

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 25

PROFESSIONAL PAPERS



**DEPARTMENT OF MINES
WESTERN AUSTRALIA**



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NEW RECORDS OF PERMIAN AND CRETACEOUS SEDIMENTS FROM THE SOUTHWESTERN PART OF THE YILGARN BLOCK

by J. Backhouse and A. C. Wilson

ABSTRACT

Early Permian palynomorphs in a claystone, immediately east of the Darling Fault and south of Donnybrook, indicate the presence of previously unrecorded Permian sediments below the Donnybrook Sandstone.

Palynological evidence supports the previously proposed Early Cretaceous age of the Donnybrook Sandstone on the eastern margin of the Perth Basin. Palynomorphs from the previously undated Nakina Formation of the Collie Basin also indicate an Early Cretaceous age. Both deposits may have accumulated during the Barremian-Aptian transgression that extensively inundated the Perth Basin.

INTRODUCTION

The Collie Basin occupies an area of 225 km², in the southwestern part of the Yilgarn Block, 150 km south-southeast of Perth (Fig. 1B). Summaries of the geology are provided by Playford and others (1975) and more recently by Kristensen and Wilson (1986). The basin is founded on Archaean basement and contains a thick (about 1 000 m) Permian succession that comprises the Stockton Formation, which includes a distinctive claystone, and the overlying Collie Coal Measures. These units are overlain by the

undated Nakina Formation. Within the southwestern Yilgarn Block, similar but smaller intracratonic Permian basins are present at Wilga and Boyup Brook. Drilling at Donnybrook on the extreme western margin of the Yilgarn Block has intersected a claystone lithologically similar to the Stockton Formation, and this unit is one of the subjects discussed here.

The western fringe of the southwestern Yilgarn Block is covered by an extensive lateritic hardcap that in many places covers thin, poorly lithified sedimentary sequences. Many of these occurrences are undated but are assumed to be of Mesozoic or

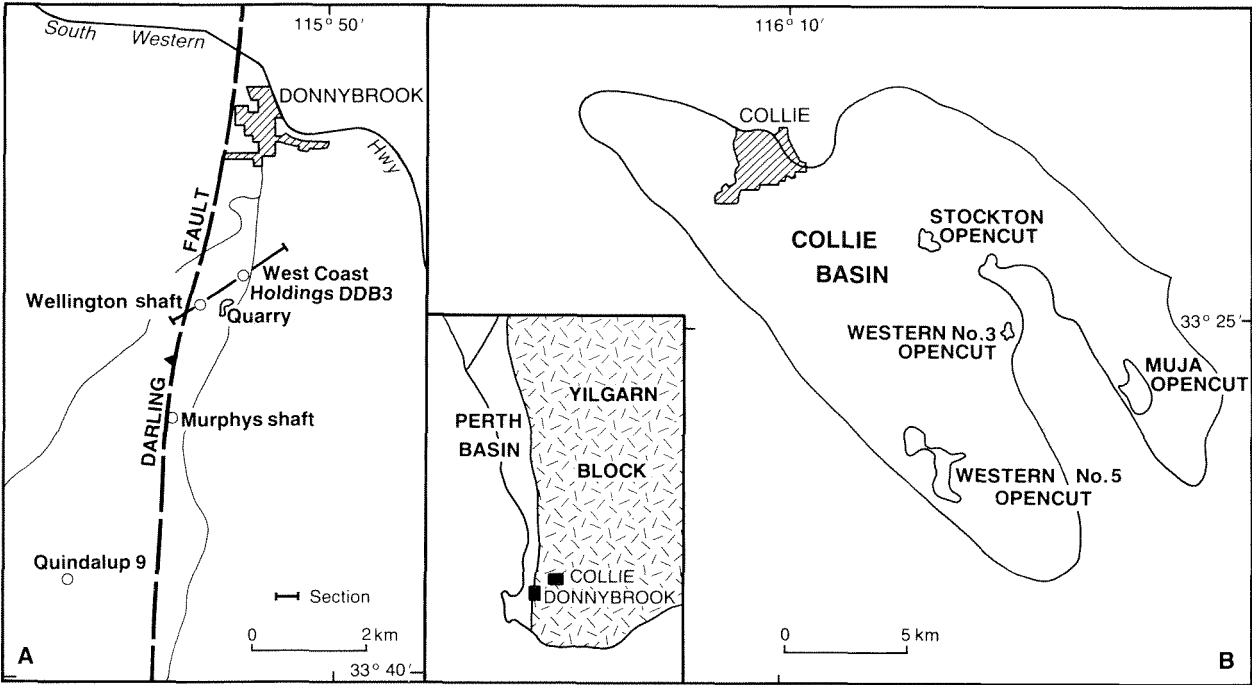


Figure 1. Locality map of Donnybrook area (A) and Collie Basin (B). A diagrammatic section through Wellington shaft and borehole DDB 3 is shown in Figure 2.

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younger age, based on lithological comparison with formations of known age. Sampling of disused opencut workings at Collie and an old exploration shaft at Donnybrook has clarified the ages of two of these units: a shale above the Donnybrook Sandstone (Donnybrook) and the Nakina Formation (Collie).

PERMIAN SEDIMENTS AT DONNYBROOK

Approximately 3 km southeast of Donnybrook and less than 1 km east of the Darling Fault, a gold exploration borehole DDB 3 (Fig. 1A), drilled (60°/270°) by West Coast Holdings penetrated a thick greenish-grey claystone between 0 m and 165 m (Fig. 2). The claystone is extensively veined by epithermal mineralization and is assumed to lie below the Donnybrook Sandstone (see Fig. 2). The claystone is underlain by Archaean gneiss.

Several samples of the claystone (between 76 m and 125 m) which is lithologically similar to the Stockton Formation at Collie, yielded an extremely sparse Permian assemblage in which the most common forms are monosaccate pollen, referable to *Plicatipollenites gondwanensis* (Balme and Hennelly), and *Microbaculispora tentula* Tiwari. Also present are *Verrucosisporites* sp. cf. *V. aspratilis* Playford and Helby, *Indotriradites splendens* (Balme and Hennelly), *Cycadopites cymbatus* (Balme and Hennelly), and bisaccate pollen. All the palynomorphs display a high level of maturation and are poorly preserved. The assemblage is correlatable with upper Stage 2 of Kemp and others (1977), and upper Unit II of Balme, in Kemp and others (1977) and Balme (1980). These biostratigraphic units are not firmly dated in terms of international ages but are probably earliest Permian (Asselian), or latest Carboniferous. The claystone interval in borehole DDB 3 is therefore correlatable, biostratigraphically and lithostratigraphically, with the Stockton Formation of the Collie Basin. Similar claystones of Stockton Formation age are known from the Vasse Shelf, showing clearly that this unit was deposited over a wide area in the southwestern part of Western Australia.

CRETACEOUS SEDIMENTS AT DONNYBROOK

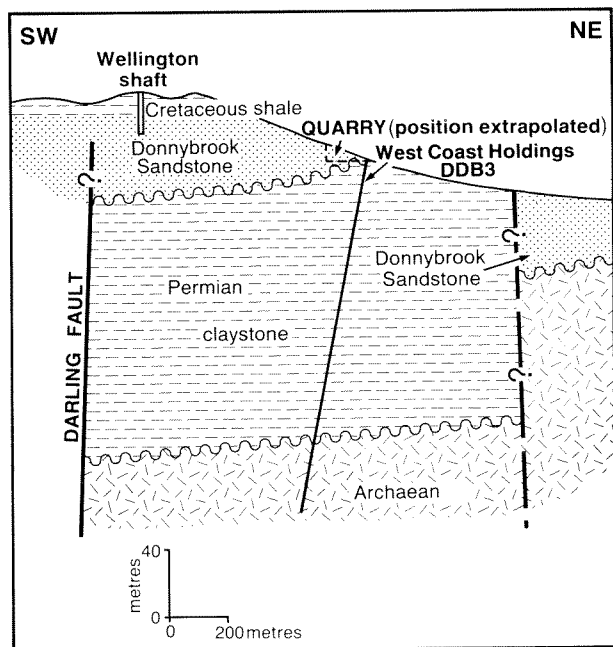
The Donnybrook Sandstone (Saint-Smith 1912), a clean, well-sorted, pale yellow sandstone, extends over an area 6.5 km north, 14.5 km south and up to 6.5 km southeast of Donnybrook (Playford and others, 1976). Balme (1956) suggested a Cretaceous age for the Donnybrook Sandstone based on a plant microfossil assemblage. He obtained this from an old coal-exploration shaft, known as Murphy's shaft, which is situated close to the Darling Fault (Fig. 1A). Playford and others (1975) considered Murphy's shaft to be in the Perth Basin, and the microfossils to represent the Leederville Formation. The material from Murphy's shaft was re-examined as part of the Perth Basin study (Backhouse, 1988), and its correlation with the Leederville Formation in the nearby Quindalup 9 borehole was confirmed. Re-

cently, other shale material from an old gold-exploration shaft, called the Wellington shaft (Fig. 1A), has been examined and found to contain miospores of Early Cretaceous age. Thus it is well established that shale of Early Cretaceous age is present south-southwest of Donnybrook, on the margin of the area covered by the Donnybrook Sandstone. The top of the Wellington shaft is approximately 500 m west and at least 30 m above a quarry in Donnybrook Sandstone (Fig. 1A). The Wellington shaft is 29 m deep, but the shale sample is probably from a horizon that occurs well above the bottom of the shaft, and stratigraphically above the Donnybrook Sandstone (Fig. 2). The implication is that the shale conformably overlies the Donnybrook Sandstone, and that the sandstone is similar in age to that unit.

THE AGE OF THE NAKINA FORMATION AT COLLIE

The Nakina Formation (Playford and others, 1975), previously known as the "Lake Beds" (Lord, 1952), is a thin sequence of claystone, sandstone, and conglomerate that unconformably overlies the Permian sequence of the Collie Basin. Lord (1952) suggested that the "Lake Beds" might be Miocene to Pliocene in age, but more recently Playford and others (1975) regarded the Nakina Formation as Eocene, based on a possible correlation with Eocene sediments at Darkin Swamp 140 km to the north.

During 1984 several samples were collected from the Nakina Formation at various exposures in working and disused opencut mines. A sample from the disused Stockton opencut 7 km east-southeast of Collie (Fig. 1B) yielded a palynomorph assemblage. Subsequently, other samples were collected to corroborate the results.



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Figure 2. Cross-section through Wellington shaft and DDB 3 borehole. For location see Figure 1A.

The rehabilitated Stockton opencut is a lake and part of a recreation area. On the northern side, immediately northwest of the car park, about 1 m of soft, grey, silty claystone (with small carbonaceous inclusions) is exposed at the base of a low cliff, just above water level. The claystone is overlain by 1–2 m of pebbly sandstone, strongly lateritized in places, and above this lie several metres of white, kaolinitic, sandy clay. Six palynologically productive samples were collected

	F 47246	F 47247	F 47248
MIOPORES			
<i>Araucariacites australis</i> Cookson	29	33	•
<i>Baculatisporites comaumensis</i> (Cookson)	16	46	
<i>Balmeiopsis limbata</i> (Balme)	•	1	
Bisaccate pollen	41	20	•
<i>Callialasporites dampieri</i> (Balme)	1	2	•
<i>C. segmentatus</i> (Balme)		•	
<i>Classopollis</i> sp.	62	61	•
<i>Contignisporites cooksonae</i> (Balme)	6	9	
<i>Cyathidites minor</i> Couper	22	18	•
<i>Densoisporites velatus</i> Weyland and Krieger	•		
<i>Dictyophyllidites equiexinus</i> (Couper)	3	4	
<i>Dictyosporites complex</i> Cookson and Dettmann	2	1	
<i>Foveosporites subtriangularis</i> (Brenner)	•	2	
<i>Ischyosporites variegatus</i> (Couper)	3	2	
<i>Januasporites multispinus</i> Backhouse		•	
<i>Matonisporites crassiangulatus</i> (Balme)	•		
<i>Microcachrydites antarcticus</i> Cookson	44	20	•
<i>Neoraistrickia equalis</i> (Cookson and Dettmann)	2	1	
<i>N. truncata</i> (Cookson)		5	
<i>Obtusisporites canadensis</i> Pocock	1		
<i>Osmundacidites dubius</i> Burger	1		
<i>Reticuloidosporites arcus</i> (Balme)	•		
<i>Retitriletes austroclavatidites</i> (Cookson)	3	9	
<i>R. circolumenus</i> (Cookson and Dettmann)	2	3	
<i>R. eminulus</i> (Dettmann)	•	•	
<i>R. tenuis</i> (Balme)	1		
<i>R. watherooensis</i> Backhouse	2	•	
<i>Sestrosporites pseudoalveolatus</i> (Couper)	•	•	
<i>Staplinisporites caminus</i> (Balme)	•		
<i>S. telatus</i> (Balme)	1	4	
ACRITARCHS AND ALGAL CYSTS			
<i>Schizocystia rugosa</i> Cookson and Eisenack			•
<i>Tasmanites</i> sp.			•
PERMIAN PALYNOMORPHS			
<i>Acanthotriletes tereteangulatus</i> Balme and Hennelly		1	
<i>Gondisporites</i> sp.		•	
<i>Indosporites splendens</i> (Balme and Hennelly)	1		
<i>Limitisporites rectus</i> Leschik	2	2	
<i>Peltacystia venosa</i> Balme and Segroves		1	
<i>Plicatipollenites</i> spp.		•	
<i>Protohaploxylinus amplius</i> (Balme and Hennelly)	1	1	•
<i>P. limpidus</i> (Balme and Hennelly)	2	1	
<i>Scheuringipollenites maximus</i> (Hart)	1	1	
<i>Striatopodocarpites fusus</i> (Balme and Hennelly)	•	2	•
Total	250	250	

Figure 3. Distribution of palynomorphs in 3 samples from the Nakina Formation, Stockton opencut.

laterally within the grey claystone at the base of this section. Three of these yielded extremely sparse assemblages of miospores and more abundant wood and cuticle fragments; the three remaining samples yielded richer assemblages and two of these were rich enough to allow counts to be made of 250 specimens. The results are shown in the palynomorph distribution chart (Fig. 3). Taxonomic details and biostratigraphic distributions for the post-Permian species listed in this chart are provided in Backhouse (1988).

The least productive of the three samples contained several specimens of the acritarch *Schizocystia rugosa* Cookson and Eisenack (Fig. 4L). This species is known from the *Balmeiopsis limbata* Zone of Valanginian – early Aptian age in the Perth Basin, although other records suggest it ranges as high as the Late Cretaceous. From its distribution pattern in the Warnbro Group *S. rugosa* may have a non-marine, aqueous origin.

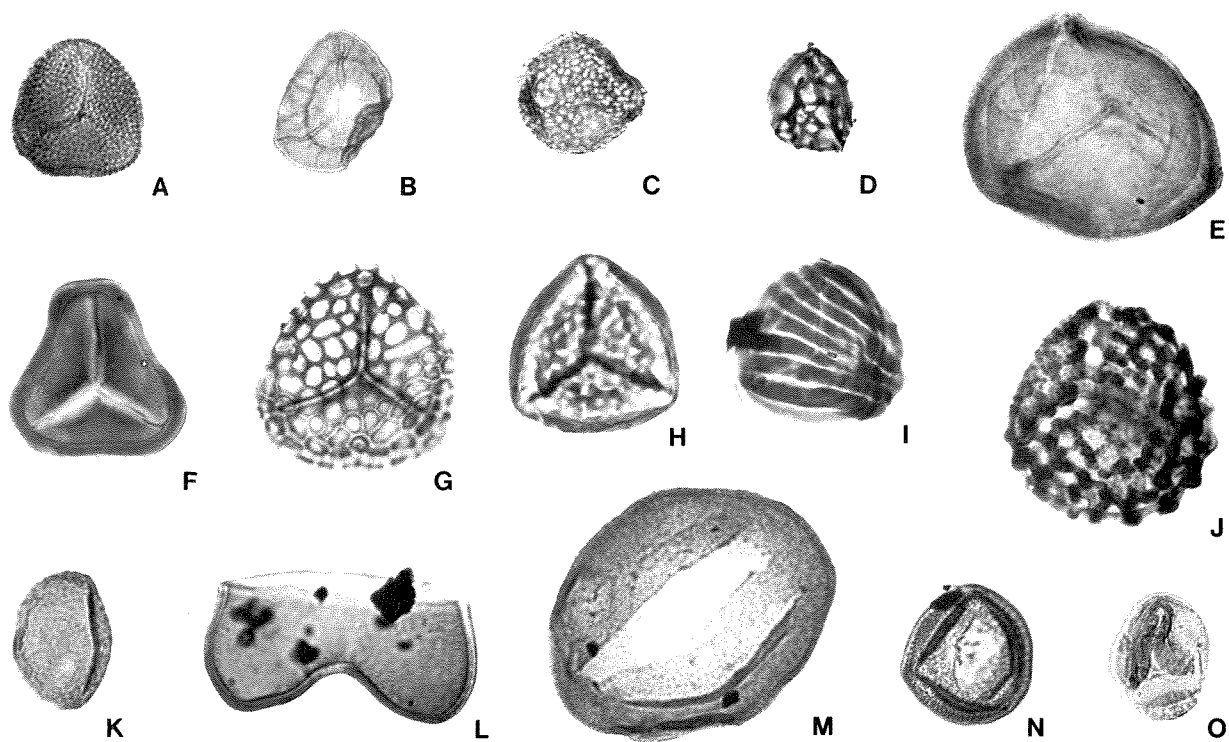
The two samples with better yields both contained *Balmeiopsis limbata* (Balme) (Fig. 4M), a species that does not range below the *B. limbata* Zone. The presence of *Retitriletes tenuis* (Balme) (Fig. 4D) is of interest because it has only been recorded previously in significant numbers from two samples, Murphy's shaft and Quindalup 9 borehole at 45–85 m (Fig. 1) in the Leederville Formation near Donnybrook. *Januasporites multispinus* Backhouse was previously thought to be restricted to the underlying *Biretisporites eneabbaensis* Zone (Backhouse, 1988), but recent work indicates that it may range into the *B. limbata* Zone, and its presence at Collie supports this. A number of other species are not known to range above the Aptian in Australia, and in particular are not known from the *Hoegisporis* Assemblage that overlies the *B. limbata* Zone in the Perth Basin.

