9	0.08	0.1
CS34S	82588	05.09.86	7.8	152	780	333	195	89	27	160	4	2	238	317	37	3	24	0.03	0.1
CS34D	82587	27.11.86	7.9	199	1 020	275	281	96	33	244	7	2	343	412	39	1	20	0.10	0.2
CS35S	82571	27.11.86	6.6	99	530	161	30	30	21	125	7	2	36	234	62	6	25	0.06	0.1
CS35D	82570	28.07.86	7.0	278	1 450	302	164	27	57	440	13	2	200	762	28	3	20	0.15	0.2
CS36S	82569	28.07.86	7.1	688	3 820	544	159	60	96	1 260	27	2	194	2 070	182	1	25	0.34	0.2
CS37D	82568	24.07.86	6.6	69	360	55	15	4	11	108	4	2	18	176	24	7	21	0.05	0.1
CS37D	82567	24.07.86	6.6	49	260	36	20	3	7	70	9	2	24	123	14	1	25	0.05	0.1

(a) High values of pH and boron are attributed to contamination from cement slurry.

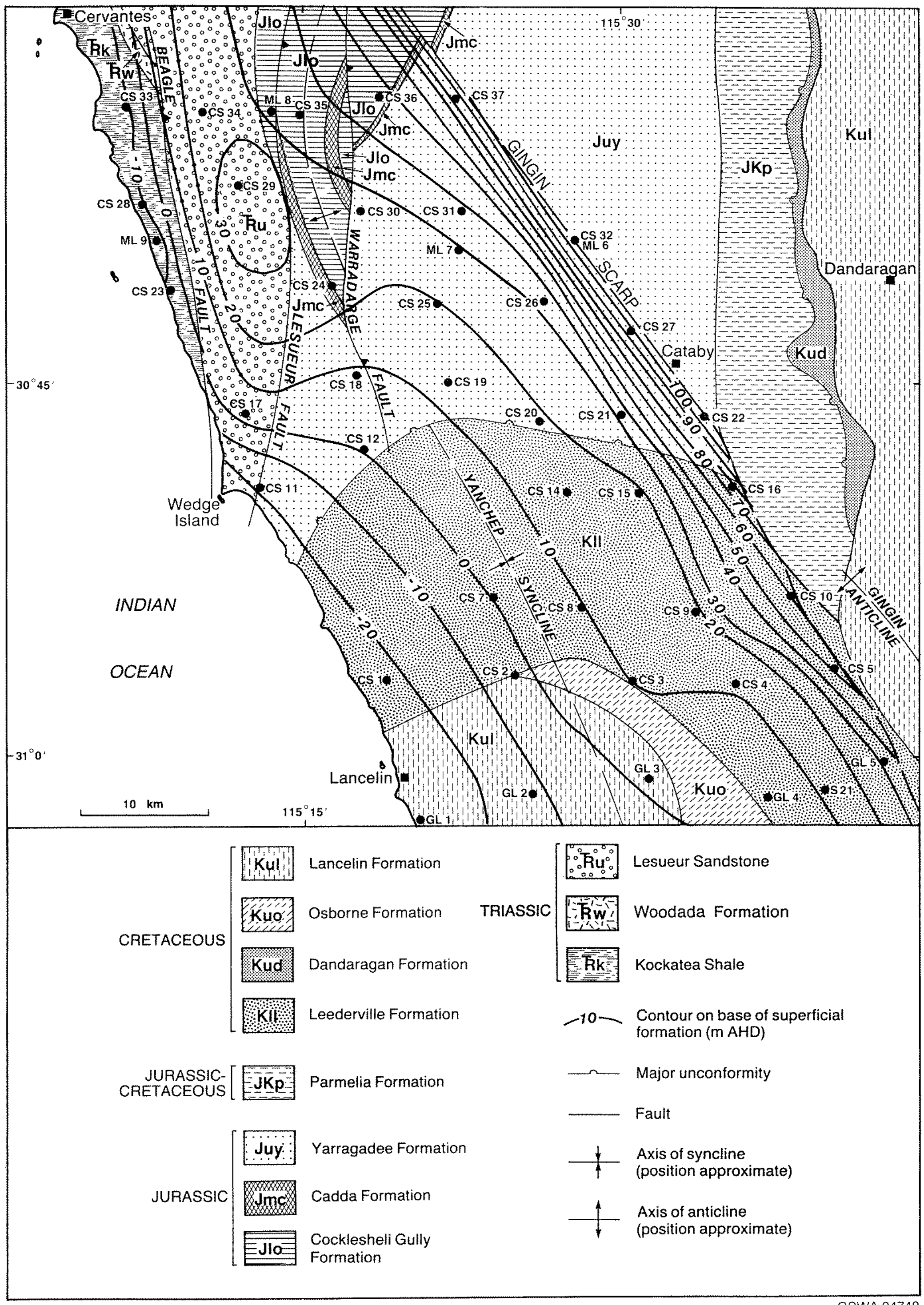


Figure 5. Mesozoic geology, and structure contours on base of superficial formations

interbedded siltstone and shale. The sediments are characteristically multicolored red, yellow, brown, pink, purple, grey and white.

The upper Cattamarra Member was intersected at two sites, and is composed of shale at site CS24 and siltstone at site CS36. The siltstone is in part carbonaceous and contains seams of coal up to 0.6 m thick.

The Cockleshell Gully Formation is believed to be a continental fluvial deposit. The formation is dated palynologically as being of Early Jurassic age.

Yarragadee Formation

The Yarragadee Formation was intersected at fourteen sites. It consists mainly of poorly sorted sandstone with very coarse to very fine subangular to subrounded quartz grains. The sediments are light to dark grey and along the Gingin Scarp are weathered to yellow and pink. At site CS11, the uppermost 59 m of the formation consists of cross-bedded sandstone.

The Yarragadee Formation is interpreted to be a continental fluvial deposit laid down during the main period of Mesozoic movement along the Darling Fault. Spores and pollen indicate a Middle to Late Jurassic age.

Leederville Formation

The Leederville Formation was intersected at 12 sites and consists of sandstone, siltstone, and shale. The sandstone is medium grey with coarse to very fine, angular to subangular, poorly to well-sorted quartz grains. The siltstone varies from light grey to dark grey and is commonly micaceous and slightly carbonaceous. The shale is medium grey to black and also contains mica and carbonaceous material.

The Leederville Formation is interpreted as a non-marine to near-shore depositional unit. Spores and pollen indicate a Valanginian to Early Aptian age.

Laterite and associated sands

Laterite and associated sands were intersected at site CS32 where they are developed on top of the weathered Yarragadee Formation. They are considered to be of Late Oligocene to Early Miocene age (Schmidt and Embleton, 1976).

Ascot Formation

The Ascot Formation rests unconformably on the Yarragadee Formation in the northern half of the project area, and on the Leederville Formation in the south. The unit appears to interfinger with the Yoganup Formation along the Gingin Scarp; elsewhere it is overlain unconformably by the Guildford Formation.

Baxter and Hamilton (1981) suggested that the Ascot Formation is a facies equivalent of the Yoganup Formation and they show that there are complex interrelationships between the two units at Cooljarloo, about 20 km northwest of Cataby. The sequence is a barrier sand with carbonate and siliceous facies, which are referred to as Ascot Formation and Yoganup Formation respectively.

The Ascot Formation was intersected at ten sites along a subsurface northwest-trending ridge parallel to the Gingin Scarp (Fig. 7). The thickness is variable as a result of post-Pliocene erosion. The sediments reach a maximum thickness of 29 m at site CS15, but are usually 10–20 m thick. The unit is characterized by buff to light-grey, coarse- to medium-grained calcarenite interbedded with sand. The calcarenite is friable to hard and contains a variable amount of quartz sand. The sand is characterized by a rich molluscan fauna and abundant spicules and foraminifera. A basal bed containing phosphate nodules and phosphatized fossils was intersected at three sites (CS4, CS19 and CS25).

The Ascot Formation is a marine calcarenite deposited in a sub-littoral inner shelf environment at a time of low supply of terrigenous sediments. The molluscan fauna and the microflora indicate a Pliocene age for the unit (Kendrick, 1981, 1986 pers. comm.; Kern, 1988a).

Yoganup Formation

The Yoganup Formation, which occurs at the foot of the Gingin Scarp, unconformably overlies sediments of the Yarragadee and Leederville Formations, and may interfinger with the Ascot Formation. It is overlain by the Guildford Formation.

The Yoganup Formation was identified at six boresites. It is 20 m thick at site CS10 but elsewhere is generally less than 10 m thick. The unit consists of buff to light-grey, coarse to fine, subangular to subrounded quartz sand which is clayey in places. Heavy minerals constitute generally less than 2% of the unit, although greater concentrations have been found along the Gingin and Munbinea Shorelines (Baxter, 1977, 1982). The formation is up to 9 km wide, and the base of the unit ranges in elevation from about 30 m AHD to 90 m AHD.

The Yoganup Formation is interpreted as a paralic sequence, the sandy unit being barrier sheets whereas the clay beds may represent interdunal or estuarine deposits (Baxter, 1981). Based on its correlation with the Ascot Formation, the Yoganup Formation is of Pliocene age.