Reworked Permian palynomorphs are present in all samples and are listed in Figure 3.

On overall quantitative grounds the assemblage from the Stockton opencut compares well with assemblages from the *B. limbata* Zone in the Perth Basin, and in particular with those from the Leederville Formation in the southern part of the basin. *Classopollis* pollen (Fig. 4N) and *Microcachrydites antarcticus* Cookson (Fig. 4O) are well represented, as are bisaccate pollen and *Baculatisporites comaumensis* (Cookson).

The weight of evidence, therefore, strongly supports a correlation of the Nakina Formation claystone in the Stockton opencut with the Leederville Formation in the Perth Basin.

Exposures of the Nakina Formation at the type section in the Western No. 3 opencut, in the Muja opencut, and possibly in the Western No. 5 opencut (Fig. 1B) lithologically resemble the exposure in the Stockton opencut, in that they include claystones and siltstones with carbonaceous inclusions; although they are all more severely oxidized and have not yielded palynomorphs. It is suggested that all, or most, exposures currently referred to the Nakina Formation, including the type section in Western No. 3 opencut, are



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Figure 4. Palynomorphs from the Nakina Formation, Stockton opencut minesite. All magnifications x 600.

A *Sestrosporites pseudoalveolatus* (Couper).

B *Staplinisporites caminus* (Balme).

C *Retitriletes watherooensis* Backhouse.

D *Retitriletes tenuis* (Balme).

E *Densoisporites velatus* Weyland and Krieger.

F *Matonisporites crassiangulatus* (Balme).

G *Retitriletes circolumenus* (Cookson and Dettmann).

H *Staplinisporites telatus* (Balme).

I *Contignisporites cooksonae* (Balme).

J *Ischyosporites variegatus* (Couper).

K *Schizocystia rugosa* Cookson and Eisenack.

L *Reticuloidosporites arcus* (Balme).

M *Balmeiopsis limbata* (Balme).

N *Calssopollis* sp.

O *Microcachryidites antarcticus* Cookson.

correlatable on lithological grounds with the section in the Stockton opencut. Therefore, at least the lower part of the Nakina Formation may be regarded as Early Cretaceous in age and, by comparison with the Warnbro Group in the Perth Basin, a Barremian to earliest Aptian age is favoured.

The small, recently discovered Boyup Brook Basin is 28 km south of the southern boundary of the Collie Basin. Exploratory drilling in the Boyup Brook Basin by the Griffin Coal Mining Company Limited has intersected a thin Early Cretaceous sequence overlying Permian coal-bearing sediments. Palynological assemblages from this material (unpublished data) are similar in overall composition to the assemblages from the Collie Basin described in this paper.

CONCLUSIONS

Prior to 1983 it was thought that there was little likelihood of there being more Permian basins in

the southwestern Yilgarn Block other than those at Collie and Wilga. The discovery of a coal-bearing Permian basin at Boyup Brook in that year, and this record of Permian strata at Donnybrook, show that Permian deposition was certainly a more widespread phenomenon than previously considered, although it may not have been continuous across the region. This is consistent with sedimentological evidence from the Collie Basin (Wilson, 1988).

The evidence put forward in this paper shows that the Nakina Formation, the Donnybrook Sandstone, and the Leederville Formation are approximate time equivalents. Cretaceous deposition on the Yilgarn Block probably took place during the extensive transgression that marks deposition from Barremian to early Aptian in the Perth Basin. No evidence exists at Collie or Donnybrook for marine deposition but the Maxicar Beds (Lowry, 1965), a probable northern equivalent of the Donnybrook Sandstone, contain bivalves of shallow-marine origin (Playford and others, 1976).

ACKNOWLEDGEMENTS

We thank Mr I. Chalmers of West Coast Holdings Ltd for access to borehole DDB 3, and for supplying extensive details of the Donnybrook area. The Griffin Coal Mining Company Limited is acknowledged for kindly permitting access to unpublished data on the Boyup Brook Basin.

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HYDROGEOLOGY OF THE BINNINGUP BOREHOLE LINE, PERTH BASIN

by A. C. Deeney

ABSTRACT

The Binningup Line, drilled during 1984 on an east-west line across the Perth Basin at Binningup, comprises six bores at four sites. The bores were drilled to a maximum depth of 800 m and have an aggregate depth of 3 060 m.

The Cockleshell Gully Formation (Early – Middle Jurassic) is unconformably overlain by the Leederville Formation (Early Cretaceous) which dips gently to the west and rests on a westward sloping erosional surface. Flat-lying superficial formations* unconformably overlie the Mesozoic sediments.

The Leederville Formation and the Cockleshell Gully Formation form confined multilayered aquifers which are largely composed of fine-grained sediments in the east. The Leederville Formation is recharged locally by downward leakage from the superficial formations, and groundwater flow is westwards. Groundwater with a salinity of less than 1 000 mg/L TDS occurs only in the upper part of the Leederville Formation and in the superficial formations. In the Leederville Formation, it extends westwards from the Wellesley River beneath a saline interface near the coast. The remainder of the Leederville Formation contains brackish to saline water. In the Cockleshell Gully Formation, brackish groundwater, with a salinity of between 2 500 and 7 000 mg/L TDS, extends to a depth of about -430 m AHD in the west. This groundwater may be derived from the Yarragadee Formation to the south. Groundwater in the remainder of the aquifer is saline and flow rates are very low.

The potential for development of the groundwater resources is limited.

INTRODUCTION

The Binningup Lines consists of six bores drilled at four sites (BPL1 to BPL4) on an east-west line across the coastal plain at Binningup, 20 km north of Bunbury (Fig. 1).

The investigation is part of a long-term drilling program to evaluate the deep groundwater resources of the Perth Basin, and was funded jointly by the Commonwealth and State Governments under the National Water Resources (Financial Assistance) Act 1978. The nearest lines of deep bores are the Harvey Line, 26 km to the north (Deeney, in press), and the Picton Line, 22 km to the south (Wharton, 1981). Additional information concerning the shallow-groundwater resources was obtained from nearby bores drilled for the Lake Clifton Project (Commander, 1984a) and the Harvey Shallow Project (Deeney, 1988).

PHYSIOGRAPHY, CLIMATE, AND LAND USE

The Binningup Line bores are situated on the Swan Coastal Plain, which is formed of shoreline and coastal dune deposits extending from the Darling Scarp to the Indian Ocean. McArthur and Bettenay (1974) have divided the coastal plain in this area into four physiographic units: an alluvial plain that has developed in front of the Darling

Scarp and three sets of stabilized dunes that are parallel to the coast. Lakes and swamps occur in the low-lying interdunal depressions.

The coastal plain in the vicinity of the Binningup Line is drained by the Wellesley River and a number of drains which discharge into it. Benger Swamp is a prominent wetland which occupies a large, shallow depression in the coastal plain close to the Darling Scarp.

The climate of the area is Mediterranean. The average annual rainfall ranges from about 900 mm near the coast to about 1 100 mm at the Darling Scarp. Rainfall generally exceeds evapotranspiration during the five months May to September. The average annual evaporation is about 1 400 mm.

Most of the land has been cleared for agriculture. Pastures on the coastal plain east of the Wellesley River are irrigated using water from dams located east of the Darling Scarp. Areas of market garden adjacent to the Old Coast Road are irrigated using local groundwater.

INVESTIGATION PROGRAM

The bores were drilled during 1984 by the Mines Department Drilling Section with a Midway Skytop rig using the mud-flush rotary method. Deep exploratory bores were drilled at each site (BPL1A, BPL2A, BPL3A, and BPL4A) Shallow

* 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).

water-supply bores BPL1W and BPL3W were constructed at sites 1 and 3. A summary of the bore data is given in Table 1.

Sludge samples were collected at 3 m intervals from the exploratory bores. On completion of drilling a suite of geophysical logs was run in each bore including gamma-ray and long-normal and short-normal resistivity logs. About 20 sidewall cores were recovered from siltstones or clays in each bore. Three intervals, designated 1 to 3 from the top down, were selected for perforation with shaped charges.

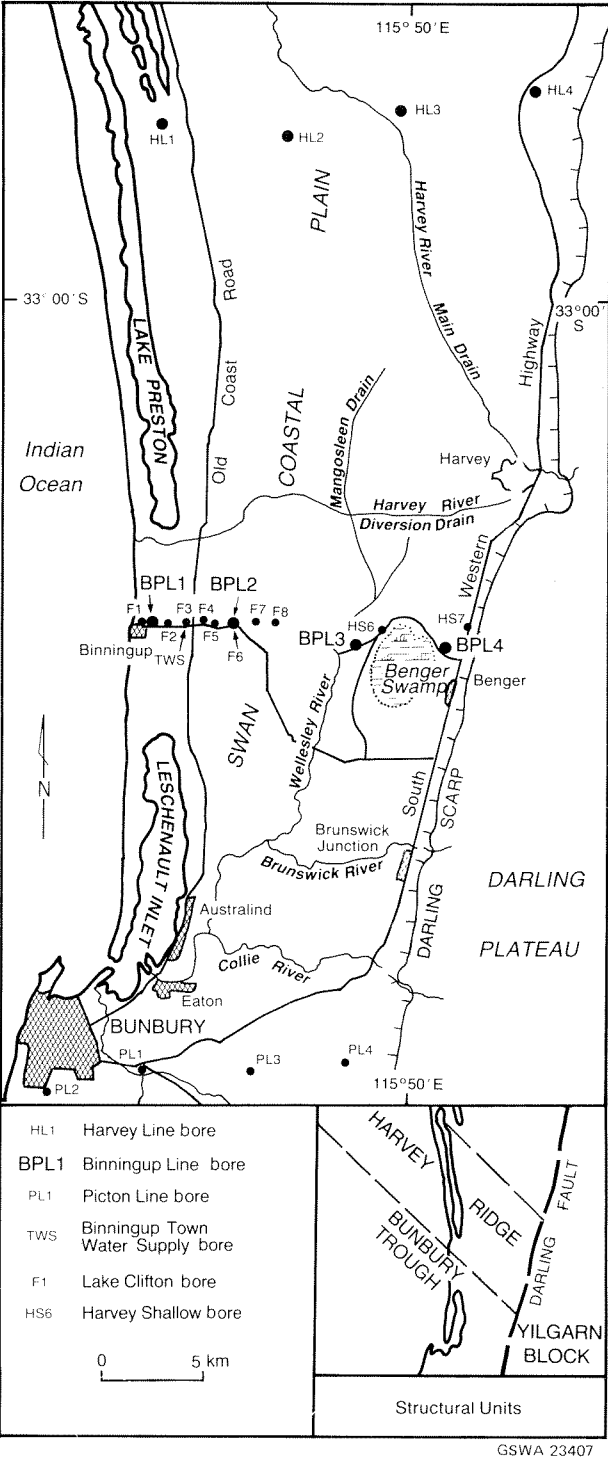


Figure 1. Locality map

TABLE 1. SUMMARY OF BORE DATA

Bore	Interval	AMG—Zone 50		Cont- menced	Cont- pleted	Total depth (m bms)	Elevation (AHD)		Top of casing (m)	Casing		Perforation interval (m bms)	Forma- tion	Water level (m b/c) 5/8/86	Potentio- metric head (a) m.AHD 5/8/86	Salinity (b) (mg/L TDS)	Airlift yield (m ³ /d)	Status of bore
		Interval	Eastings	Northings			Natural surface (m)	Total depth (m bms)		Depth (m bms)	Diameter (mm)							
BPL1A	1		378400	6331600	17.7.84	20.8.84	806.5	2.035	2.953	64.0	25	102-108	Kll	+0.05	2.5	890	270	Observation
	2								3.390	776.0	80	341-347	Jlo	+0.80	3.9	2510	245	Observation
	3								—	52.5	260	627-633	Jlo	—	—	22300	640	Abandoned
BPL1W			378400	6331600	1.3.84	6.3.84	18.0	—	—	8.5	154	8.5-11.5 (c)	Q	—	—	2810	440	Abandoned
									16.093	71.8	25	65-71	Kll	12.61	3.5	850	430	
BPL2A	1		382600	6331400	26.6.84	16.7.84	600.0	15.214	16.152	597.0	80	268-274	Jlo	12.63	3.8	4690	40	Observation
	2								—	55.0	260	584-590	Jlo	—	—	22000(f)	2(f)	Abandoned
	3								—	598.5	154							
	1								13.529	102.0	25	114-120	Kll	5.84	7.8	6510	40	Observation

BPL3A	2 3	388500	6330300	23.5.84	25.6.84	800.5	12.482	13.556	786.0	80	267-276	<i>Jlo</i>	4.87	10.8	2500(d)	<1(f)	Observation
								—	792.5	154							
BPL3W		388500	6330300	28.2.84	29.2.84	33.0	—	—	14	154	14-17(c)	<i>Q</i>	—	—	1750	390	Abandoned
	1							16.033	91.5	25	72-76	<i>Kll</i>	7.03	9.1	8500(d)	<1(f)	Observation
BPL4A	2	393000	6330200	16.4.84	22.5.84	802.6	14.897	16.065	750.5	80	255-260	<i>Jlo</i>	17.15	0.1(g)	26100	15	Observation
	3							—	54.0	260	560-566	<i>Jlo</i>	—	—	26000(d)	2(f)	Abandoned
									759.5	154							

bns Below natural surface. btc Below top casing. *Q* Superficial formations. *Kll* Leederville Formation. *Jlo* Cockleshell Gully Formation

(a) Potentiometric heads have been corrected for the density distribution resulting from the salinity variations with depth. (b) Airlift samples taken at completion. TDS by calculation. (c) Screened interval. (d) Salinity estimated from long-normal resistivity log. (e) Artesian flow rate. (f) Insufficient supply to fully develop interval by airlift. (g) Not representative of potentiometric head in the aquifer.

TABLE 2. CHEMICAL ANALYSES OF WATER SAMPLES (mg/L)

Bore interval	GSHA sample number <i>a</i>	pH	EC mS/m (@ 25°C)	TDS	TH	TA	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	NO ₃	SiO ₂	B	F
BPL1A1	79763	8.6	175	890	463	192	80	64	135	37	51	131	429	9	<1	22	0.3	0.1
BPL1A2	79764	8.9	428	2 510	68	473	14	8	964	14	84	406	1 060	150	<1	14	—	2.7
BPL1A3	79765	7.9	3 230	22 300	2 690	155	557	316	7 500	73	<2	189	11 900	1 800	<1	14	—	0.4
BPL1W	79755	8.6	492	2 810	552	247	45	107	869	30	48	204	1 380	208	1	21	0.34	0.4
BPL2A1	79760	8.6	158	850	389	298	100	34	165	8	63	235	320	24	<1	21	0.17	0.2
BPL2A2	79761	8.6	824	4 690	82	262	18	9	1 760	24	57	204	2 420	289	<1	9	1.5	1.1
BPL3A1	79759	8.5	1 100	6 510	878	200	149	123	2 160	40	42	159	3 560	342	6	11	1.6	0.9
BPL3W	79754	8.2	328	1 750	526	235	92	72	464	3	15	256	849	96	<1	35	0.08	0.2
BPL4A2	79757	7.6	3 890	26 100	6 520	67	2 010	365	7 560	76	<2	82	15 600	462	<1	11	0.09	0.5

Analyses carried out by Government Chemical Laboratories, Perth

(a) Airlift samples taken at completion.

EC—Electrical conductivity.

TDS—Total dissolved solids by calculation at 180°C.

TH—Total hardness at calcium carbonate.

TA—Total alkalinity as calcium carbonate.

Each exploratory bore was completed, with 155 mm casing which extends below the lower interval, and was pressure cemented. The lower interval was perforated, developed and abandoned prior to the perforation of the middle and upper intervals. A string of 80 mm galvanized iron (GI) pipe, extending below the lower interval, was installed with 12 m of flame-cut slots opposite the middle interval and compressible packers set above and below the middle interval to seal the annulus. This bore construction allows the middle and upper intervals to be monitored; observation of the upper interval was facilitated by the installation of 25 mm GI pipe in the annulus. The 80 mm and 25 mm pipes in BPL1A were fitted with gate valves to control artesian flows.

The water-supply bores were completed with 155 mm casing and in-line stainless-steel screens.

Each interval was developed by airlifting and surging to obtain a clear uncontaminated water sample for chemical analysis by the Government Chemical Laboratories (Table 2). Flow rates from bore-hole intervals BPL2A3, BPL3A3, BPL3A2, BPL4A3 AND BPL4A1 were insufficient to allow full development, and comparison of the measured salinities of the samples with the salinities estimated from the long-normal resistivity logs indicates that they are not representative of the formation waters.

It was not possible to obtain reliable potentiometric head measurements for the lower intervals prior to their abandonment because of the difficulties encountered in their development. Water levels in the middle and upper intervals have been measured once a month since completion. The potentiometric head in the middle interval of BPL4A has risen continuously during the monitored period and may not be representative. Using the method of Luszczynski (1961), values of potentiometric head given in Table 1 and in Figure 3 have been corrected for the density distribution resulting from salinity variations with depth. This allows the comparison of heads in a vertical direction. The differences between measured and corrected heads ranged from 0.5 m to 2.0 m.

After completion, gas-cut artesian flows were observed from the middle and upper intervals in BPL1A. The gas consists predominantly of methane or ethane, and the quantity appears to have increased during the monitoring period due perhaps to accumulation in the bore casing. This may have affected the measured potentiometric heads.

GEOLOGY

SETTING

The Binningup Line of bores was drilled in the Harvey Ridge, a structural subdivision of the Perth Basin (Playford and others, 1976), which forms the northern boundary of the Bunbury Trough (Fig 1). The Harvey Ridge is probably fault bounded, and extends northwest from the Darling Fault. The Bunbury Trough is a deep graben bounded on the east by the Darling Fault and on the west by the Busselton Fault. Precambrian basement may occur at a depth of only 5 km below the surface along the Harvey Ridge whereas the Bunbury Trough probably contains at least 10 km of Phanerozoic sediments (Playford and others, 1976).

STRATIGRAPHY

Sediments encountered in the Binningup Line bores range in age from Early Jurassic to Holocene. The formations recognized are given in Table 3 and described below.

Cockleshell Gully Formation

The Cockleshell Gully Formation (Willmott, 1964) was encountered in all the exploratory bores. It consists of angular to subangular, weakly cemented quartz sandstone, which is often silty and contains accessory pyrite and garnet, and weakly consolidated siltstone and shale. The siltstone and shale are micaceous, generally multi-coloured and contain minor to trace amounts of carbonaceous material.

TABLE 3. STRATIGRAPHIC SUCCESSION IN THE BINNINGUP LINE BORES

Age	Formation	Thickness (m)				Summary lithology	Remarks
		BPL1	BPL2	BPL3	BPL4		
QUATERNARY	Superficial formations	29	37	22	24	Sand, sandy clay, clay, limestone, calcarenite	Unconfined aquifer, groundwater is fresh to brackish
UNCONFORMITY							
EARLY CRETACEOUS	Leederville Formation	165	116	122	75	Sandstone, siltstone, shale	Multilayered aquifer, groundwater is marginal to saline
UNCONFORMITY							
EARLY-MIDDLE JURASSIC	Cockleshell Gully Formation	606	437	651	700	Sandstone, siltstone, shale	Multilayered aquifer, groundwater is brackish to saline

The Cockleshell Gully Formation is about 2 km thick (Playford and others, 1976) of which a maximum thickness of 700 m was intersected in BPL4A. It is unconformably overlain by the Leederville Formation.

In BPL1A and BPL2A, individual beds are up to 30 m thick, and the sandstones are poorly sorted and generally fine to very coarse grained, whereas in BPL3A and BPL4A, the sandstones are moderately sorted and very fine to fine grained, and the beds are about 6 m thick. These differences between the sequences in the east and the west are readily apparent on the gamma-ray logs, which show a smaller range and a more uniform response with depth in BPL3A and BPL4A. Individual beds cannot be correlated between bores.

Owing to oxidation of the sediments, few of the samples yielded palynomorphs. Sludge samples from BPL1A yielded assemblages dominated by *Classopollis* pollen which indicates a general age of Early Jurassic (Backhouse, 1984). One sidewall core from BPL2A and one from BPL4A yielded assemblages which probably belong to the *D. harrisii* Assemblage sub-zone of Filatoff (1975). This indicates an age of Early to Middle Jurassic (Pleinsbachian - Aalenian) and a non-marine environment of deposition (Backhouse, 1985, 1986a). The colour of the sediments and absence of well-developed coal seams indicates that the sequence may belong to the Eneabba Member of the Cockleshell Gully Formation.

Leederville Formation

The Leederville Formation (Cockbain and Playford, 1973) was encountered in all the exploratory bores and consists of quartz sandstone, siltstone and shale. The sandstones are grey, silty, weakly cemented, poorly sorted, and generally fine to very coarse grained. They frequently include thin layers of lime-cemented and pyrite-cemented sandstone. The siltstones and shales are generally dark grey, mottled olive-green, or yellow brown. They are multicoloured in BPL4A, indicating that the sequence has been weathered. The siltstones and shales are usually micaceous and contain minor to trace amounts of carbonaceous material. A basal section ranging in thickness from 40 m to 90 m, which contains a greater percentage of siltstone and shale, can be recognized in all the exploratory bores.

The Leederville Formation thins eastwards from BPL3A, and thickens westwards from BPL2A; the maximum thickness (170 m) was intersected in BPL1A (Fig. 2). This reflects the variation in elevation of the underlying unconformity surface. The Leederville Formation is unconformably overlain by the superficial formations.

Few of the sidewall cores yielded palynomorphs because of the weathering of the sediments. The palynomorphs indicate a non-marine environment of deposition and can be placed in the *B. limbata* zone (Backhouse, 1984, 1985, 1986b). This indicates an age of Early Cretaceous (Valangian to Aptian) which is consistent with the Leederville Formation. The South Perth Shale is not recognized as a separate unit in this part of the

Perth Basin, and the whole of the Early Cretaceous sequence is assigned to the Leederville Formation.

Superficial formations

Following Allen (1976), the Cainozoic sediments of the Swan Coastal Plain in this area are referred to as the superficial formations. They have been described in detail by Commander (1984a) and Deeney (in press).

The superficial formations consist of sand, limestone, silt, and clay, and exhibit a marked variation in lithology both laterally and vertically. They form a stratigraphically complex sequence which comprises sediments of marine, littoral, alluvial, and eolian origin. In the western and central parts of the coastal plain they consist of sand, limestone, and minor amounts of silt and clay. These deposits interfinger with a sequence which, adjacent to the Darling Scarp, consists of clay, clayey sand, and minor gravel.

The superficial formations form a flat-lying sequence, which ranges in thickness from about 20 m to 50 m and extends westwards from the Darling Scarp. They rest unconformably on a gentle westward - sloping erosional surface.

STRUCTURE

The inferred geological structure along the Binningup Line is shown in Figure 2.

The Cockleshell Gully Formation has been block faulted along northwest-trending faults. It dips southwestwards at a low angle (Playford and others, 1976) into the Bunbury Trough and has been downfaulted against Precambrian granitic rocks of the Yilgarn Block by the Darling Fault.

The positions of the faults shown in Figure 2 have been determined from geological evidence obtained during drilling, and from geological sections and structure contour maps based on seismic surveys, given in Playford and others (1976).

The Yarragadee Formation, which is present in the Bunbury Trough, has been removed from the Harvey Ridge by erosion.

The Leederville Formation unconformably overlies the Cockleshell Gully Formation, rests on a gentle westward-sloping erosional surface, and dips westwards at a low angle. Cope (1972) has suggested that differential compaction of sediments over faulted Precambrian basement may have controlled the deposition of the Cretaceous sediments in the onshore Perth Basin. The thickening of the Leederville Formation west of BPL2A may therefore be the result of flexure and differential compaction of sediments over faults marginal to the Harvey Ridge.

HYDROGEOLOGY

SUPERFICIAL FORMATIONS

The anisotropic unconfined aquifer formed by the superficial formations has been discussed in detail by Commander (1984a) and Deeney (in press). The saturated thickness of the aquifer is about 30 m except where it decreases close to the Darling Scarp (Fig. 3).

Figure 2. Geological section

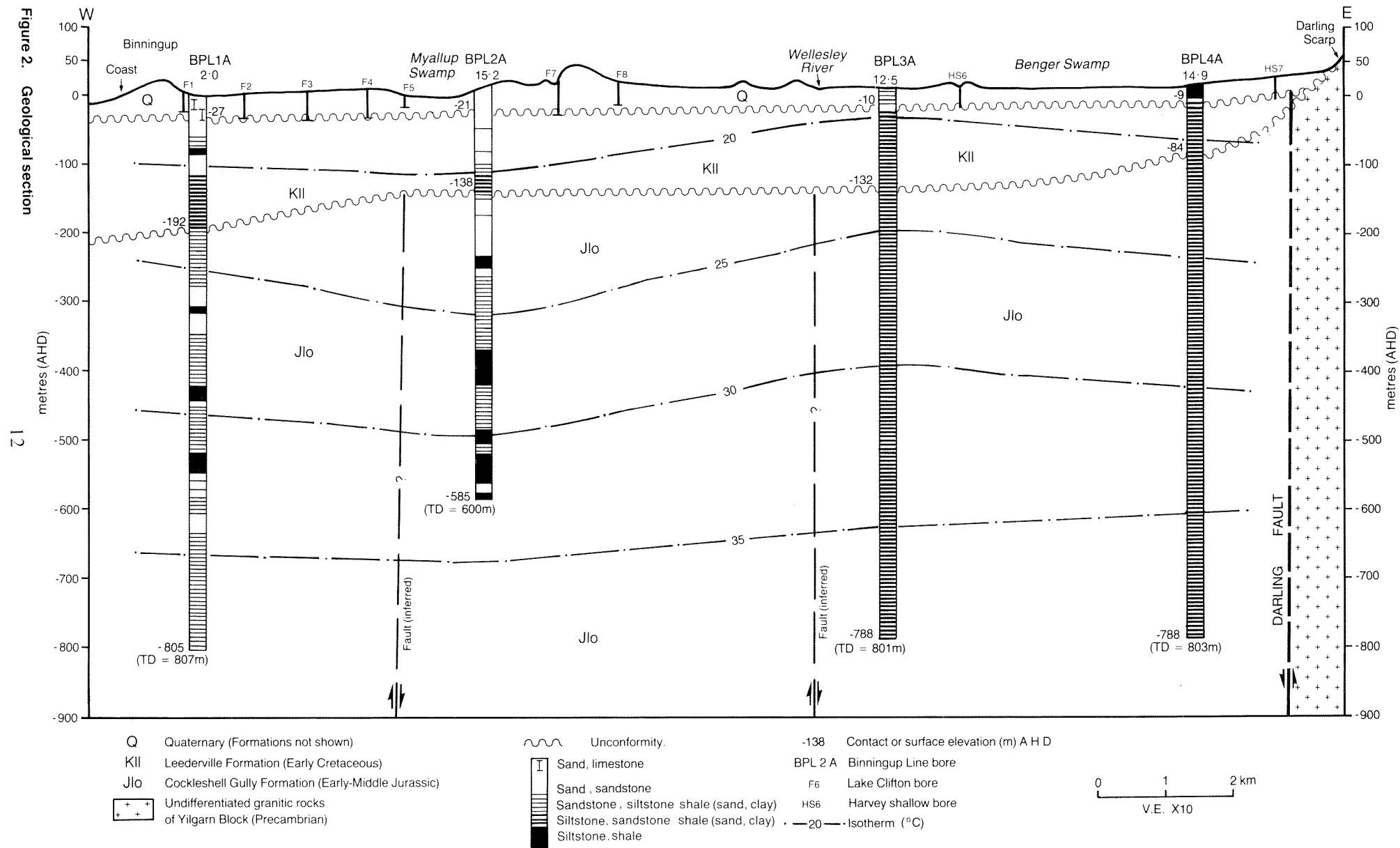
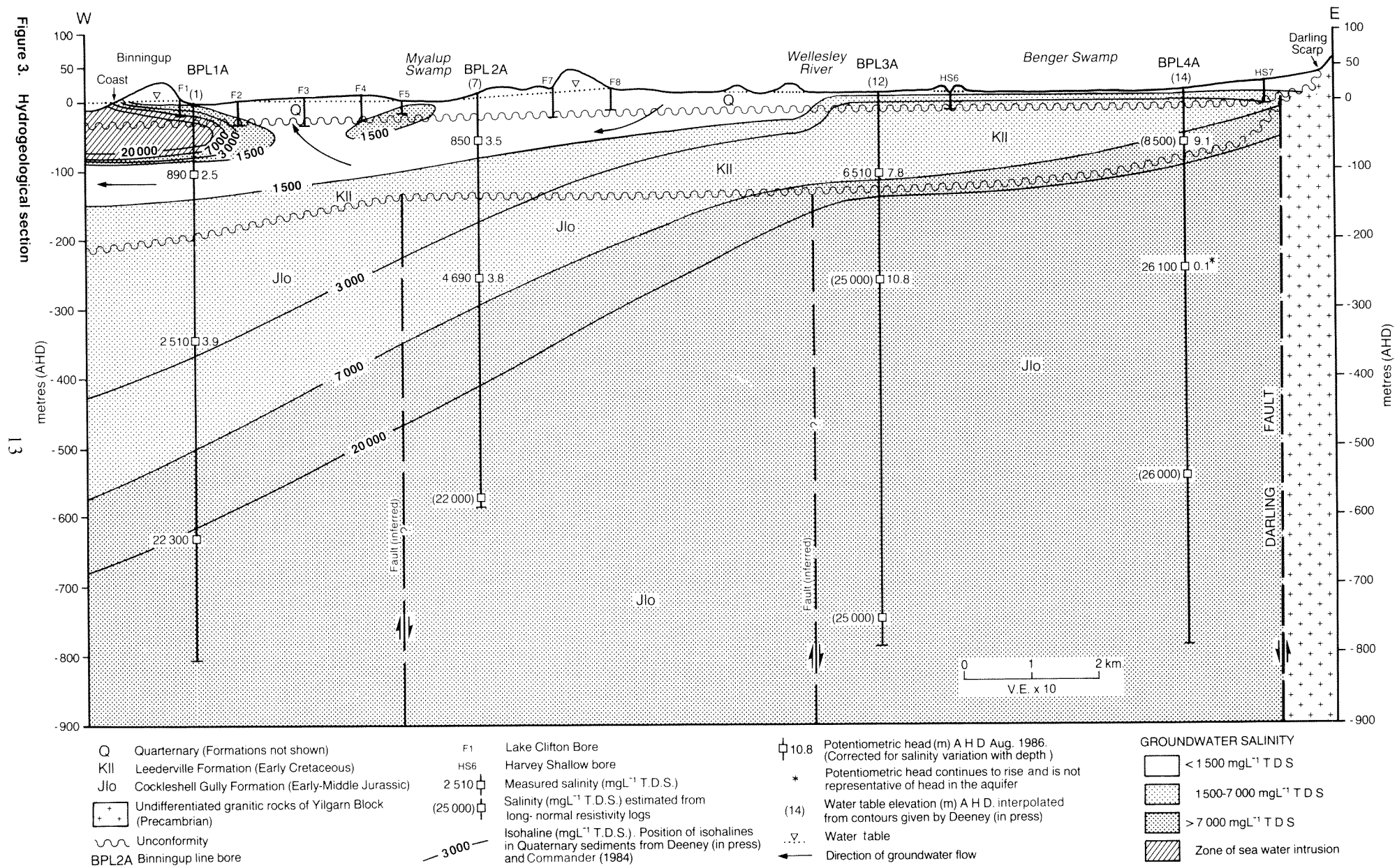


Figure 3. Hydrogeological section



The aquifer is recharged by percolating rainfall, but a large proportion of infiltration is lost by evapotranspiration.