Guildford Formation

The Guildford Formation occurs in the subsurface between the Coastal Belt and the Gingin Scarp. It unconformably overlies the Ascot or Yoganup Formations where these are present; otherwise it overlies Mesozoic strata. The formation is unconformably overlain by the Bassendean Sand and possibly by the Tamala Limestone along the Coastal Belt.

The Guildford Formation was intersected at 23 sites and is typically between 30 and 40 metres thick. A maximum thickness of 53 m was encountered at site CS26. The formation is characterized by both a sandy and a clayey facies, the latter occurring mainly along the Gingin Scarp where it interfingers with the sand facies to the west. The sand is light grey with coarse to fine, subangular to subrounded quartz. Accessory minerals are generally not abundant, although minor heavy minerals and feldspar may occur. The clay is commonly brown to grey and sandy. In some places limonite-cemented sandstone ('coffee rock') is developed at or near the watertable. Its development may be controlled by the presence of permeable zones within the formation.

Most of the unit is of fluvial origin, with estuarine and shallow marine intercalations, especially at the base

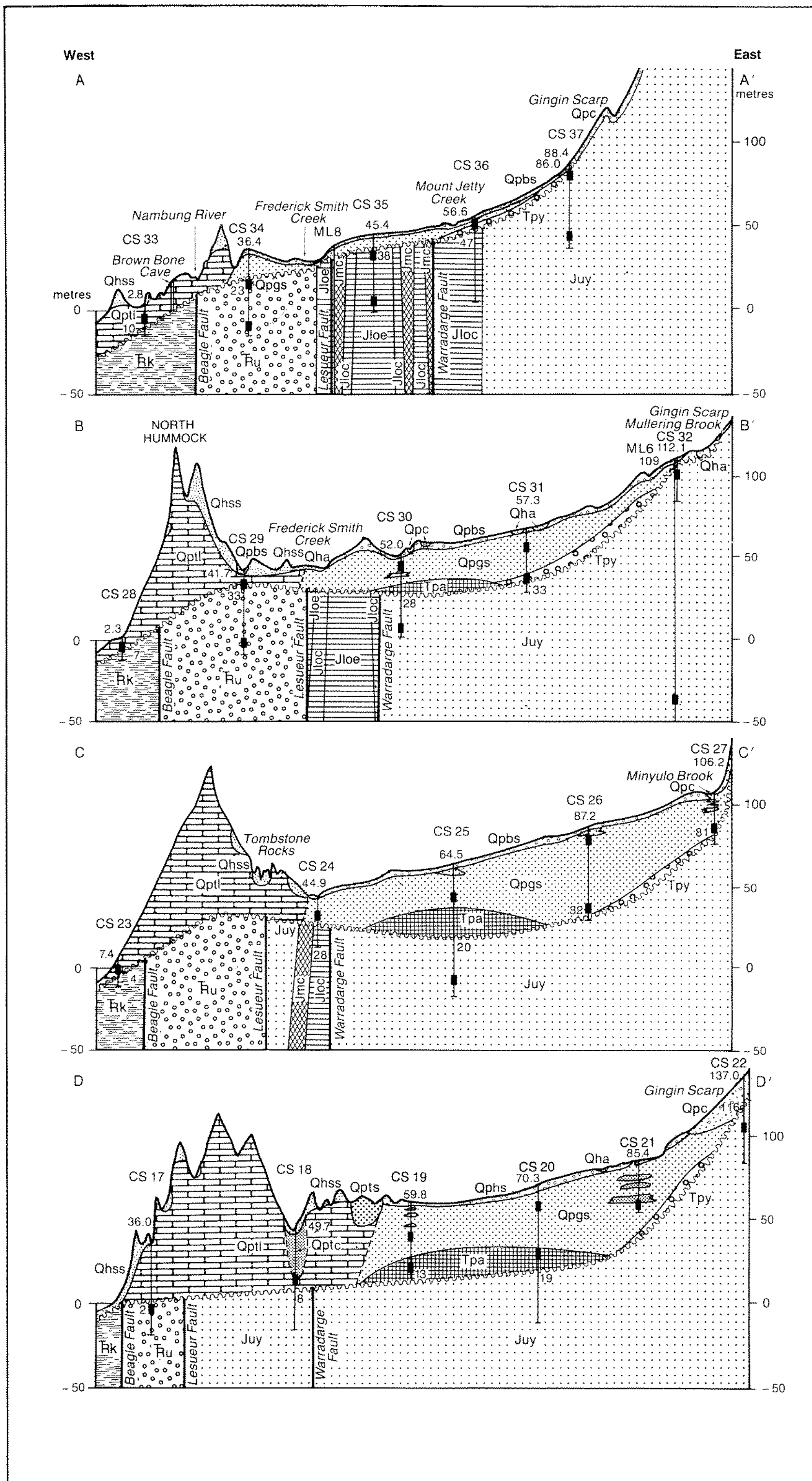
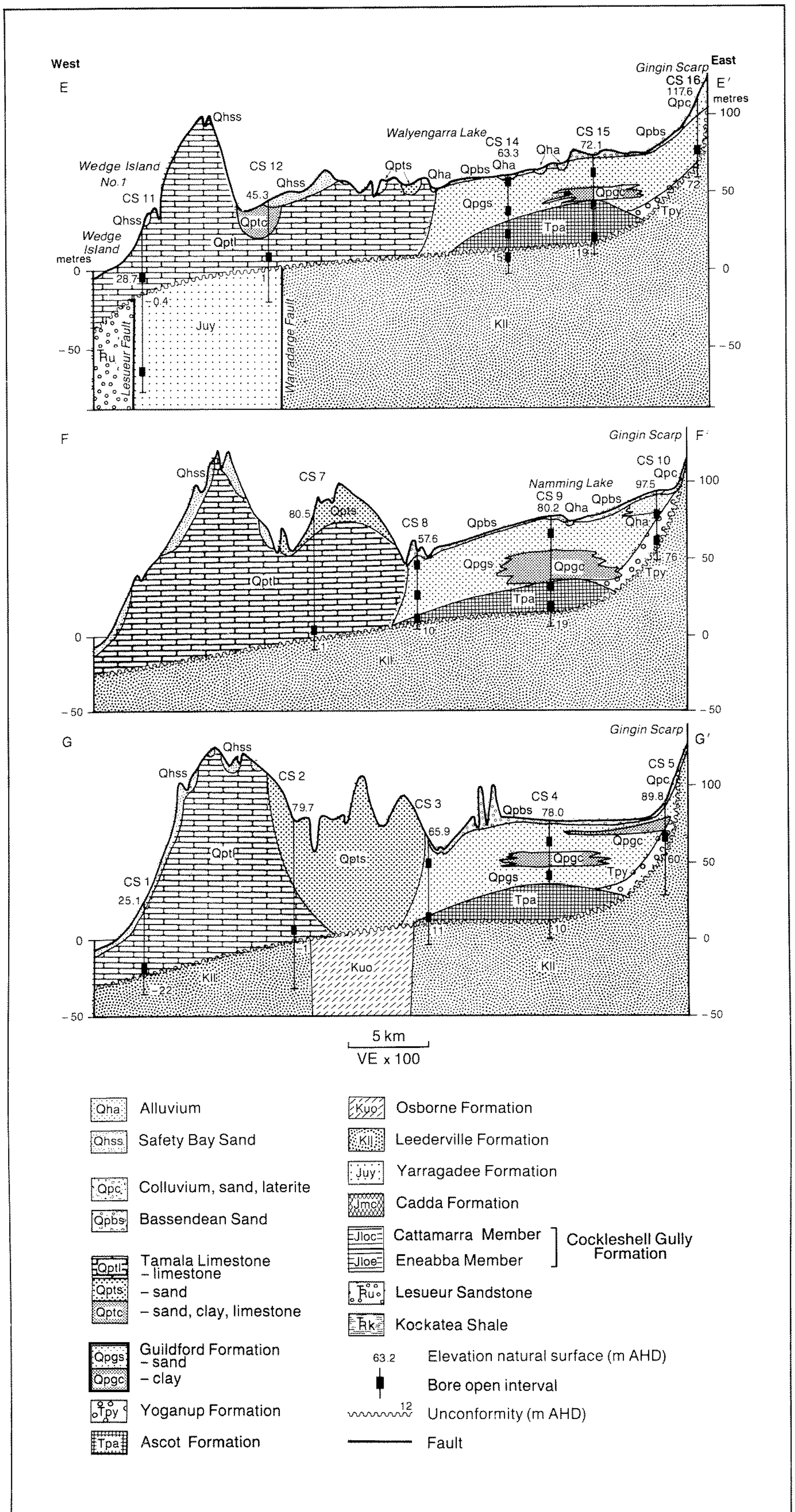


Figure 6. Geological cross sections (see Fig. 4 for locations)