Groundwater flow is generally westwards from the Darling Scarp and the seasonal variation in the water-table level is generally in the range 1–2 m. Groundwater discharges locally to watercourses and swamps, to the Leederville Formation, and to the Indian Ocean across a saline interface.

Groundwater west of the Wellesley River is generally fresh to marginal; and the salinity ranges from 250 mg/L TDS to 1 500 mg/L TDS. Locally, close to discharge areas, it is brackish with a salinity of between 1 500 and 7 000 mg/L TDS. The groundwater is also brackish east of the Wellesley River.

Significant abstraction for irrigation occurs adjacent to the Old Coast Road.

Groundwater in the aquifer west of the Wellesley River constitutes an important resource in view of the limited quantity of low-salinity water in the deeper aquifers.

LEEDERVILLE FORMATION

The Leederville Formation forms a multilayered aquifer consisting of sandstone, siltstone, and shale; the percentage of sandstone increases westwards from about 50% at BPL4 to about 80% at BPL1. It ranges in thickness from 75 m at BPL4 to 165 m at BPL1. A small quantity of natural gas is present in the Leederville Formation in the vicinity of BPL1.

The Leederville Formation is recharged by downward leakage from the superficial formations. The main recharge area is between the Wellesley River and Myalup Swamp, where the superficial formations consist predominantly of sand and where there is a downward potentiometric gradient (Fig. 3). East of the Wellesley River, there is also a downward potentiometric gradient; however, there is likely to be very little recharge because the superficial formations consist predominantly of clay in this area.

Groundwater flow in the Leederville Formation is westwards to discharge offshore. Discharge may also occur into the discharge formations between Myalup Swamp and the saline interface (Fig. 3) as there is a potential for upward leakage. In the low-lying area west of Myalup Swamp artesian flows may be encountered.

The freshest groundwater in the aquifer (salinity between 850 mg/L and 1 500 mg/L TDS) occurs in a zone extending westwards from the main recharge area and beneath the saline interface. A salt-water wedge extends from the overlying superficial formations approximately 45 m into the Leederville Formation and between 1 km and 2 km inland from the coast. The remainder of the Leederville Formation contains brackish to saline groundwater (salinities in the range 1 500 to 19 000 mg/L TDS) associated with sediments of low permeability. Low-salinity groundwater is present in the Leederville Formation west of the Wellesley River, because leakage from the

superficial formations in this area exceeds the throughflow in the Leederville Formation east of the Wellesley River.

Groundwater in the Leederville Formation is of the sodium chloride type, and normally contains dissolved iron in concentrations which would require treatment for domestic, industrial, or public water supply purposes. A sample from Binningup town water-supply bore, located 2 km east of the townsite, had an iron concentration of 0.5 mg/L. Concentrations of boron and fluoride in the samples of fresh groundwater are less than 0.3 mg/L (Table 2).

The natural seasonal variation in potentiometric head is about 0.5 m. Water levels in BPL2A3 are affected by local abstraction for irrigation, and this gives rise to a seasonal change of approximately 2.5 m (Fig 4). There is some potential for further development of the upper part of the aquifer west of the Wellesley River for irrigation or industrial supplies. Elsewhere, higher salinities and lower yields limit its use.

COCKLESHELL GULLY FORMATION

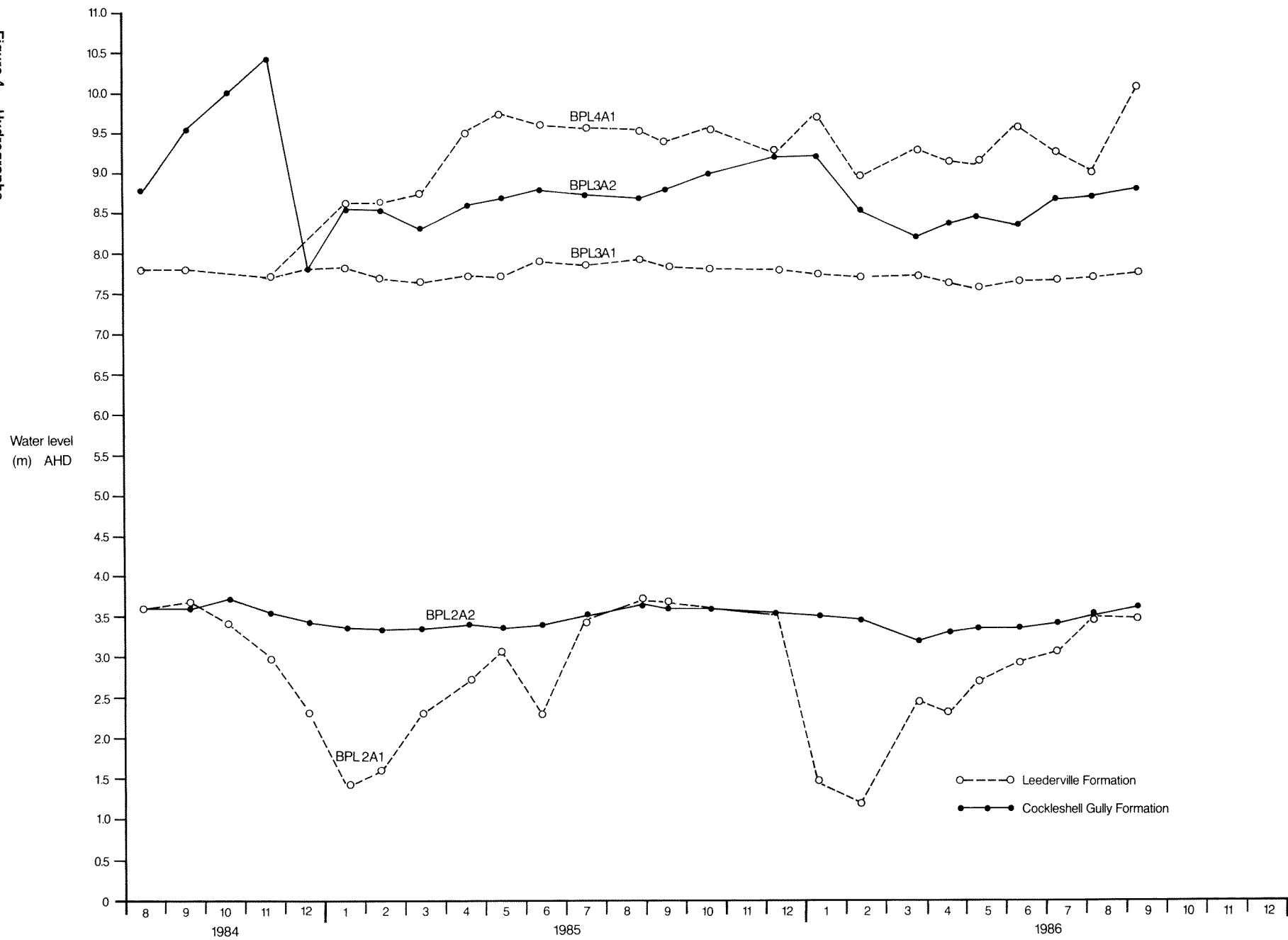
The Cockleshell Gully Formation forms a confined, multilayered aquifer, which is composed of siltstone and shale interbedded with fine-grained sandstone in the east, and fine-grained to very coarse-grained sandstone in the west. A small quantity of natural gas is present in the Cockleshell Gully Formation in the vicinity of BPL1.

An active groundwater flow system probably exists only in the west, where it extends to a depth of about -430 m AHD in BPL1A and -300 m AHD in BPL2A. This flow system may represent the northern extension of the flow system formed by the Yarragadee Formation in the Bunbury area (Commander, 1984b) in which groundwater flow is northwestwards. The potentiometric head in BPL2A2 is almost equal to the potentiometric head in BPL1A2, and this suggests that the westward component of groundwater flow is minimal. Potentiometric heads in the Cockleshell Gully Formation are higher than those in the Leederville Formation; therefore, recharge of the Cockleshell Gully Formation by downward leakage probably does not occur at this locality. However, it may occur further to the north.

In the east, and at depth in the west where the groundwater is saline, groundwater movement is likely to be very slow. Artesian flows may be encountered in low-lying areas near the coast. The natural seasonal variation in potentiometric head in the Cockleshell Gully Formation is about 0.5 m (Fig. 4).

The groundwater salinity in the Cockleshell Gully Formation ranges from 2 510 to 26 100 mg/L TDS. The active flow system in the west contains brackish groundwater with a salinity range of 2 500 to 7 000 mg/L while the remainder of the aquifer contains saline groundwater. The salinity distribution probably reflects the distance from recharge and the low permeability of the sediments. Groundwater in the Cockleshell Gully Formation is of the sodium chloride type.

Figure 4. Hydrographs



No bores are producing water from the Cockleshell Gully Formation; future development is limited by high salinities and by low yields in the east. The formation may be suitable for the injection of liquid waste at depth in the west, where the groundwater is saline and thick sandstones occur.

GROUNDWATER TEMPERATURE

In order to ensure that natural geothermal gradients had been re-established, temperature logs were run to the base of the 80 mm pipe in each deep bore approximately eighteen months after completion of drilling. Generally, temperature gradients ranged from 2.3°C to 2.7°C per 100 m, but higher gradients of up to 5°C per 100 m were associated with shales of low thermal conductivity. The results are shown as isotherms in Figure 2.

CONCLUSIONS

Drilling of the Binningup Line bores has provided new information on the deep aquifers of the Perth Basin near Binningup.

The Leederville Formation unconformably overlies the Cockleshell Gully Formation, and it is unconformably overlain by a thin sequence of superficial formations. In the eastern part of the area, the Leederville Formation and the Cockleshell Gully Formation consist of siltstones interbedded with fine-grained sandstones, and borehole yields are likely to be low.

Groundwater with a salinity of less than 1 000 mg/L TDS occurs only in the superficial formations and in a 45 m thick section in the western part of the Leederville Formation. Groundwater in the Cockleshell Gully Formation is brackish (2 500 – 7 000 mg/L TDS) in the west and saline (7 000 – 26 000 mg/L TDS) at depth and in the east. A salt-water wedge extends approximately 1.5 km inland in the base of the superficial formations and the top of the Leederville Formation.

The groundwater resources have only limited potential for further development.

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BUSSELTON SHALLOW-DRILLING GROUNDWATER INVESTIGATION, PERTH BASIN

by K-J. B. Hirschberg

ABSTRACT

The Busselton shallow-drilling project was undertaken to investigate the hydrogeology of this area, and to provide a network of bores for long-term monitoring. It extended over an area of about 800 km² on the coastal plain between Dunsborough and Capel, in the southern Perth Basin. Between October 1983 and October 1984, bores ranging to a maximum depth of about 100 m were drilled at 36 sites. Clusters of two to four bores were drilled at each site — a total of 107 bores and an aggregate depth of 4827 m.

The geological sequence in this area consists of predominantly clayey superficial formations, ranging in thickness from 3 m to 18 m, that unconformably overlie the Cretaceous Leederville Formation — a sequence of interbedded sand and shale. The thickness of the Leederville Formation ranges from about 50 m in the west and east to about 500 m in the centre of the Bunbury Trough. The Leederville Formation unconformably overlies the Permian Sue Coal Measures or the Early to Middle Jurassic Cockleshell Gully Formation in the west, and the Late Jurassic Yarragadee Formation, and locally the Cretaceous Bunbury Basalt, in the east.

Several aquifer systems exist in this region. The superficial formations contain unconfined groundwater, but because of their limited thickness and their predominantly clayey lithology, this aquifer is of minor importance for the area. The salinity increases northwards, and is usually too high for domestic use. The underlying older formations are multilayered, confined aquifers. Recharge to the Sue Coal Measures, the Cockleshell Gully Formation, and the Yarragadee Formation, is by downward groundwater movement from the Leederville Formation, which, in turn, is recharged by direct infiltration of rainfall on the Blackwood Plateau, and from the superficial formations in part of the coastal plain. Direction of flow is from the Blackwood Plateau towards the coast. In the northern parts of the coastal plain, upward hydraulic heads in the Leederville Formation result in artesian flow in bores.

The salinity of the groundwater in the confined aquifers is generally below 500 mg/L T.D.S. Along the coast, saltwater intrusion has occurred.

The Leederville Formation is the most important aquifer in this region; however, all confined aquifers have the potential for considerable further development.

INTRODUCTION

LOCATION

The Busselton shallow-drilling project area extends over an arcuate area about 60 km long from Dunsborough to about Capel, and comprises an area of about 800 km² (Fig. 1). The main centre of population is Busselton, approximately 190 km south of Perth.

PURPOSE AND SCOPE

The Busselton shallow-drilling project is a southwestward extension of the Bunbury shallow-drilling project (Commander, 1984). Its objectives are to define the lateral and vertical extent of the unconfined aquifer formed by the superficial formations, and its relationship with the upper 100 m of the underlying confined aquifer systems.

The project is part of a long-term program to evaluate the groundwater resources of the Perth Basin. It was jointly funded by the Commonwealth and State Governments under the National Water Resources Assessment Programme.

CLIMATE AND LAND USE

The region has a Mediterranean climate characterized by warm dry summers and cool wet winters. The average annual rainfall for Busselton is about 825 mm, most of it falling from May to August. The average annual evaporation is about 1100 mm.

Most of the coastal area has been cleared for agriculture, whereas areas inland of the Whicher Scarp are still forested.

Mining for heavy minerals is taking place around Capel, and along the Whicher Scarp southwest and southeast of Capel.

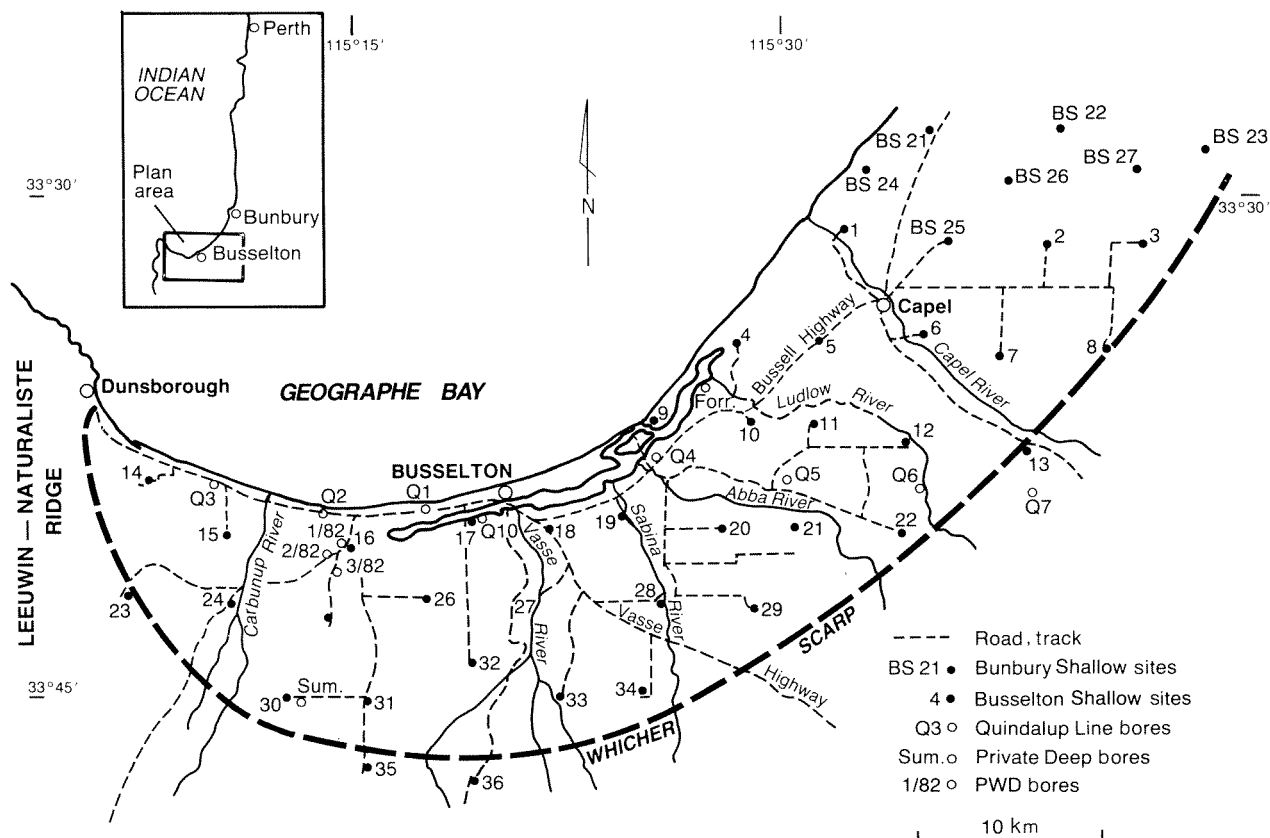


Figure 1. Location plan

GSWA 23587

PHYSIOGRAPHY

The investigation area lies on the Swan Coastal Plain (Saint-Smith, 1912). The plain has an average width of 15 km; it is bounded in the west by the Leeuwin-Naturaliste Ridge, and in the south and southeast by the Whicher Scarp. The scarp was formed by marine erosion along an old coastline and separates the coastal plain from the Blackwood Plateau in the south (McArthur and Bettenay, 1960). The plateau rises from about 40 m at the foot of the scarp to an average elevation of about 160 m AHD.