West
East
E
E′
Gingin Scarp
CS 16
117.6
Qpc
metres
100
Qhss
Walyengarra Lake
CS 14
63.3
Qha
CS 15
72.1
Qpbs
Wedge Island No.1
CS 12
45.3
Qhss
Qpts
CS 11
Qhss
Wedge Island
Qptc
Qptl
Qpgs
Qpgc
Tpa
Tpy
28.7
-0.4
Juy
Ru
Lesueur Fault
Yarragadee Fault
Kll
F
F′
CS 7
80.5
CS 8
57.6
Namming Lake
CS 9
80.2
CS 10
97.5
G
G′
CS 1
25.1
CS 2
79.7
CS 3
65.9
CS 4
78.0
CS 5
89.8
Kuo
5 km
VE x 100
Qha Alluvium
Qhss Safety Bay Sand
Qpc Colluvium, sand, laterite
Qpbs Bassendean Sand
Tamala Limestone
Qptl - limestone
Qpts - sand
Qptc - sand, clay, limestone
Guildford Formation
Qpgs - sand
Qpgc - clay
Tpy Yoganup Formation
Tpa Ascot Formation
Kuo Osborne Formation
Kll Leederville Formation
Juy Yarragadee Formation
Jmc Cadda Formation
Jloc Cattamarra Member
Jloe Eneabba Member
Cockleshell Gully Formation
Ru Lesueur Sandstone
Rk Kockatea Shale
63.2 Elevation natural surface (m AHD)
Bore open interval
12 Unconformity (m AHD)
Fault

GSWA 24741

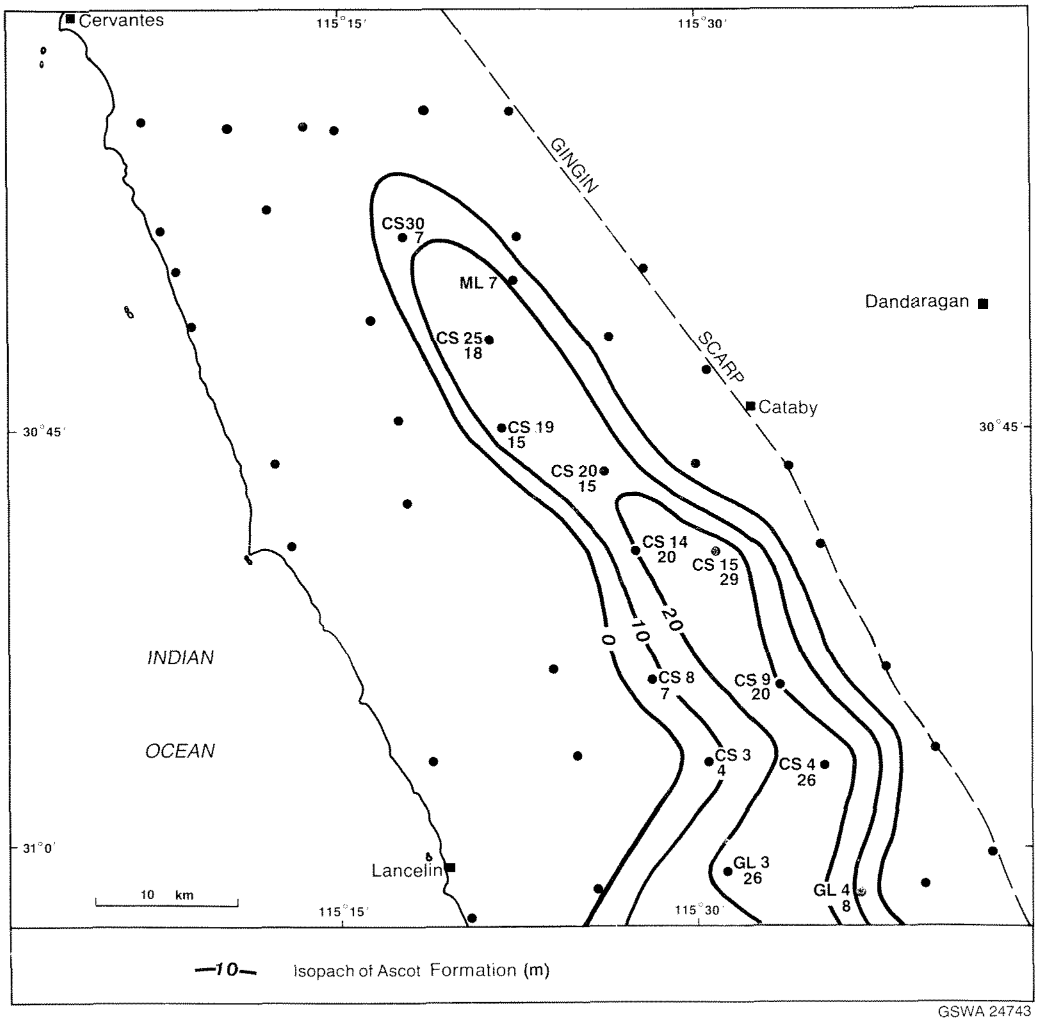


Figure 7. Extent and thickness of the Ascot Formation

(Playford et al., 1976). The fauna and the stratigraphic position suggest a Pleistocene age (Darragh and Kendrick, 1971).

Tamala Limestone

The Tamala Limestone was deposited as coastal sand dunes (lime-sand eolianite) along the Coastal Belt. It unconformably overlies Mesozoic strata and possibly the Guildford Formation along its eastern margin, and is disconformably overlain by the Safety Bay Sand.

The Tamala Limestone outcrops extensively along the coast and adjacent islands. It was intersected at eleven sites. The thickness of the formation varies greatly, depending on the topography. It is probably up to 150 m thick south of the Nambung National Park. Three lithological facies, limestone, sand, and clay were recognized (Figs 5 and 6).

The limestone facies is buff to pale yellow, weathering to grey, and consists of quartzo-calcareous sand commonly cemented into limestone. The carbonate fragments are mainly foraminifers and mollusc shells. Accessory heavy minerals (up to 5%), glauconite, and feldspar occur. The limestone varies from strongly lithified to friable. Hard calcrete horizons (capstone) occur in places and may be overlain by grey to brown fossil soils and underlain by softer limestone with abundant fossil root structures. The formation also shows large-scale eolian cross-bedding.

Well-developed cave systems occur in the limestone at a number of localities in the Nambung National Park, e.g. Brown Bone and Nambung Caves (Figs 1 and 5).

The sandy facies is restricted to the southwest where the Tamala Limestone is commonly leached at the surface, leaving a residue of yellow to white quartz sand (Figs 4 and 6). This can be up to 100 m thick where the limestone facies is absent. The contact between sand and unleached limestone is irregular, and rounded pinnacles of limestone sometimes extend upwards into the sand. At The Pinnacles, near Cervantes, the loose sand has been blown away to expose the limestone pinnacles.

A clayey lacustrine facies consisting of lenticular interbeds of sand, clay and limestone was intersected at sites CS12 and CS18 (Fig. 6).

The Tamala Limestone is of Late Pleistocene age (Playford et al., 1976).

Bassendean Sand

The Bassendean Sand forms the Bassendean Dunes, a series of low sandhills resulting from the reworking of underlying sand units. The formation disconformably overlies the Yoganup and Guildford Formations, and possibly overlaps the eastern edge of the Tamala Limestone.

The Bassendean Sand was intersected at 21 sites where it has an average thickness of 1–2 m. Elsewhere, depending on the topography, it may reach a maximum thickness of about 30 m. The formation consists of light-grey, coarse to fine, subangular to subrounded and moderately sorted quartz with traces of heavy minerals. Thin clay beds may also occur. 'Coffee rock' is commonly developed at or near the watertable.

The Bassendean Sand was deposited as sand dunes at various periods during the Late Pleistocene to Holocene.

Safety Bay Sand

The Safety Bay Sand forms the coastal dune and beach sediments of the Quindalup Dunes. The formation extends discontinuously along the coast and up to 14 km inland, and disconformably overlies the Tamala Limestone. Large mobile dunes occur at Lancelin and in the Nambung National Park.

The Safety Bay Sand was intersected at eight sites where a maximum thickness of 3 m was encountered, although it is thicker elsewhere. Coastal mobile dunes are as much as 100 m above AHD and the base is about 5 m below sea level at the coast.

The formation consists of buff, calcareous, weakly lithified sand. The quartz is medium to fine, angular to rounded and moderately sorted. The calcium carbonate content is generally greater than 50% and includes carbonate grains, foraminifers and mollusc fragments. Traces of heavy minerals also occur.

The Safety Bay Sand is of Holocene age and its deposition is continuing.

Alluvial, colluvial, and swamp deposits

Alluvial deposits occur along the Moore River and, to a lesser extent, along Caren Caren, Minyolo, and Mullering Brooks. Sandy alluvial deposits about 12 m thick were intersected at site CS10. They consist of buff to grey, coarse- to fine-grained, subangular to subrounded quartz.

Colluvial deposits occur along the Gingin Scarp and consist of gravel, sand, silt, clay, and laterite derived from the laterite-capped Arrowsmith Region and Dandaragan Plateau. These deposits were intersected at site CS16.