The coastal plain comprises several physiographic units that were named by McArthur and Bettenay (1974): an alluvial plain (Pinjarra Plain) in the south and southeast; a discontinuous area of low, irregularly shaped sand dunes (Bassendean Dunes); and a coastal belt parallel to the coastline, with stabilized and mobile dunes (Spearwood and Quindalup Dunes) separated by interdunal inlets, lagoons, and swamps.

DRAINAGE

A number of perennial rivers originating on the Blackwood Plateau drain the region (Fig. 1). Large parts of the low-lying coastal plain are subject to inundation, and numerous surface drains have been constructed to counter flooding.

PREVIOUS WORK

The geology of the southern Perth Basin has been described by Low (1971 and 1972), Lowry (1965), and Playford and others (1976).

As early as 1913, Maitland reported on the occurrence of artesian water in this region. Later, drilling was carried out near the Abba River (Low, 1958), and for town water supplies at Busselton (Passmore, 1962) and Capel (Emmenegger, 1963).

Probert (1968) reported on deep exploratory drilling for groundwater in the Busselton area, based on the Quindalup Line bores Q 1 to Q 5. The Quindalup Line was extended between 1974 and 1979, and the hydrogeology revised by Wharton (1981).

Shallow exploratory drilling to a depth of about 100 m was carried out between Bunbury and Capel between 1975 and 1980 (Commander, 1984), and the present project is an extension of this drilling.

DRILLING AND TESTING

The Busselton shallow-drilling project commenced in October 1983 and was completed in October 1984. Drilling was conducted at 36 sites spaced on an approximate 5 km grid (Fig. 1). A total of 103 monitoring bores with an aggregate depth of 4 827 m was drilled by the Mines Department Drilling Section using Jacro and Edson mudrotary drilling rigs. At each site, a cluster of two or three bores was drilled: a deep bore (d) to a depth of about 100 m; a shallow bore (s) to a few metres below the water table; and, at most sites, an intermediate bore (i) into the uppermost sands of the Leederville Formation. Details of all bores are given in Table 1.

TABLE 1. BOREHOLE DATA

Bore	Grid ref. AMG Zone 50 (100 m)		Date completed	Elev. top casing (m AHD)	Total depth (m)	Observation interval (m)		Aquifer	Potentio- metric head (m AHD)	Salinity (mg/L TDS)	Status of bore
	Eastings	Northing									
1 s	3 644	62 902	2/84	3.394	5.5	2.5 -	5.5	Q	0.174	6 830	Observation
i	3 644	62 902	10/83	3.354	10.75	7.75-	10.75	Q	0.409	916	Observation
d	3 644	62 902	10/83	3.241	102.0	96.0 -	102.0	Kl	3.711	268	Observation
2 s	3 754	62 896	10/83	25.699	6.0	2.75-	5.75	Q	22.409	957	Observation
i	3 754	62 896	2/84	25.805	21.5	15.0 -	21.0	Kl	24.055	4 790	Observation
d	3 754	62 896	11/83	25.710	101.75	91.0 -	97.0	Kl	9.39	613	Observation
p	3 754	62 896	11/84	25.289	97.0	91.0 -	97.0	Juy	9.419	650	Pump bore
3 s	3 803	62 898	11/83	36.376	8.0	2.0 -	8.0	Q	33.416	1 000	Observation
i	3 803	62 898	11/83	36.381	22.0	16.0 -	22.0	Kl	33.761	140	Observation
d	3 803	62 898	11/83	36.403	80.75	54.0 -	60.0	Kl	33.953	501	Observation
4 s	3 590	62 838	2/84	3.190	7.5	2.0 -	5.0	Q	-0.197	1 570	Observation
i	3 590	62 838	10/83	3.394	9.0	6.0 -	9.0	Q	-0.296	2 170	Observation
d	3 590	62 838	10/83	3.384	101.0	87.0 -	93.0	Kl	-0.466	745	Observation
5 s	3 629	62 839	2/84	12.537	5.5	2.5 -	5.5	Q	9.165	1 290	Observation
i	3 629	62 839	10/83	12.604	10.0	6.0 -	9.0	Q	9.163	1 680	Observation
d	3 629	62 839	10/83	12.623	101.5	95.0 -	101.0	Juy	-6.497	228	Observation
6 s	3 690	62 842	11/83	30.152	6.0	0.0 -	6.0	Q	27.182	470	Observation
i	3 690	62 842	11/83	30.091	19.0	13.0 -	19.0	?Q	19.571	1 210	Observation
d	3 690	62 842	11/83	30.251	100.0	84.5 -	90.5	?Juy	19.581	419	Observation
7 s	3 729	62 839	11/83	35.235	8.0	2.0 -	8.0	Q	28.325	184	Observation
i	3 729	62 839	11/83	35.244	16.0	10.0 -	16.0	?Juy	28.284	173	Observation
d	3 729	62 839	11/83	35.449	100.0	89.0 -	95.0	?Juy	22.489	496	Observation
8 s	3 784	62 840	2/84	67.714	10.5	7.5 -	10.5	Kl	56.414	720	Observation
d	3 784	62 840	11/83	67.844	53.0	32.0 -	38.0	Kl	43.474	390	Observation
9 s	3 538	62 796	11/83	2.507	6.0	0.0 -	6.0	Q	0.212	24 500	Observation
i	3 538	62 796	11/83	2.546	13.0	7.0 -	13.0	Q	0.436	1 950	Observation
d	3 538	62 796	11/83	2.582	101.75	95.0 -	101.0	Kl	7.042	323	Observation
10 s	3 594	62 798	12/83	12.686	7.5	1.5 -	7.5	Q	8.737	544	Observation
i	3 594	62 798	2/84	12.874	31.5	25.0 -	31.0	Kl	8.849	1 870	Observation
d	3 594	62 798	12/83	12.810	100.0	93.5 -	99.5	Kl	7.81	1 330	Observation
p	3 594	62 798	11/84	12.512	101.0	93.5 -	99.5	Kl	7.522	1 260	Pump bore
11 s	3 630	62 795	11/83	22.889	6.0	0.0 -	6.0	Q	18.629	580	Observation
i	3 630	62 795	11/83	22.915	16.0	10.0 -	16.0	Kl	19.055	1 420	Observation
d	3 630	62 795	11/83	22.978	100.0	89.0 -	95.0	Kl	14.778	329	Observation
12 s	3 683	62 787	11/83	33.584	6.0	0.0 -	6.0	Q	28.874	210	Observation
i	3 683	62 787	11/83	33.551	12.0	6.0 -	12.0	?Q	28.981	790	Observation
d	3 683	62 787	11/83	33.562	100.0	82.0 -	88.0	Kl	28.932	304	Observation
13 s	3 739	62 786	2/84	51.321	7.0	3.0 -	6.0	Kl	45.211	520	Observation
d	3 739	62 786	11/83	50.726	40.0	31.0 -	37.0	Kl	39.076	269	Observation
14 s	3 269	62 755	3/84	4.531	5.5	2.5 -	5.5	Q	1.991	12 200	Observation
i	3 269	62 755	3/84	4.110	21.5	15.0 -	21.0	Kl	2.10	1 330	Observation
d	3 269	62 755	2/84	4.246	100.0	50.0 -	56.0	Kl	0.216	322	Observation
15 s	3 314	62 730	3/84	7.498	7.0	4.0 -	7.0	Q/Kl	4.222	960	Observation
i	3 314	62 730	3/84	7.532	30.5	27.0 -	30.0	Kl	2.793	320	Observation
d	3 314	62 730	2/84	7.511	100.0	74.0 -	80.0	Kl	3.235	341	Observation
p	3 314	62 730	10/84	7.294	81.0	74.0 -	80.0	Kl	3.314	340	Pump bore
16 s	3 383	62 728	3/84	2.720	6.0	2.6 -	5.6	Q/Kl	0.40	1 260	Observation
i	3 383	62 728	3/84	2.722	31.5	25.0 -	31.0	Kl	0.962	508	Observation
d	3 383	62 728	2/84	2.562	100.0	93.0 -	99.0	P	1.312	13 600	Observation
17 s	3 445	62 738	3/84	3.614	4.6	1.6 -	4.6	Q/Kl	0.114	7 500	Observation
i	3 445	62 738	3/84	3.492	30.9	23.9 -	29.9	Kl	(later repaired) damaged	670	Observation
d	3 445	62 738	2/84	3.404	100.0	83.0	89.0	Kl		4.604	225
18 s	3 488	62 738	2/84	5.225	6.0	3.0 -	6.0	Q	2.36	907	Observation
i	3 488	62 738	2/84	5.283	33.5	27.5 -	33.5	Kl	3.583	334	Observation
d	3 488	62 738	12/83	5.168	100.0	81.0 -	87.0	Kl	5.133	230	Observation
19 s	3 525	62 747	12/83	7.522	8.0	2.0 -	8.0	Q	3.282	530	Observation

TABLE 1. BOREHOLE DATA (continued)

Bore	Grid ref. AMG Zone 50 (100 m)		Date completed	Elev. top casing (m AHD)	Total depth (m)	Observation interval (m)		Aquifer	Potentio- metric head (m AHD)	Salinity (mg/L TDS)	Status of bore
	Easting	Northing									
i	3 525	62 747	2/84	7.561	33.5	27.5 -	33.5	K1	4.601	312	Observation
d	3 525	62 747	12/83	7.506	100.0	79.0 -	85.0	K1	6.676	253	Observation
20 s	3 585	62 734	2/84	18.706	6.0	2.5 -	5.5	Q	16.526	13 300	Observation
i	3 585	62 734	2/84	18.629	17.5	11.5 -	17.5	Q/K1	16.829	3 430	Observation
d	3 585	62 734	12/83	18.468	101.0	95.0 -	101.0	K1	19.188	250	Observation
21 s	3 619	62 736	2/84	25.142	6.4	3.0 -	6.0	Q	23.262	320	Observation
i	3 619	62 736	2/84	25.000	19.5	13.5 -	19.5	K1	22.72	347	Observation
d	3 619	62 736	12/83	25.227	100.0	81.0 -	87.0	K1	20.797	373	Observation
22 s	3 679	62 735	11/84	45.668	14.0	9.6 -	12.6	K1	43.548	490	Observation
d	3 679	62 735	12/83	45.636	101.75	90.0 -	96.0	K1	38.506	352	Observation
23 s	3 261	62 694	3/84	39.866	14.0	7.8 -	13.8	K1	32.856	303	Observation
i	3 261	62 694	3/84	39.801	23.5	17.4 -	23.4	K1	29.491	256	Observation
d	3 261	62 694	3/84	39.898	100.0	86.0 -	92.0	K1	23.328	410	Observation
24 s	3 321	62 693	3/84	22.642	7.0	4.0 -	7.0	Q/K1	16.172	290	Observation
i	3 321	62 693	3/84	22.491	18.5	12.25 -	18.25	K1	14.211	564	Observation
d	3 321	62 693	3/84	22.454	101.75	94.0 -	100.0	K1	13.304	283	Observation
25 s	3 373	62 682	3/84	16.909	9.5	3.5 -	9.5	K1	13.579	302	Observation
i	3 373	62 682	3/84	16.803	26.0	22.4 -	25.4	K1	13.653	254	Observation
d	3 373	62 682	2/84	16.890	100.0	91.0 -	97.0	K1	16.24	285	Observation
26 s	3 147	62 691	2/84	12.124	8.5	5.5 -	8.5	Q/K1	9.194	3 210	Observation
i	3 147	62 691	2/84	12.116	27.5	24.5 -	27.5	K1	9.496	757	Observation
d	3 147	62 691	2/84	12.028	101.75	87.0 -	93.0	K1	9.378	309	Observation
27 s	3 483	62 684	2/84	15.916	6.0	2.5 -	5.5	K1	14.046	1 340	Observation
i	3 483	62 684	2/84	16.092	24.5	18.5 -	24.5	K1	14.336	620	Observation
d	3 483	62 684	2/84	16.081	101.75	87.0 -	93.0	K1	13.634	243	Observation
p	3 483	62 684	10/84	16.094	93.0	87.0 -	93.0	K1	13.634	250	Pump bore
28 s	3 551	62 696	2/84	25.535	6.7	3.5 -	6.5	Q	21.895	2 080	Observation
i	3 551	62 696	2/84	25.247	31.5	25.0 -	31.0	K1	20.237	752	Observation
d	3 551	62 696	12/83	25.322	101.75	93.0 -	99.0	K1	17.682	382	Observation
29 s	3 596	62 697	2/84	34.512	9.0	5.5 -	8.5	K1	32.592	390	Observation
i	3 596	62 697	2/84	34.496	23.5	17.0 -	23.0	K1	flowing	318	Observation
d	3 596	62 697	12/83	34.433	101.75	87.0 -	93.0	K1	flowing	220	Observation
30 s	3 345	62 639	3/84	35.456	5.5	2.5 -	5.5	Q	31.386	650	Observation
i	3 345	62 639	3/84	35.578	26.5	20.0 -	26.0	K1	26.958	250	Observation
d	3 345	62 639	3/84	35.240	100.0	91.0 -	97.0	K1	21.10	251	Observation
31 s	3 396	62 638	3/84	30.208	5.5	2.5 -	5.5	Q	26.98	310	Observation
i	3 396	62 638	3/84	30.085	23.5	17.0 -	23.0	K1	damaged	195	Observation
d	3 396	62 638	3/84	30.185	100.0	94.0 -	100.0	K1	30.037	230	Observation
32 s	2 448	62 658	3/84	23.517	5.5	2.5 -	5.5	Q/K1	20.147	3 840	Observation
i	2 448	62 658	3/84	23.386	27.5	24.5 -	27.5	K1	20.596	1 350	Observation
d	2 448	62 658	2/84	23.328	100.0	81.0 -	87.0	K1	14.728	407	Observation
33 s	3 500	62 639	3/84	31.638	9.0	5.0 -	8.0	K1	29.438	174	Observation
i	3 500	62 639	3/84	31.637	30.5	24.5 -	30.5	K1	28.957	192	Observation
d	3 500	62 639	2/84	31.481	100.0	90.0 -	96.0	K1	23.251	226	Observation
34 s	3 547	62 643	3/84	47.694	6.0	2.0 -	5.0	K1	42.304	220	Observation
i	3 547	62 643	3/84	47.724	18.5	12.5 -	18.5	K1	42.164	285	Observation
d	3 547	62 643	2/84	47.717	100.0	78.0 -	84.0	K1	25.897	196	Observation
35 s	3 395	62 596	3/84	59.933	6.5	3.5 -	6.5	K1	52.103	160	Observation
d	3 395	62 596	2/84	59.797	101.75	92.0 -	98.0	K1	41.357	209	Observation
36 s	3 451	62 591	3/84	71.167	8.0	5.0 -	8.0	K1	65.797	121	Observation
d	3 451	62 591	2/84	70.944	100.0	81.0 -	87.0	K1	20.474	248	Observation

Q—Quaternary

K1—Leederville Formation

Juy—Yarragadee Formation

P—Sue Coal Measures

Strata samples were collected at 3 m intervals and portions are stored at the GSWA core library at Dianella.

Gamma-ray and normals resistivity logs were run in each deep bore. Between three and six sidewall cores from each of the deep bores were taken for palynological analysis.

The monitoring bores were equipped with 80 mm diameter PVC casing (100 mm diameter PVC in two of the bores), with slotted sections of 3 m or 6 m length near the bottom.

The bores were developed and water samples obtained by airlifting. Water samples were analyzed by the Government Chemical Laboratories (Table 3).

All bores were levelled to Australian Height Datum (AHD) by the Surveys and Mapping Division of the Mines Department.

Four bores constructed for pumping tests were drilled at sites BN2, BN10, BN15 and BN27, about 30 m from the monitoring bores which were used for observation during the pumping tests. The pumping bores were equipped with 154 mm steel casing and with 154 mm stainless-steel screen over the same intervals as the slots in the respective deep monitoring bores. A short pumping test program consisting of a four-stage step-drawdown test to determine bore efficiency, followed by an eight-hour constant-rate test, was carried out at each of the four sites. Pumping rates were restricted by the relatively small diameter of the borehole casing, which allowed only a medium-yield pump to be installed. Aquifer parameters were calculated by standard-type curve-matching procedures of time-drawdown curves from the deep monitoring bores. The results are given in Table 4.

GEOLOGY

SETTING

The area lies in the southern Perth Basin, which is subdivided by the Busselton Fault into the Bunbury Trough in the east and the Vasse Shelf in the west (Fig. 2). The Bunbury Trough is bounded in the east by the Darling Fault, and it contains about 6 km of Phanerozoic sediments, whereas on the Vasse Shelf, the sediments may be underlain by Precambrian basement at a depth of less than 2 km (Playford and others, 1976). The Vasse Shelf is separated from the Proterozoic Leeuwin Block, in the west, by the Dunsborough Fault.

STRATIGRAPHY

The stratigraphic succession in this region has been described by Playford and others (1976) and by Wharton (1981) and is summarized in Table 2. Sediments intersected during drilling range in age from Permian to Quaternary.

Sue Coal Measures

The Sue Coal Measures (Playford and Low, 1972) occur on the western part of the Vasse Shelf, where they are unconformably overlain by the Leederville Formation. They were intersected in bore BN 16d below 50 m and have also been encountered in PWD bores 1/82, 2/82 and 3/82, and in Quindalup Line bores Q 2 and Q 3 (Fig. 3). The Sue Coal Measures consist of multicoloured shale, varying from white to grey, green, black, and red-brown; and moderately consolidated, fine- to coarse-grained quartz sandstone. Accessory feldspar and pyrite are common. Carbonaceous material was intersected in BN 16d at a depth of 65 m to 70 m. Microflora indicates a Permian age (Artinskian) and a non-marine depositional environment.

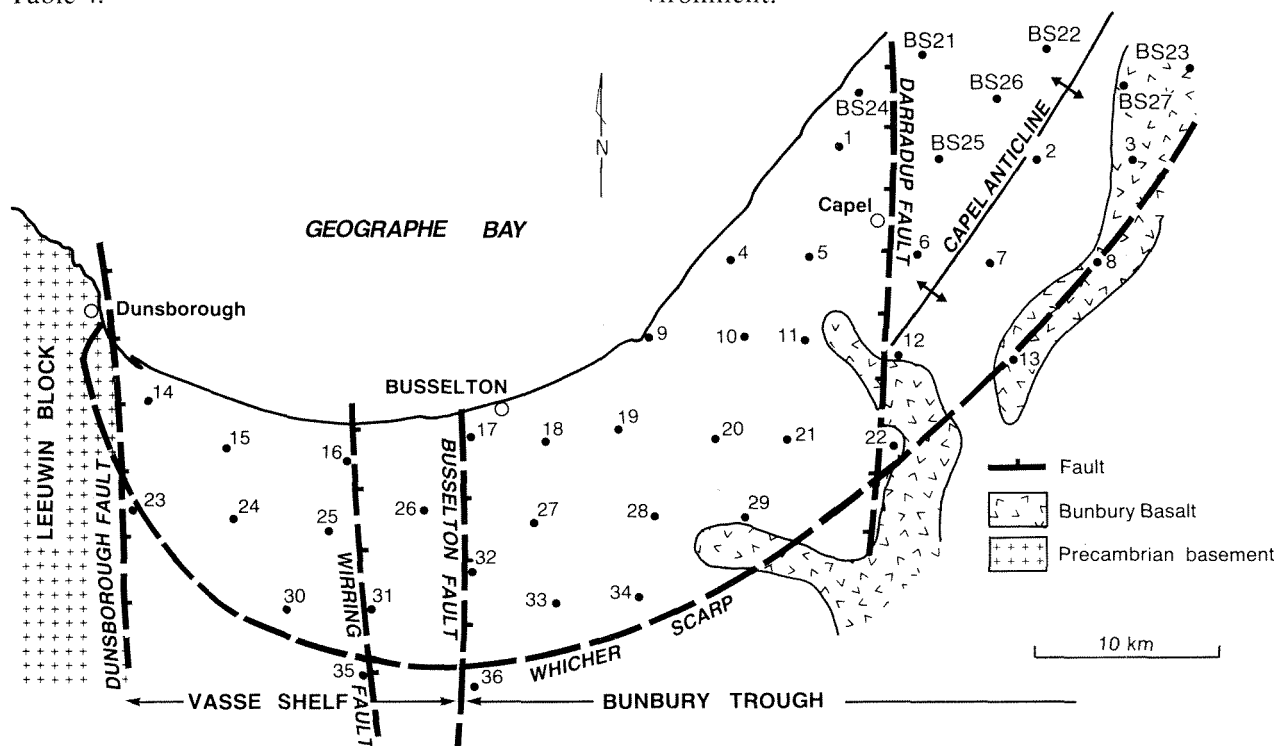


Figure 2. Structural setting

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TABLE 2. STRATIGRAPHY OF THE BUSSELTON AREA

Age	Formation	Maximum thickness (m)	Lithology
CAINOZOIC:			
Quaternary	Alluvial and estaurine deposits	10	Mud, silt, sand
(Holocene)	Safety Bay Sand	10	Sand
(Pleistocene)	Tamala Limestone	15	Sandy calcarenite
	Bassendeau Sand	15	Sand
	Guildford Formation	18	Clay, minor sand
Tertiary-Quaternary (Pleistocene-Pliocene?)	Yoganup Formation	15	Sand, conglomerate
UNCONFORMITY			
MESOZOIC:			
Early Cretaceous	Leederville Formation	500	Sand, siltstone, shale
	Bunbury Basalt	85	Basalt
UNCONFORMITY			
Middle-Late Jurassic	Yarragadee Formation	1 400	Sandstone, minor shale
Early Jurassic	Cockleshell Gully Formation	1 500	Sandstone, shale
Triassic	Lesueur Sandstone (a)	2 396	Sandstone
	Sabina Sandstone (a)	148	Sandstone
PALAEOZOIC:			
Permian	Sue Coal Measures	1 838	Sandstone, shale, coal

(a) Not encountered in Busseilton Shallow bores.

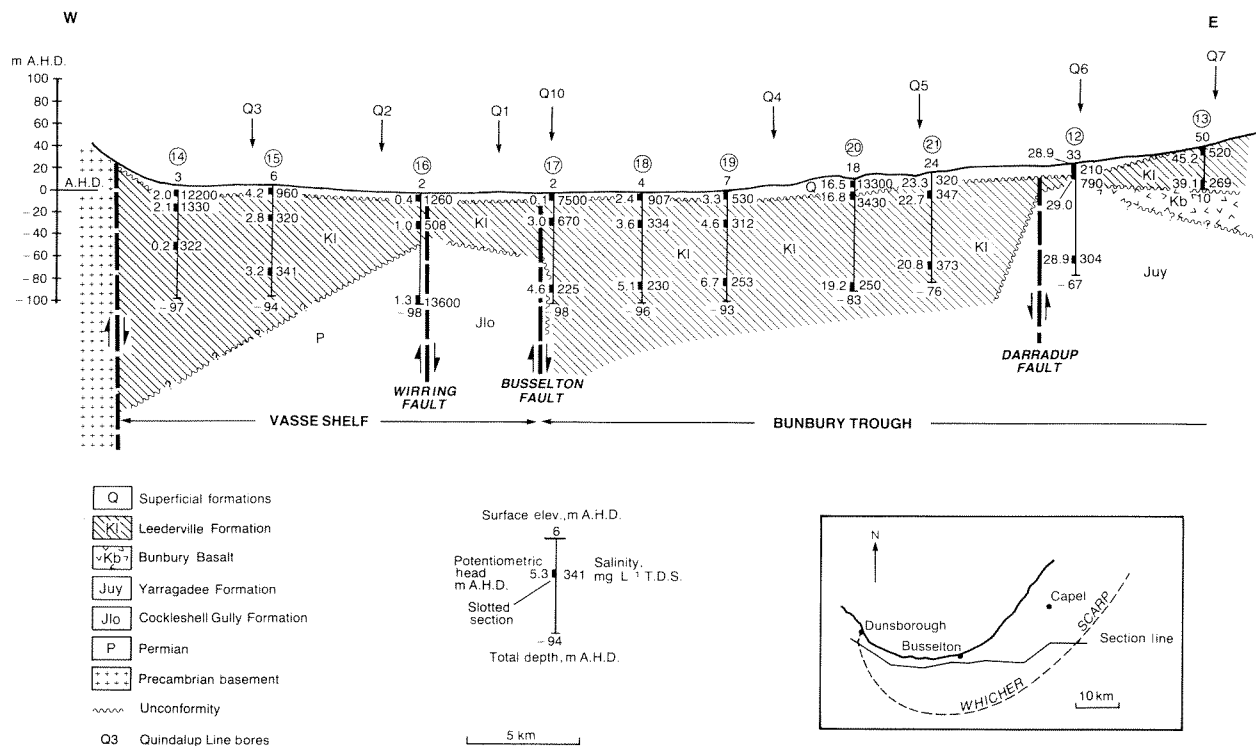


Figure 3. Hydrogeological cross-section showing aquifer relationships

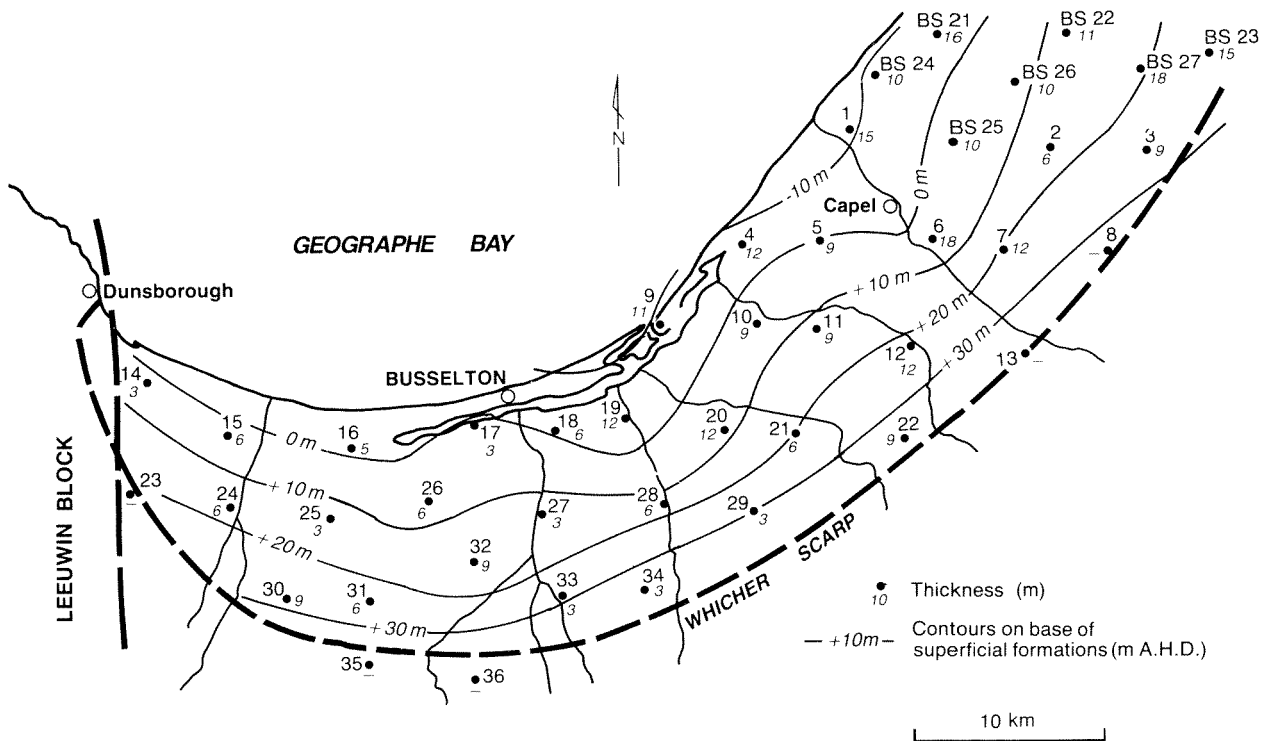


Figure 4. Base and thickness of superficial formations

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Cockleshell Gully Formation

The Cockleshell Gully Formation (Playford and others, 1976) is unconformably overlain by the Leederville Formation in the eastern part of the Vasse Shelf (Fig. 3). It was encountered at 84 m in Q 1 (Wharton, 1981), but was not intersected in any of the Busselton Shallow bores. The formation consists of interbedded sands and shales and is of Early to Middle Jurassic age.

Yarragadee Formation

The Yarragadee Formation (McWhae and others, 1958) occurs throughout the Bunbury Trough and is unconformably overlain by the Leederville Formation or, locally, by the Bunbury Basalt (Fig. 3). It attains a maximum known thickness of 1400 m in the east, in Q 9 (Wharton, 1981). The formation was intersected in five of the Busselton Shallow bores (BN 2d, BN 5d, BN 6d, BN 7d, and BN 12d).

The Yarragadee Formation consists predominantly of medium- to coarse-grained, weakly consolidated, quartz sandstone, with subordinate interbeds of grey shale, siltstone, and quartz pebbles. In bore BN 7d, the formation was predominantly clayey and contained some carbonaceous material. Palynology indicates a Late Jurassic age and a non-marine environment of deposition.

Bunbury Basalt

The Bunbury Basalt (McWhae and others, 1958) occurs locally between the Leederville and Yarragadee Formations in the Bunbury Trough

(Fig. 3). It appears to have been deposited in valleys eroded into the Yarragadee Formation. It was intersected in bores BN 3d, BN 8d, and BN 13d, at depths of about 70 m, 50 m, and 40 m, respectively, and drilling was terminated in fresh basalt. The petrological characteristics have been described by Trendall (1962), Burgess (1978), and Wilde and Walker (1979). Its age is probably Neocomian (Playford and others, 1976).

Leederville Formation

The Leederville Formation (Cockbain and Playford, 1973) extends throughout the area. On the coastal plain, it is unconformably overlain by superficial formations, and it outcrops on the Blackwood Plateau, where the top few metres are usually lateritized. The formation was encountered at all sites. It locally overlaps the Dunsborough Fault on to the Leeuwin Block.

The Leederville Formation consists of generally fine- to medium-grained quartz sandstone and interbedded grey shale which is often silty, micaceous, carbonaceous, and contains occasional coal stringers. Individual beds are generally five metres or less in thickness. Feldspar, heavy minerals, and pyrite are common. The proportion of shale appears to increase gradually from east to west. Individual beds are not persistent and usually cannot be correlated between neighbouring bores. The upper part of the formation has been eroded, and thickness ranges from about 50 m on the Vasse Shelf to about 500 m in the Bunbury Trough.