Holocene lake and swamp deposits are common in the Bassendean Dunes, where numerous fresh to saline lakes occur, and to a lesser extent in the Spearwood Dunes. They include various clay, sand, peat, marl and diatomaceous deposits and rarely exceed 3 m in thickness.

Hydrogeology

Flow system

The superficial formations are considered to constitute a single aquifer containing a mainly unconfined groundwater flow system. Significant variations occur within the system owing to the differences in hydraulic conductivities of the Guildford Formation and Tamala Limestone. The groundwater flow system is bounded to the west by the Indian Ocean and to the east by the limit of superficial formations along the Gingin Scarp. The area covered in this paper extends from the Moore River in the south to the Nambung River in the north. Along the Gingin Scarp, there are hydraulic connections between the superficial formations and the adjacent Mesozoic formations to the east.

Groundwater flow in the superficial formations is generally in a westerly direction. Downward leakage from the flow system is thought to be significant in the eastern part of the coastal plain from the Guildford and Ascot Formations into the underlying Mesozoic aquifers. Upward leakage, by discharge from the Mesozoic aquifers into the flow system, takes place in the coastal area and in the northeast (Figs 8 and 9). Upward leakage also occurs from the Yarragadee Formation in the northeast where the Warradarge Fault acts as a hydraulic barrier to westward groundwater movement below the superficial formations. In the southwest and northwest, where the superficial formations overlie the impermeable Coolyena Group and Kockatea Shale respectively, there is no leakage from or into the flow system.

The saturated thickness of the superficial formations varies substantially in the area. It exceeds 50 m in the southeast, and decreases northward to less than 10 m in the Nambung River area and toward the coast (Figs 8 and 10). The superficial formations are unsaturated east of Grey where the watertable is in the Lesueur Sandstone (Figs 10 and 11).

Watertable configuration

The watertable slopes westwards from the Gingin Scarp toward the sea where groundwater discharge occurs. The watertable contours are sub-parallel to the coast and the predominant flow directions are to the west and southwest (Fig. 11).

In the Bassendean Dunes, the watertable is generally close to the surface and numerous lakes and swamps occur in interdunal depressions (Fig. 8). The watertable in the Tamala Limestone is generally deep and unrelated to the topography of the Coastal Belt.

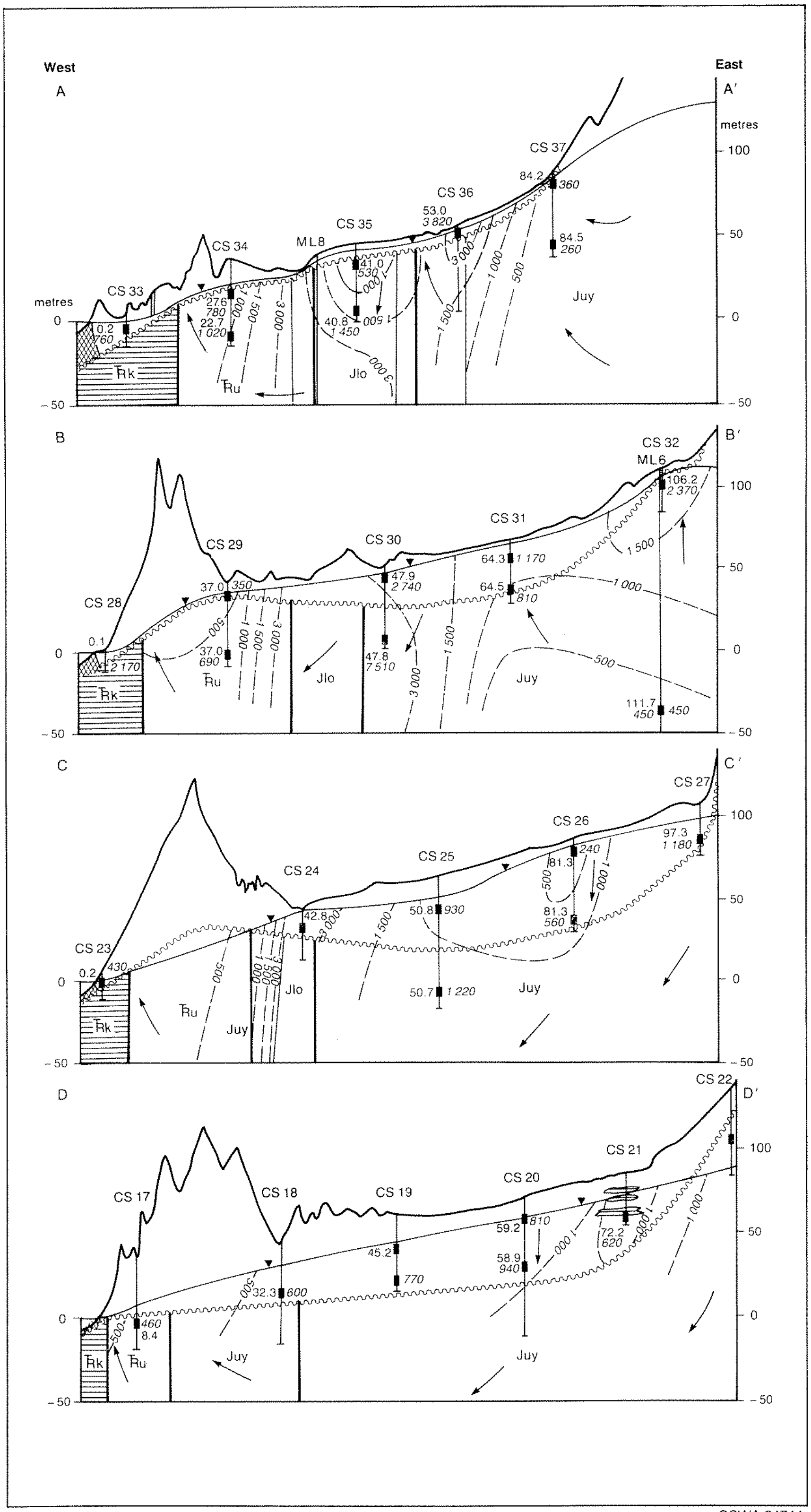
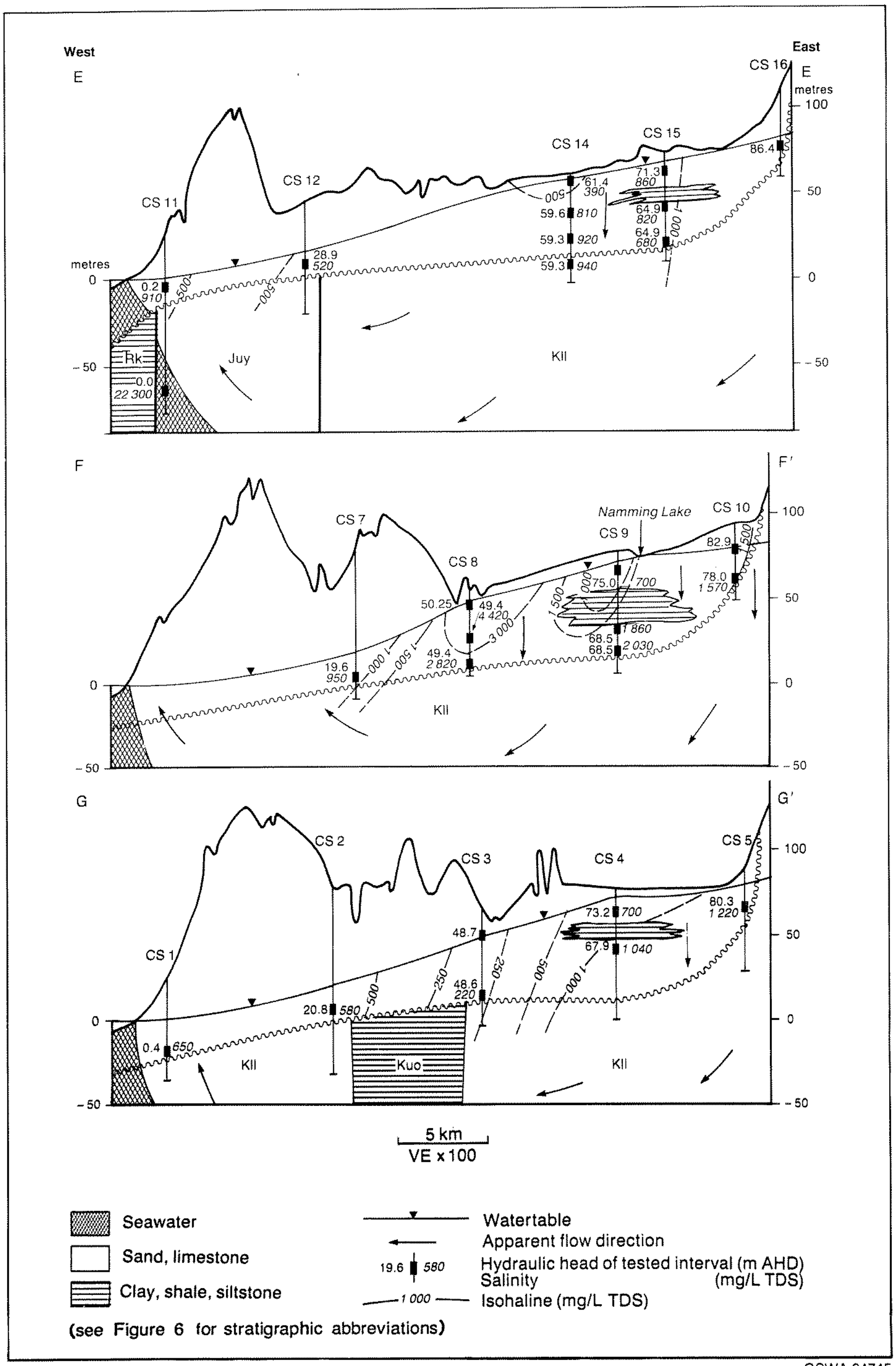