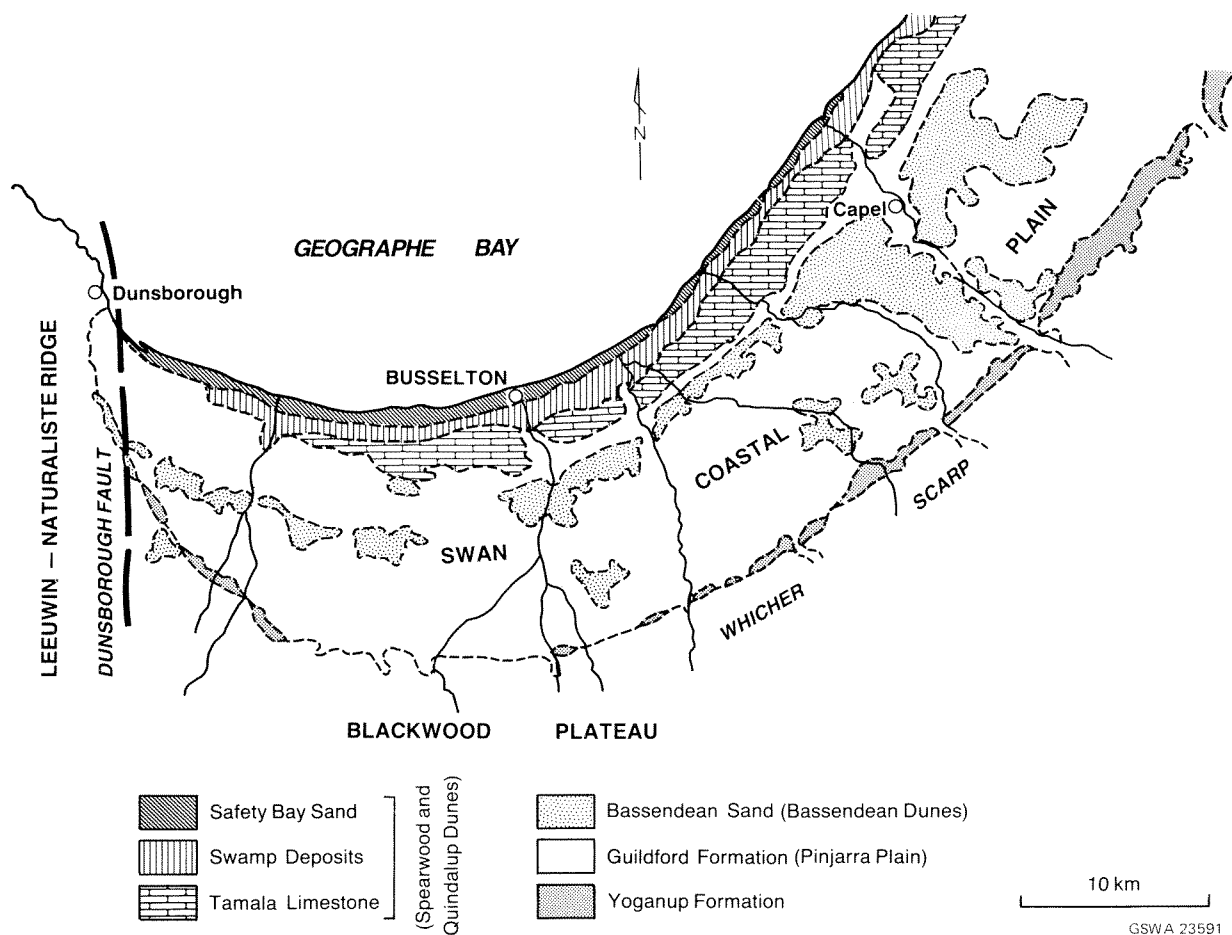


Figure 5. Surface geology and physiographic units of the Swan Coastal Plain

Palynological determinations indicate an Early Cretaceous age. The environment of deposition was mainly non-marine, but occasional marine or shallow near-shore marine horizons are present in some of the bores.

Superficial formations

The Cainozoic sediments of the coastal plain in the Perth Area are referred to collectively as the superficial formations (Allen, 1976), and this convention is adopted here. They rest on an erosional surface which slopes gently from the Whicher Scarp to the coast; and in the Busselton Shallow bores they range in thickness from 3 m to 18 m (Fig. 4). The formations overlap the Dunsborough Fault and overlie granitic rocks of the Leeuwin Block, and they also extend along the main valleys cut into the Whicher Scarp.

The superficial formations comprise littoral, alluvial, eolian, and lacustrine deposits (Fig. 5); and range in age from late Pliocene to Holocene.

The Yoganup Formation (Low, 1971) is a shore-line deposit which occurs discontinuously along the base of the Whicher Scarp (Fig. 5). It consists of leached and ferruginized beach sand, conglomerate, and clay, and is locally lateritized. It contains some of the major heavy-mineral deposits of this region (Baxter, 1977). The formation was intersected only at site BN 22, where it had abundant disseminated heavy minerals. The age of the formation is probably Late Pliocene or Early Pleistocene (Playford and others, 1976).

The Guildford Formation (Low, 1971) is an alluvial deposit which extends from the Yoganup Formation towards the coast and covers large parts of the coastal plain. It also extends into the major valleys of the Whicher Scarp (Fig. 5). The average thickness of the formation increases from about 6 m in the west to about 20 m in the Capel region. It consists mainly of multicoloured clay and sandy clay, but contains occasional discontinuous sand layers and lenses. A ferruginous horizon commonly occurs in the zone of water-table fluctuation.

The Bassendean Sand (Playford and Low, 1972) occurs as a series of dunes that unconformably overlies the Guildford Formation. The dunes form a discontinuous belt of low hills which decreases in width from east to west (Fig. 5). The formation consists of fine to medium, white or yellow, quartz sand and in the Capel area contains accumulations of heavy minerals at its base (Baxter, 1977). Marine fossils exposed in pits at Capel have been dated as Pleistocene (Playford and others, 1976).

The Tamala Limestone (Playford and others, 1976) forms elongate dunes in a 2–3 km wide belt parallel to the coastline (Fig. 5). It unconformably overlies the Leederville Formation and probably also the Guildford Formation. The maximum thickness of the formation in this region is about 15 m. It consists of yellow to grey calcareous eolianite, often with clay interbeds, and locally contains shells. In BN 4, the clay is glauconitic and indicates marine conditions during deposition.

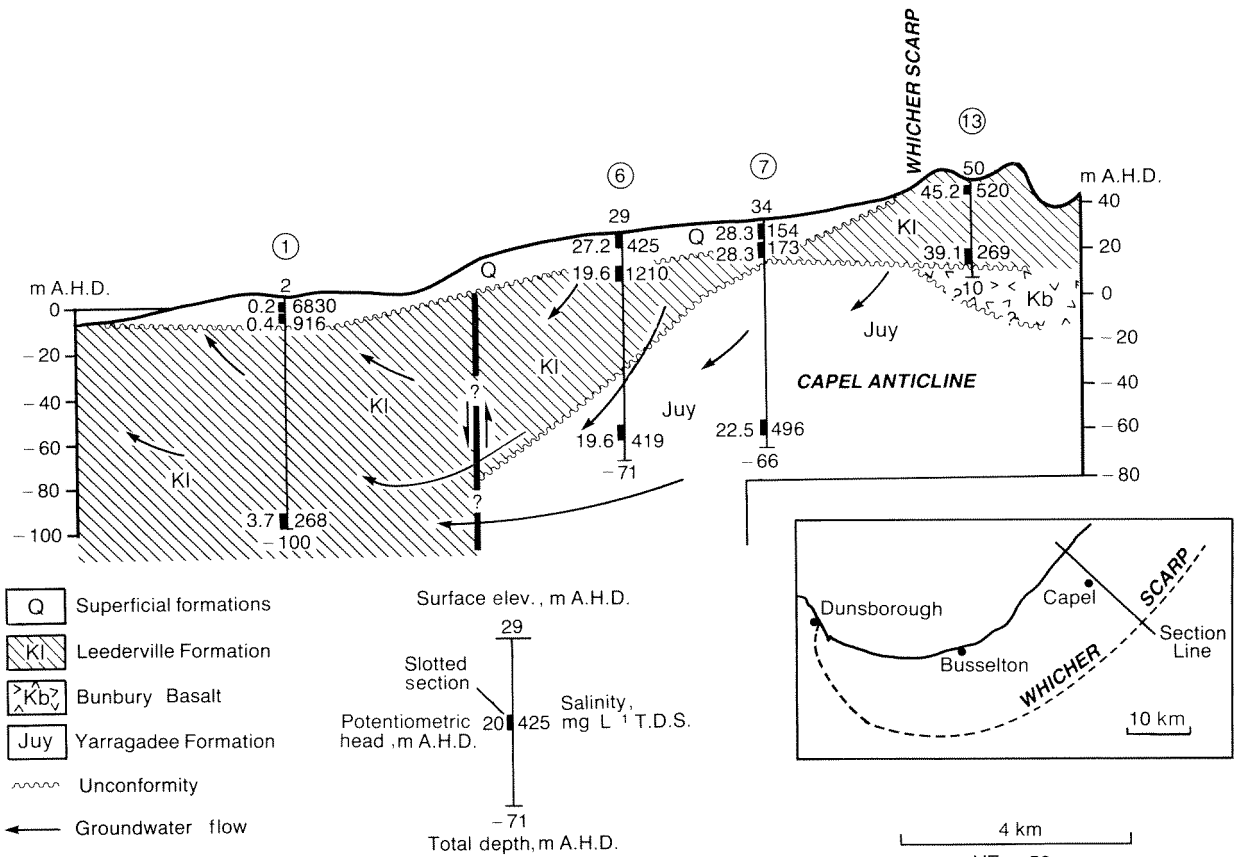


Figure 6. Hydrogeological cross-section through Capel Anticline

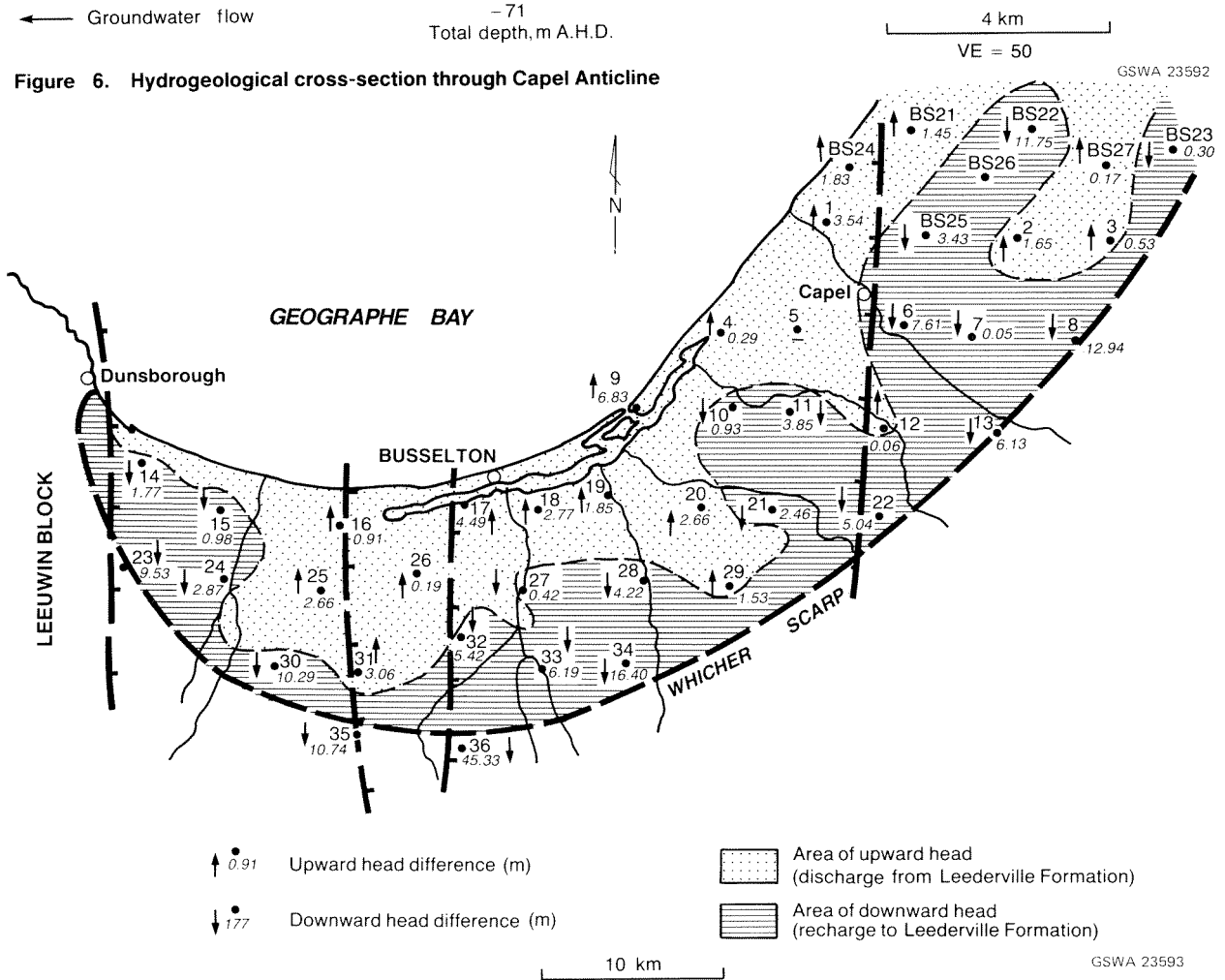


Figure 7. Hydraulic-head difference between superficial formations and Leederville Formation

The age is probably Late Pleistocene (Playford and others, 1976).

The Safety Bay Sand (Playford and Low, 1972) forms a narrow coastal belt of stabilized and mobile dunes of fine wind-blown sand with a high content of shell debris and calcified root channels. Locally, humic and carbonaceous material marks older soil horizons in the succession and fills present interdunal depressions. In the area between Wonnerup and Quindalup, the dunes rise to 3 or 4 m above sea level, whereas farther to the northeast, outside the investigation area, they attain elevations of more than 20 m. They overlie Tamala Limestone and alluvial and estuarine clays.

A belt of alluvial and estuarine deposits parallels the coastline a short distance inland. Alluvium of Holocene age occurs along the river valleys.

STRUCTURE

The sediments of the southern Perth Basin occupy a graben, bounded in the east by the Darling Fault, and in the west by the Dunsborough Fault.

The pre-Cretaceous sediments of the graben are faulted by north-trending faults. The major faults are the Busselton, Wurring, and Darradup Faults (Figs 2 and 3). The Busselton Fault separates the Vasse Shelf, an area of relative uplift in the west, from the deeply down-faulted Bunbury Trough in the east. On the Vasse Shelf, the Leederville Formation attains a thickness of only 50 to 130 m, and it unconformably overlies Permian or Early

Jurassic sediments. In the Bunbury Trough, the Leederville Formation attains a thickness of up to 500 m, and overlies the Yarragadee Formation or, locally, the Bunbury Basalt.

Flexing within the Bunbury Trough has formed the Capel Anticline, which extends in a wide arc from south of Bunbury towards Yoganup and then parallels the Whicher Scarp. Along the axis of the anticline, the Yarragadee Formation is closer to the surface than elsewhere (Fig. 6).

HYDROLOGY

GROUNDWATER FLOW SYSTEMS

Two main flow systems are present in this area: the unconfined aquifer in the superficial formations, and the confined aquifer system in the underlying formations.

The unconfined aquifer is dominated by vertical flow; recharge is to the confined aquifers in the southern part of the coastal plain, and discharge from the confined aquifers into the unconfined aquifer in the northern part of the plain.

The confined aquifers are in hydraulic continuity. Groundwater flow is downward in the south, then about horizontal, and upward near the coast.

SUPERFICIAL FORMATIONS

Extent and lithology

The superficial formations are an anisotropic unconfined aquifer with a saturated thickness of

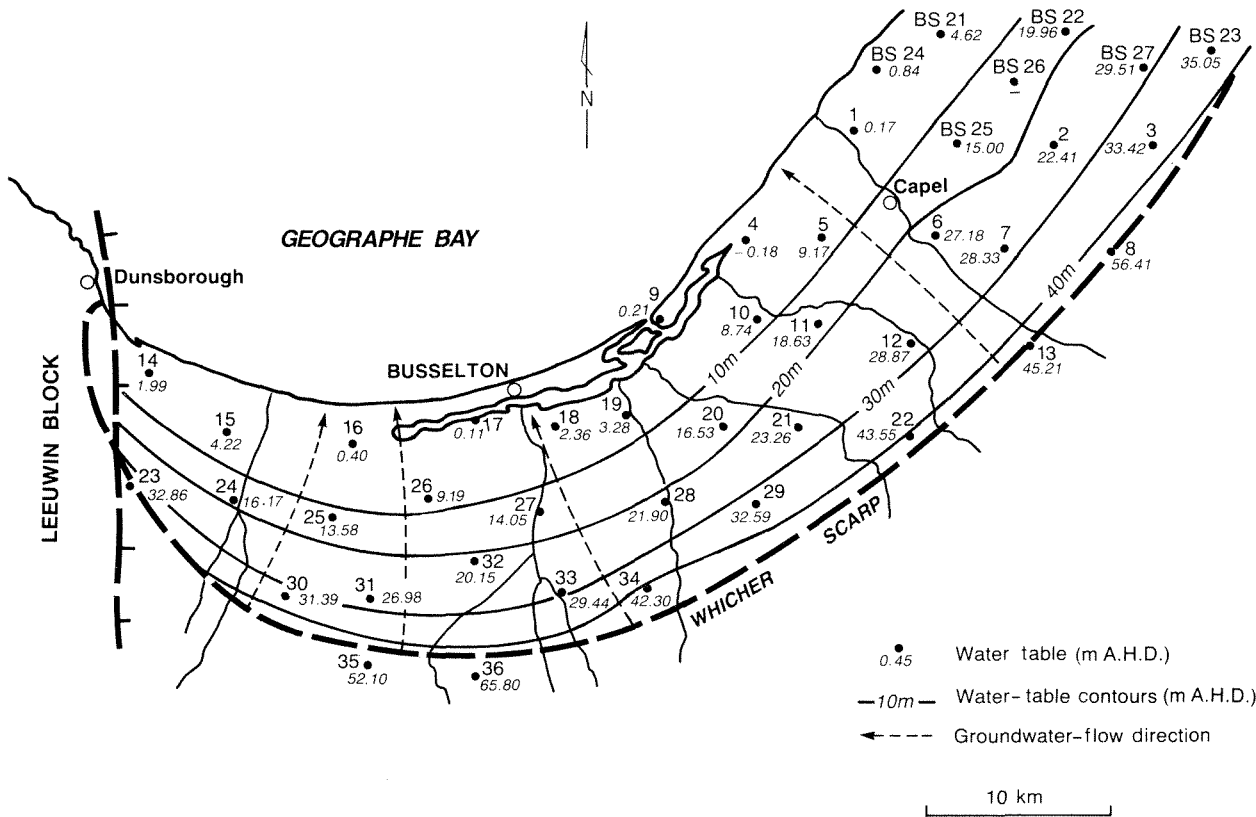


Figure 8. Water-table contours (11/3/85)

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generally 5 m or less. The formations are predominantly clayey, apart from the region of Bassendean Sand and the coastal belt of Tamala Limestone and Safety Bay Sand.