Figure 8. Hydrogeological cross sections (see Fig. 4 for locations)



GSWA 24745

12245—3

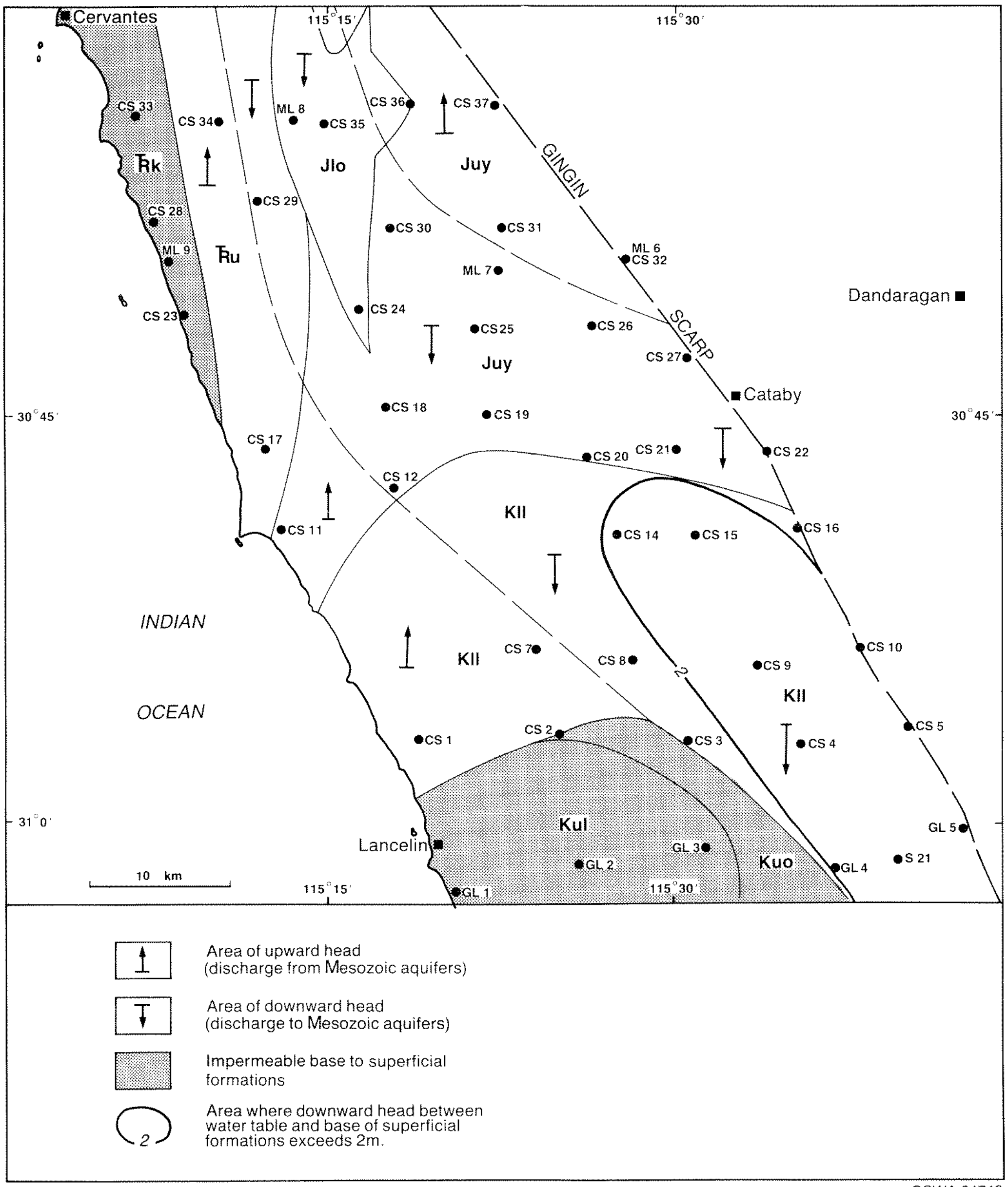


Figure 9. Hydraulic-head difference between superficial formations and underlying Mesozoic aquifers

The level of the watertable in the Guildford Formation is controlled mainly by the land surface and the aquifer is maintained in a virtually full condition. Any excess recharge is accounted for by increased transpiration and evaporation from swamps. The hydraulic gradient in the Guildford Formation is controlled mainly by the slope of the land surface. At the contact of the Guildford Formation with the Tamala Limestone there is a sharp increase in the hydraulic gradient which is due largely to contrasting hydraulic conductivities, but possibly also to a zone of subsurface seepage caused by the karstic nature of the Tamala Limestone. The hydraulic gradient is very low along the coast between Wedge Island and Lancelin, reflecting the high transmissivity of the Tamala Limestone.

Recharge

Recharge to the superficial formations is mainly by direct infiltration of rainfall and associated runoff. There is only episodic recharge from streams originating on the Dandaragan Plateau and Arrowsmith Region as these do not flow during the whole year. When the Nambung River is active it recharges the groundwater system via caves near the coast.

There is recharge by upward leakage from the Mesozoic aquifers in the northeast and the coastal area. At site CS32 (ML6) there is an upward hydraulic head gradient of 5.5 m over 140 m in the top of the Yarragadee Formation (Figs 8 and 9). Along the coast where

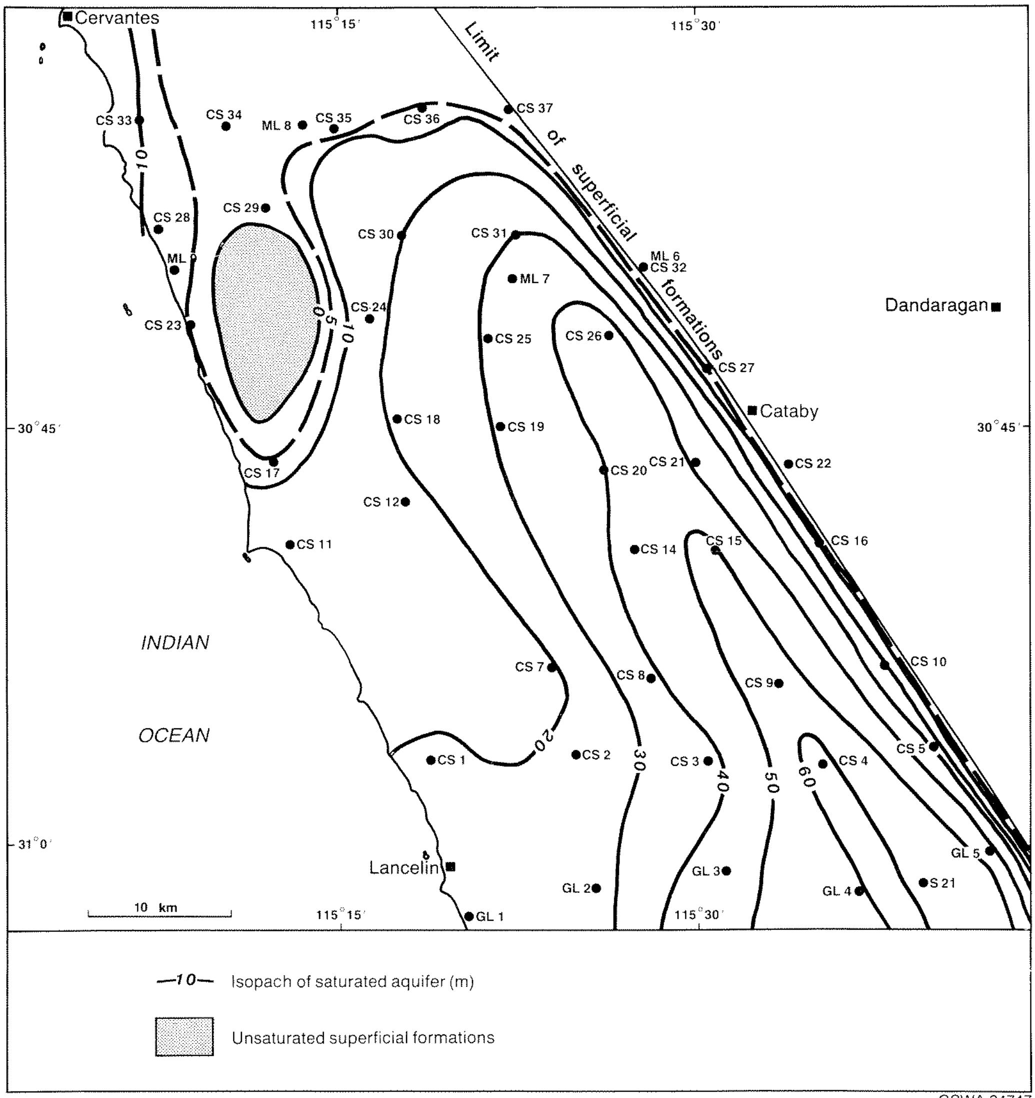


Figure 10. Superficial formations: saturated aquifer thickness

the Lesueur Sandstone, Yarragadee and Leederville Formations subcrop beneath the superficial formations there is also potential for upward leakage. This is due to regional groundwater discharge along the coast and a hydraulic barrier formed by the impermeable Kockatea Shale.

Recharge to the aquifer varies according to seasonal rainfall. In 1985 rainfall was well below average, whereas in the following two years there was near-average rainfall (Kern, 1988a). Lower watertable levels reflected the low rainfall in 1985 but recovery followed the increased precipitation of the succeeding years (Fig. 12). Recharge also varies spatially, depending upon landuse, vegetation cover, and depth to the watertable.

There is considerable variation in the response of waterlevels to winter rainfall. The waterlevels in the Guildford Formation respond quickly to rainfall and are highest in September–October and lowest in March–April with a typical seasonal range of 0.3–1.7 m. The largest seasonal changes of over 1 m occur in the wetlands southwest of Cataby (Figs 2 and 12). Smaller waterlevel variations occur where the flow system is confined by beds of clay and where the aquifer is in downward hydraulic connection with the Leederville Formation (CS15I and CS15D on Fig. 12). The smallest seasonal fluctuation of less than 0.2 m occurs in the Tamala Limestone.

Recharge can also occur from summer rainfall, and a waterlevel rise was recorded in bore CS14S in March 1986 following heavy rainfall in February of that year (Fig. 12).

Net recharge contributing to groundwater flow, expressed as a percentage of rainfall, can be estimated from the ratio of the concentration of chloride ions in rainfall (input) with the minimum concentration in groundwater. The lowest chlorinities averaged 94 mg/L and were recorded at bores CS3D, CS14S and CS26S where recharge is solely by rainfall. The chloride

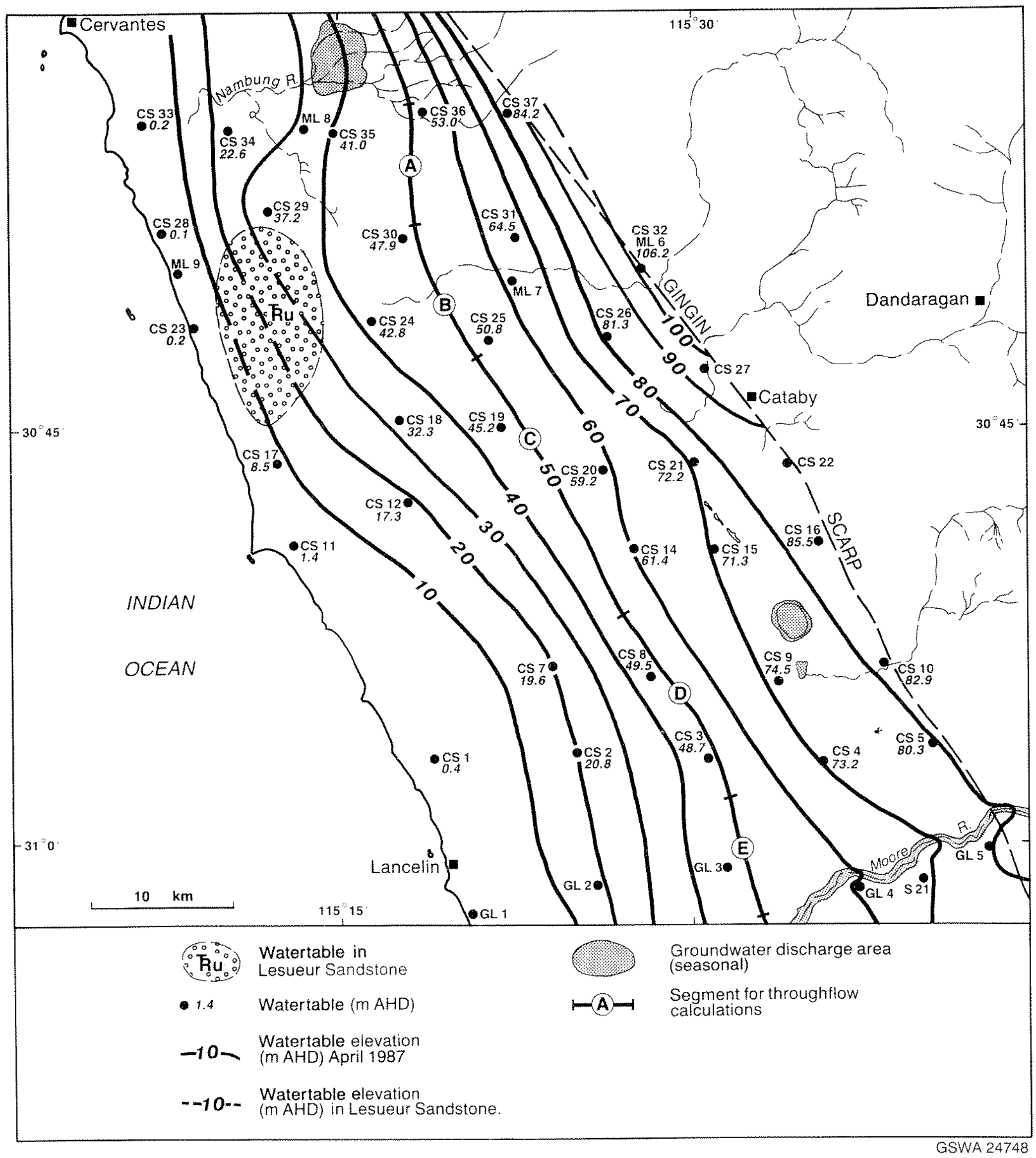


Figure 11. Watertable contours in the superficial formations

concentration in rainfall recorded at Boothendarra, about 30 km north of Cataby, was approximately 7.8 mg/L (Hingston and Gailitis, 1977), which matches the long-term mean annual chloride concentration in rainfall (7.5 mg/L) on the Gnangara groundwater mound to the south (Farrington and Bartle, 1988). From the chloride ion ratio the rainfall recharge is estimated to be 8% of average annual rainfall. Using the same method, a recharge rate of about 7% was determined for the area to the south (Moncrieff and Tuckson, 1989).

The extent of recharge from streams draining the Gingin Scarp seems to be minor since there is no marked effect on the watertable contours (Fig. 11).

Throughflow

The westward groundwater flow through the superficial formations in the Bassendean Dunes area (about 800 km^2) has been calculated, using the Darcy equation, as 44 x 10^6 m^3/year (Kern, 1988a).

The hydraulic conductivity and hydraulic gradient are difficult to establish for the Tamala Limestone owing to its karstic nature. However, the throughflow at the coast resulting from recharge over the Coastal Belt (about 1200 km^2) can be calculated from chloride data using a recharge rate of about 7.5% of average rainfall. This

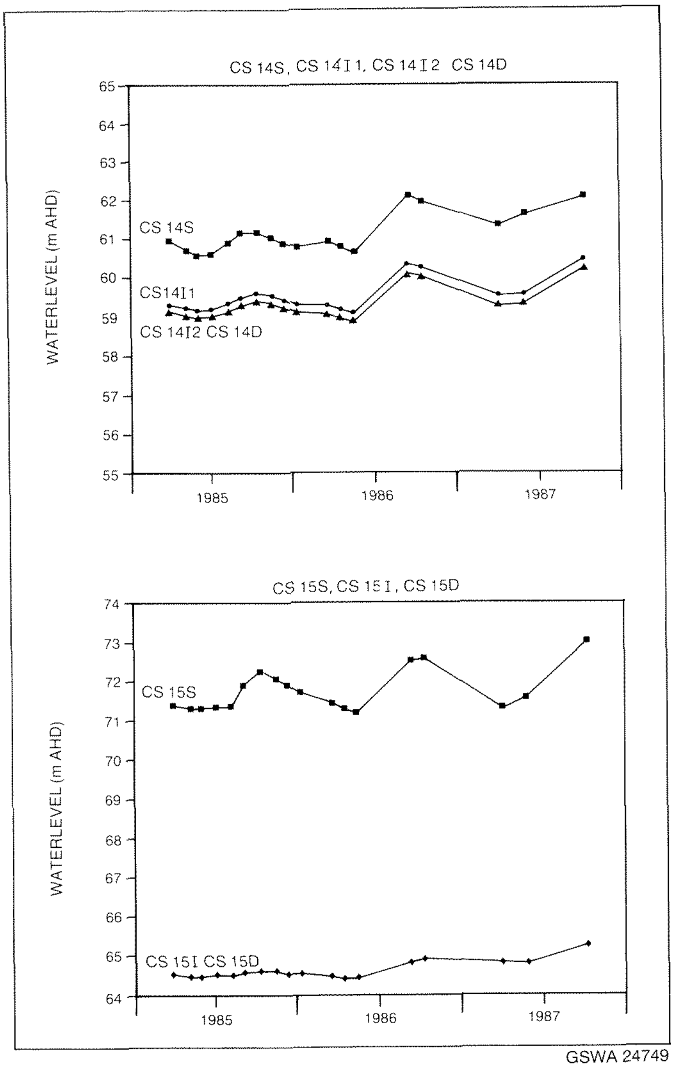


Figure 12. Selected bore hydrographs

gives a throughflow of about 55.6 x 106 m^3/year for the Coastal Belt.

Therefore, the total outflow at the coast between Cervantes and Lancelin is estimated to be 100 x 10^6 m^3/year. These figures are probably conservative because no account is taken of upward leakage from the Mesozoic aquifers.

Discharge

Groundwater discharge occurs mainly along the shoreline above a saltwater wedge. The interface between fresh groundwater and the seawater wedge was intersected at sites CS11 and CS28. The watertable contours on Figure 11 imply seasonal groundwater discharge to the Moore River in the Regans Ford area and also to the Nambung River north of CS35. Discharge by evapotranspiration also occurs in the Bassendean Dunes where the watertable is shallow. The numerous lakes and swamps, as well as phreatophytic vegetation, also give rise to significant groundwater losses.

The maximum head difference between the watertable and the underlying Mesozoic formations occurs in the southeast where the saturated aquifer thickness exceeds 50 m in conjunction with the thickest section of clay in the Guildford Formation (Fig. 8). This difference reaches 6.5 m at site CS15. The substantial downward hydraulic gradient in the southeast implies that significant discharge may occur by leakage into the underlying Leederville Formation.

Storage

The volume of the saturated sediments in the project area is estimated to be 50 x 10^9 m^3. Most of the sediments are sand and limestone with the clay of the Guildford Formation constituting less than 3%. The specific yield is assumed to be 0.2, as for similar sediments in the Perth area (Cargeeg et al., 1987). Consequently the volume of groundwater in storage in the project area is about 10 x 10^9 m^3. Assuming a recharge rate of 8% of average annual rainfall (620 mm), this figure represents about 100 years of recharge over the whole project area (2000 km^2).

Groundwater quality

Salinity

Superficial formations

The variation in groundwater salinity at the watertable is shown in Figure 13. The pattern of vertical groundwater salinity variation is shown in the hydrogeological cross sections (Fig. 8).

The groundwater salinity is less than 1000 mg/L total dissolved solids (TDS) in two-thirds of the area. The salinity is lowest in the Coastal Belt, and this probably results from additional recharge from rainfall with the deep watertable in the area preventing evapotranspirative losses.

Local areas with groundwater salinity greater than 1000 mg/L occur along the Gingin Scarp where the Guildford Formation is clayey, and in areas with numerous lakes and swamps where the watertable is shallow. Brackish groundwater is also found along drainage lines. The salinity exceeds 3000 mg/L in both the vicinity of Frederick Smith Creek and the upper section of the Nambung River where there is seasonal groundwater discharge.

The configuration of the isohalines generally demonstrates the effects of evapotranspiration from lakes and swamps. Monitoring of major lakes has shown that the water ranges from fresh to saline. Lake Guraga has an exceptionally high salinity, as much as 30 000 mg/L toward the end of summer (Fig. 3). Plumes of higher salinity groundwater are believed to extend downgradient from the lakes, with a plume at the base of the aquifer observed at boresite CS9 (Fig. 8). In the

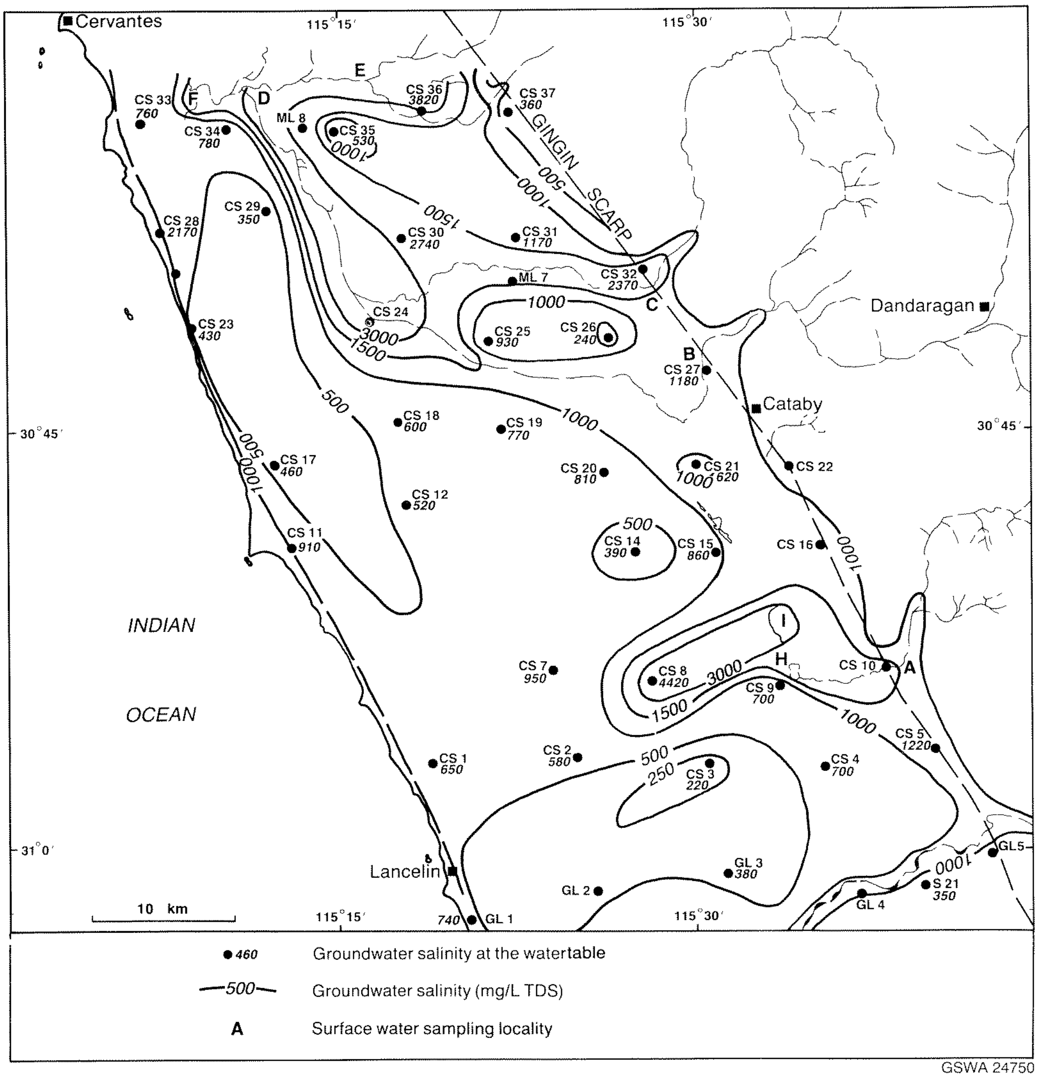


Figure 13. Groundwater salinity at the watertable

southeast, where there is a substantial downward hydraulic gradient, this higher salinity groundwater is likely to recharge the Leederville Formation. The highest groundwater salinities (in excess of 3000 mg/L) were recorded at boresites CS8, CS24, and CS36 which are situated in extensive swamplands.

The regional salinity pattern is also controlled by drainages which contribute brackish water from the flushing of salinized areas east of the Gingin Scarp.

Mesozoic formations

The quality of the groundwater in the Yarragadee Formation also ranges from fresh to saline. The salinity increases upward at site CS32 where there is also upward groundwater discharge (Fig. 8). There is a significant increase in salinity in the Yarragadee Formation westward toward the Warradarge Fault where there is downward leakage of saline groundwater from the superficial formations. The groundwater salinity reaches 7510 mg/L in bore CS30D.

Most of the Cockleshell Gully Formation contains brackish groundwater. This is due to the low permeability of the interbedded siltstone and shale, and also to recharge by brackish water from the overlying superficial formations.

The groundwater salinity in the Lesueur Sandstone is generally low except along the Lesueur Fault where there is leakage of saline groundwater from the Cockleshell Gully Formation, and seasonal recharge from Frederick Smith Creek. The coastal seawater wedge was penetrated in the Lesueur Sandstone in bore CS11D, but fresh groundwater was encountered in the superficial formations in bore CS23D, only 200 m from the coast.

Hydrochemistry

Chemical analyses of the groundwater are given in Table 3 and are plotted in Figure 14.

The trilinear diagram (Fig. 14) indicates that the groundwater chemistry is mainly of the sodium

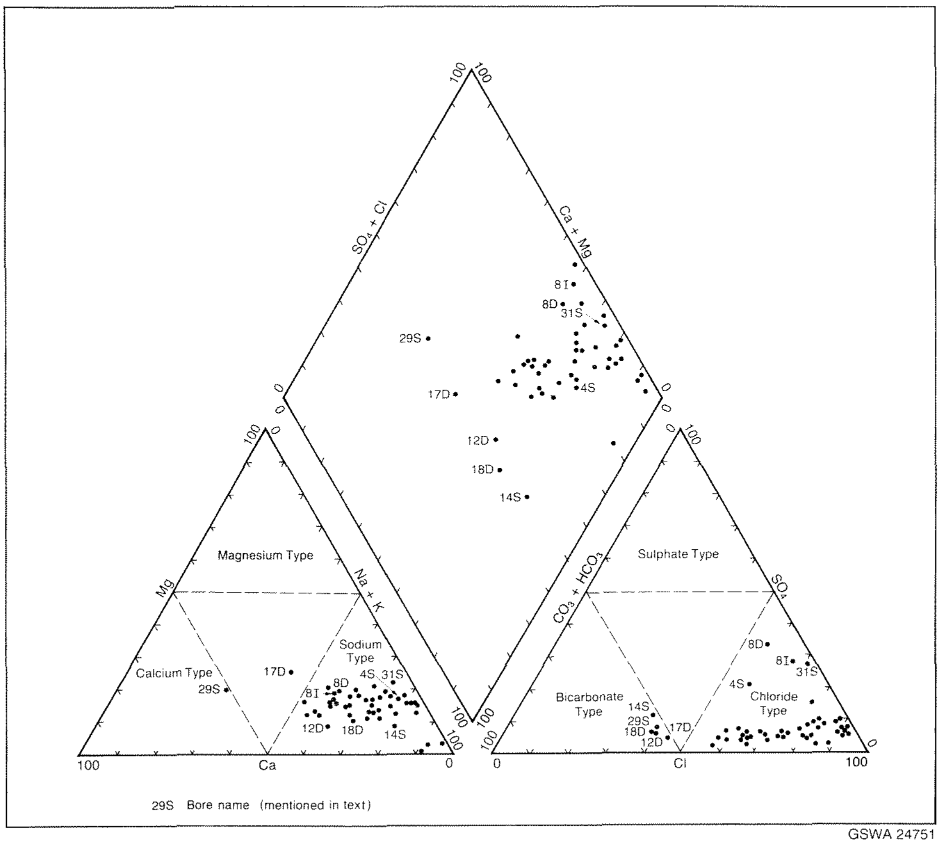


Figure 14. Piper trilinear diagram

bicarbonate to sodium chloride type. High chloride proportions coincide with higher salinity, whereas the proportions of bicarbonate are more significant in lower salinity water (CS14S and CS17D) and also in the Tamala Limestone (CS12D, CS18S and CS29S).

Sulfate concentration exceeds 20% of the total anions in bores CS4S, CS8I, CS8D and CS31S. This is likely to have resulted from oxidation of the abundant organic matter in the wetland soils.

Nitrate content is generally low but several high values, with a maximum of 12 mg/L (CS29S), may indicate groundwater contamination. Silica attains fairly high values (up to 62 mg/L) compared with values from the area to the south (Moncrieff and Tuckson, 1989). Boron and fluorine values are generally lower than 1.0 and 0.5 mg/L respectively and lie within normal background concentrations.

The groundwater pH is neutral with values ranging from 6.5 to 8.5. It is very slightly alkaline in the Ascot Formation and Tamala Limestone.

The similarity between the chemical compositions of the groundwater in the superficial formations and in the underlying Mesozoic aquifers confirms that these are in close hydraulic connection.

Conclusions

The drilling has shown that the superficial formations thin to the north from a thickness of some 50 m near the Moore River to less than 10 m near the Nambung River. The drilling has also defined the northern extent of both the Ascot and the Leederville Formations beneath the Swan Coastal Plain, and the subcrop of Triassic and Jurassic formations.

Groundwater in the unconfined superficial formations in the Coastal Belt area has a salinity of less than 1000 mg/L. However, the salinity ranges from 250 to 3850 mg/L in the Bassendean Dunes area where the watertable is shallow. The highest salinities were recorded in bores located in extensive swamplands and in the vicinity of drainage lines.

The groundwater storage of the superficial formations is estimated to be about 10 x 10^9 m^3, two-thirds of which is fresh with a salinity less than 1000 mg/L. The total outflow of fresh groundwater at the coast is estimated to be 100 x 10^6 m^3/year. The major groundwater resources occur in the southeast, between Caren Caren Brook and the Moore River, where the saturated thickness in the superficial formations is about 50 m and the salinity lies between 500 and 1000 mg/L.

References

ALLEN, A. D., 1976, Outline of the hydrogeology of the superficial formations of the Swan Coastal Plain: Western Australia Geological Survey, Annual Report 1975, p. 31–42.

BAXTER, J. L., 1977, Heavy mineral sand deposits of Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 10, 148p.

BAXTER, J. L., 1981, Geology of mineral sand deposits in Western Australia, *in* Selective reference papers for mineral-sand mining: Western Australia School of Mines, WAIT-AID Ltd, Perth.

BAXTER, J. L., 1982, History of mineral sand mining in Western Australia, *in* Reference papers; Exploitation of mineral sands: Western Australia School of Mines, WAIT-AID Ltd, Perth.

BAXTER, J. L., and HAMILTON, R., 1981, The Yoganup Formation and the Ascot Beds as possible facies equivalents: Western Australia Geological Survey, Annual Report 1980, p. 42–43.

BIRD, K. J., and MOYES, C. P., 1971, Walyering No. 1 well completion report: West Australian Petroleum Pty Ltd; Petroleum Search Subsidy Acts (P.S.S.A.) Report (unpublished); Western Australia Geological Survey, S-series Open File, microfilm roll 6.

BRIESE, E. H., 1979, The geology and hydrogeology of the Moora borehole line: Western Australia Geological Survey, Annual Report 1978, p. 16–22.

CARGEEG, G. C., BOUGHTON, G. N., TOWNLEY, L. R., SMITH, G. R., APPLEYARD, S. J., and SMITH, R. A., 1987, Perth water balance study: Western Australia Water Authority, v. 1–2.

DARRAGH, T. A., and KENDRICK, G. W., 1971, *Zenatiopsis ultima* sp. nov., terminal species of the *Zenatiopsis* lineage (Bivalvia: Mactridae) with notes on its stratigraphic significance on Flinders Island and in the Perth Basin, southern Australia: Royal Society of Victoria. Proceedings, v. 84, p. 87–91.

FARRINGTON, P., and BARTLE, G. A., 1988, Accession of chloride from rainfall on the Gnangara groundwater mound, Western Australia: Australia CSIRO Division of Land Resources Management, Perth Technical Memorandum 88/1.

HINGSTON, F. J., and GAILITIS, V., 1977, Salts in rainfall in Western Australia (1973–1974): Australia CSIRO Division of Land Resources Management, Perth Technical Memorandum 77/1.

KENDRICK, G. W., 1981, Molluscs from the Ascot Beds from Cooljarloo heavy minerals deposits, Western Australia: Western Australia Geological Survey, Annual Report 1980, p. 44.

KERN, A. M., 1988a, The geology and hydrogeology of the superficial formations between Cervantes and Lancelin, Perth Basin: Western Australia Geological Survey, Hydrogeology Report 1988/32 (unpublished).

KERN, A. M., 1988b, Cataby project bore completion reports: Western Australia Geological Survey, Hydrogeology Report 1988/43 (unpublished).

LOW, G. H., 1972, Explanatory notes on the Moora 1:250 000 geological sheet, Western Australia: Western Australia Geological Survey, Record 1972/21.

LOWRY, D. C., 1974, Dongara–Hill River, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

MOYES, C. P., 1970, Wedge Island stratigraphic well, Perth Basin: Western Australian Petroleum Pty Ltd, Petroleum Search Subsidy Acts (P.S.S.A.) Report (unpublished), Western Australia Geological Survey, S-series Open File, microfilm roll 55.

MONCRIEFF, J. S., and TUCKSON, M., 1989, Hydrogeology of the superficial formations between Lancelin and Guilderton, Perth Basin: Western Australia Geological Survey, Report 25, Professional Papers, p. 39–57.

MONCRIEFF, J. S., 1989, Hydrogeology of the Gillingarra borehole line, Perth Basin: Western Australia Geological Survey, Report 26, Professional Papers, p. 105–126.

PLAYFORD, P. E., COCKBAIN, A. E., and LOW, G. H., 1976, Geology of the Perth Basin, Western Australia: Western Australia Geological Survey, Bulletin 124, 311p.

SCHMIDT, P. W., and EMBLETON, B. J. J., 1976, Palaeomagnetic results from sediments of the Perth Basin, Western Australia and their bearing on the timing of regional lateritization: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 19, p. 257–273.