Recharge

Recharge to the unconfined aquifer is mainly by direct infiltration of rainfall, and, in part of the area bordering the coast (Fig. 7), by upward leakage from the Leederville Formation.

Groundwater flow

The water table, which slopes gradually from the Whicher Scarp to the coast, closely parallels the land surface. The water-table contours parallel the present coastline (Fig. 8), and flow directions are to the northwest in the eastern part, and to the north and northeast in the western part of the region.

The seasonal variation of the water table is generally between 0.5 m and 2 m over most of the area, but exceeds 2 m in some areas near the Whicher Scarp where the sediments are particularly clayey (Fig. 9). Hydrographs of two typical sets of bores are shown on Fig. 10.

Discharge

The unconfined groundwater discharges over a salt-water wedge near the coast into the ocean. A large amount of discharge occurs into the rivers and the dense network of drains, but this is dispersed fairly evenly across the coastal plan. Owing to the very shallow water table, the loss of

groundwater from evapotranspiration is likely to be substantial. In an area extending for a few kilometres north of the Whicher Scarp, the hydraulic heads in the superficial formations are higher than in the underlying Leederville Formation, and discharge by downward leakage occurs (Fig. 7); however, because of the clayey nature of the sediments leakage rates are likely to be low.

Groundwater quality

For about half of the area, the salinity ranges between 500 and 1000 mg/L T.D.S.; there is a gradual increase from the Whicher Scarp towards the coast (Fig. 11). A wedge of salt-water occurs along the coast as indicated by the high salinity in some of the shallow bores. In the case of the shallow bore at site BN 20, which is situated in extensive swampland, the high salinity is likely to be due to evaporative concentration.

Analyses of groundwater from the various bores are given in Table 3. A comparison shows that the percentages of the major ions are similar for practically all bores, indicating a close relationship between the different aquifers.

The dominant ions in the shallow bores are sodium and chloride. Calcium and magnesium are significant in the limestone environment near the coast. Some disproportionately high sulphate values (bores BN 1s, 5s, 11s and 30s) are possibly due to fertilizer application. Iron and manganese are known to be generally present in high concentrations, although these parameters were not analyzed from the shallow bores. Silica attains fairly high values, with a maximum of 45 mg/L.

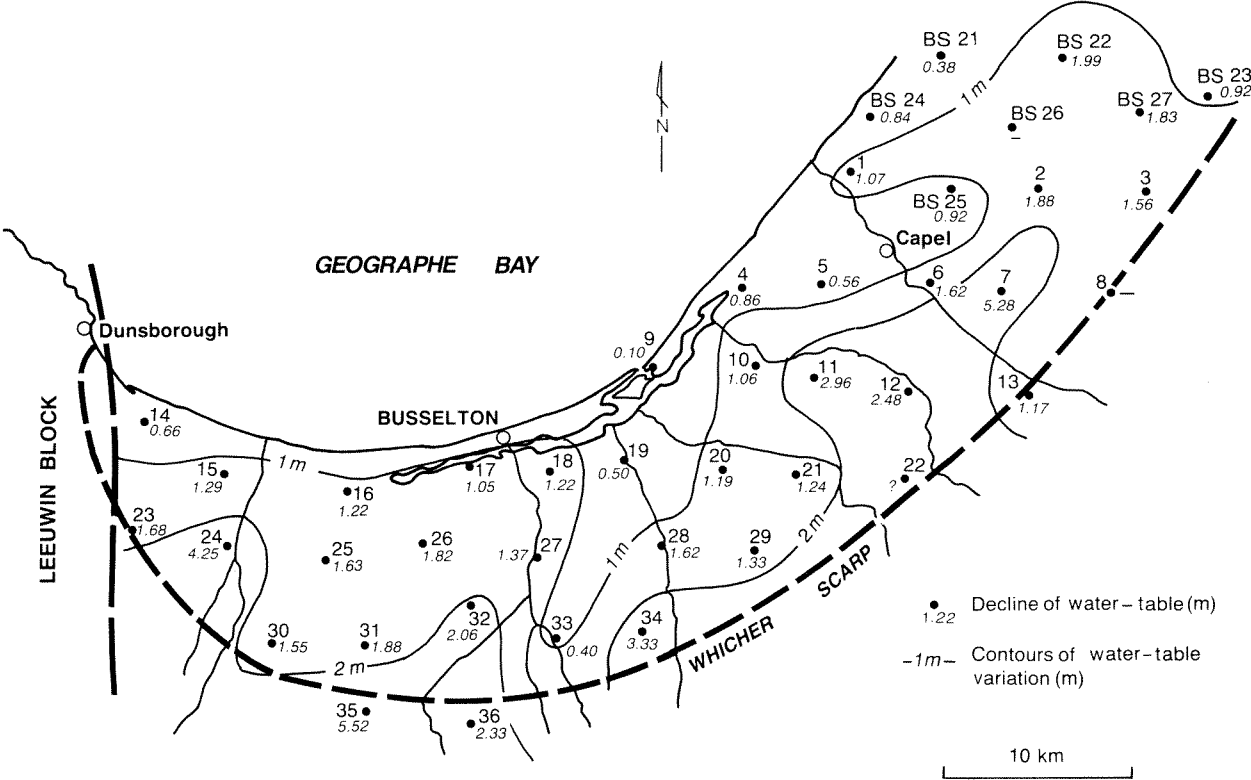


Figure 9. Seasonal variation in water-table elevation

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Nitrate values are generally low, but several high values, with a maximum of 13 mg/L, indicate point-source pollution. All other parameters are within normal background concentrations.

Throughflow

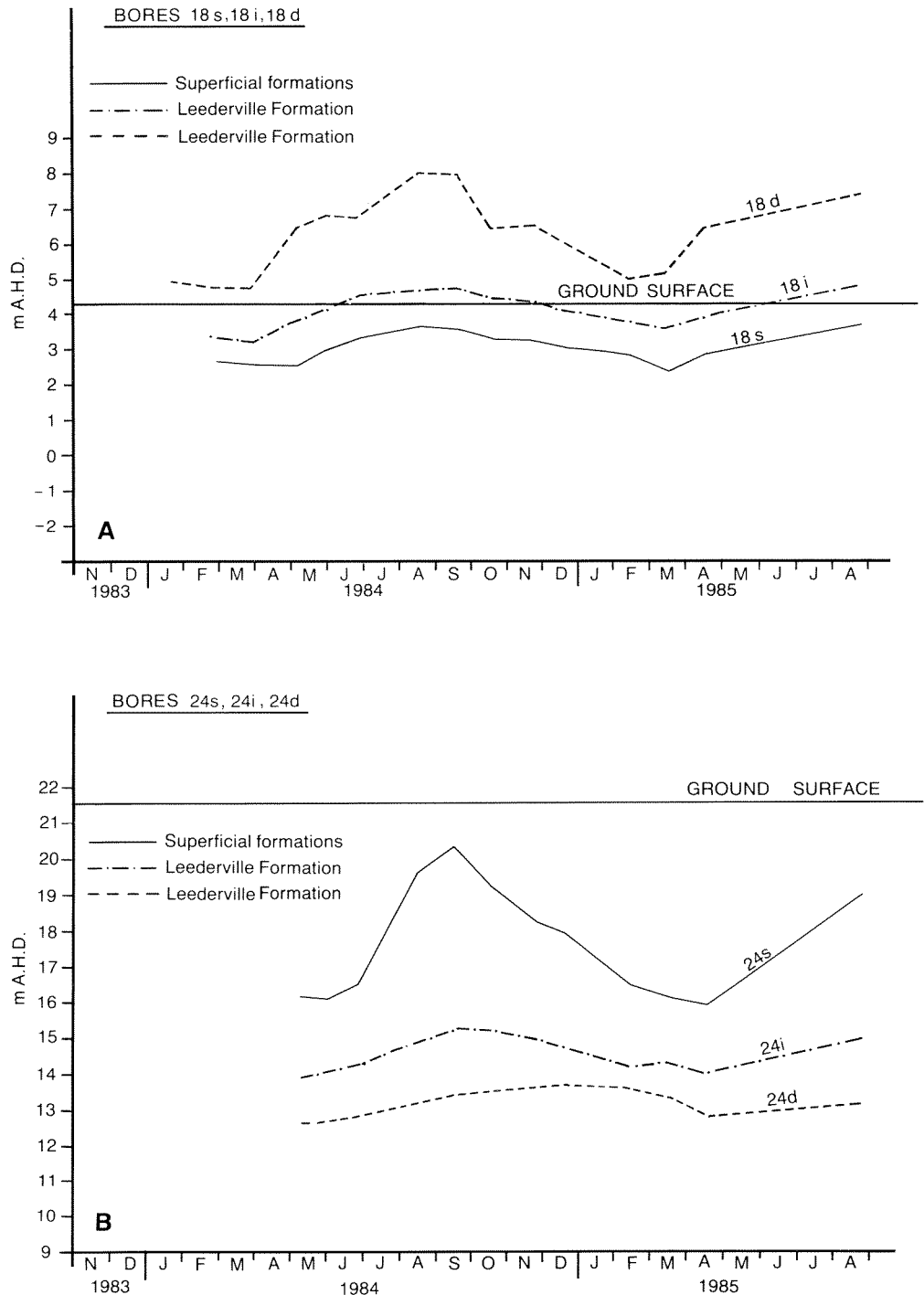
No pumping test data are available for the superficial formations, and for an estimate of the throughflow, the hydraulic conductivity has been assumed to be between 0.5 and 5 m/d.

The average annual throughflow for the superficial formations is estimated to be in the

order of $0.001 - 0.01 \times 10^6 \text{ m}^3/\text{km}$. This very low figure for horizontal flow stresses the fact that this aquifer is dominated by vertical flow.

Development

The shallow groundwater is used extensively for domestic and farm water supplies, mostly by means of soaks. Records of about 1500 shallow soaks, wells, and bores, on the coastal plain between Capel and Dunsborough, are held by the Geological Survey of Western Australia.



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Figure 10. Hydrographs

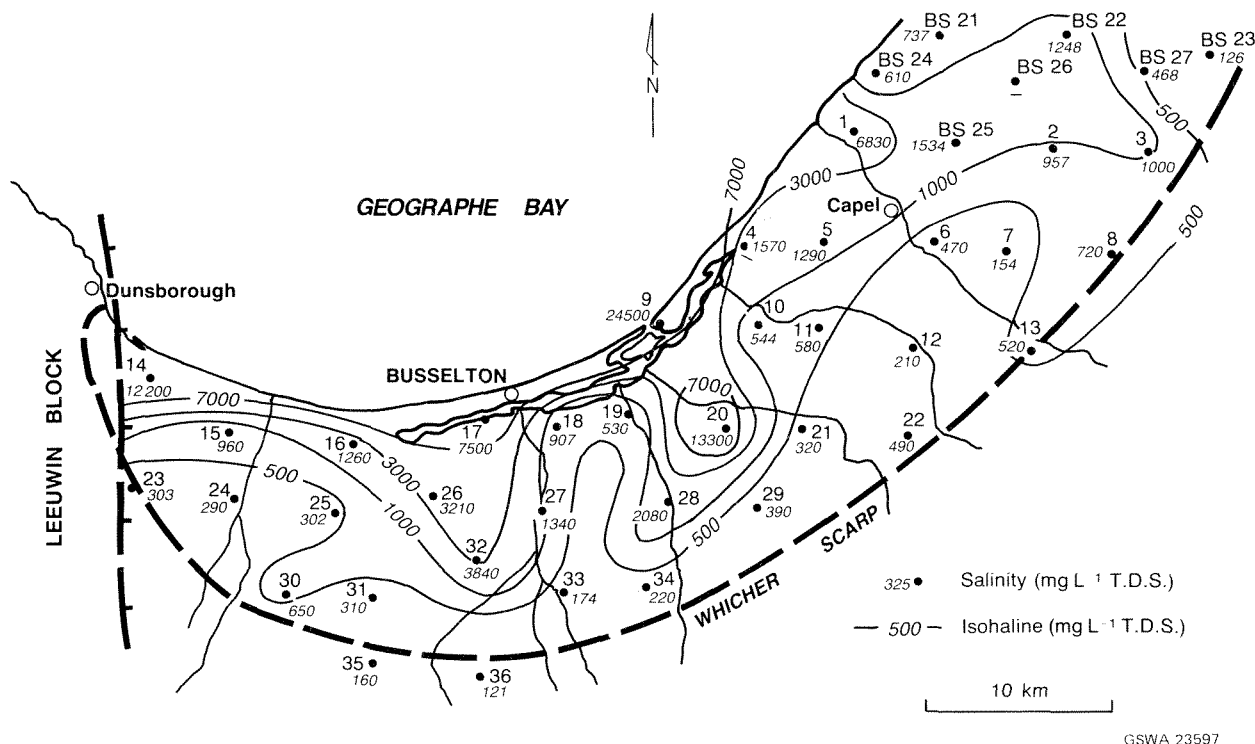


Figure 11. Salinity of groundwater in superficial formations

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LEEDERVILLE FORMATION

Extent and Lithology

The Leederville Formation forms a multilayered, confined aquifer of interbedded sand and shale; its average thickness is between 150 m and 200 m over most of the area, except for the northeast, where it thins over the Capel Anticline, and for part of the Vasse Shelf area. In the fault-angle depression of the Wurring Fault, the formation is about 500 m, e.g. Q 10 (Wharton, 1981).

Recharge

Recharge occurs by direct infiltration of rainfall on the Blackwood Plateau where the formation crops out, and by downward leakage from the superficial formations adjacent to the Whicher Scarp (Fig. 7).

Groundwater flow

The potentiometric contours for March 1985 are shown on Figure 12. Groundwater flow is from the scarp towards the coast, and the potentiometric contours trend broadly parallel to the present coastline. The low hydraulic heads in bores BN 5d and BN 30d are caused by local groundwater abstraction.

Groundwater flow in the Leederville Formation is illustrated by the hydrogeological cross-section (Fig. 13).

The seasonal fluctuation of the potentiometric heads in the Leederville Formation is generally in the range of 1 m to 2 m (Fig. 14).

Discharge

Discharge occurs offshore and, over an area of upward hydraulic gradient that extends several kilometres inland, by upward leakage into the superficial formations (Fig. 7). Discharge also occurs over wide areas of the Blackwood Plateau and the southern part of the coastal plain where the hydraulic gradient is downward, by downward leakage into underlying aquifers.

Throughflow

Throughflow calculations were done separately for the Vasse Shelf area and for the Bunbury Trough west of the Darradup Fault, using Darcy's formula:

$$Q = K i b l \quad (1)$$

Where Q = throughflow, m^3/d

K = hydraulic conductivity, m/d

i = hydraulic gradient

b = saturated thickness, m

l = width of throughflow section, m

The values for the hydraulic conductivity were derived from the pumping tests (Table 4). The low hydraulic conductivity at site BN 15, when compared with those at sites BN 10 and BN 27, confirms the indication from lithological and geophysical logs that the clay content of the Leederville Formation gradually increases from east to west.

TABLE 3. CHEMICAL ANALYSES OF WATER SAMPLES (mg/L)

Bore No.	GSWA Sample No.	Date sampled	pH	Conductivity mS/m at 25°C	TDS	TH	TA	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	NO ₃	SiO ₂	B	F	Fe	Mn
1s	82925	20/02/84	7.9	1 050	6 830	1 200	315	160	202	2 030	37	2	384	2 590	1 600	<1	14	—	0.2	—	—
1i	82509	20/10/83	8.1	167	916	160	290	31	19	280	17	<2	354	311	61	<1	20	0.23	0.3	—	—
1d	82508	18/10/83	8.0	47.8	268	65	108	13	9	59	19	<2	132	66	22	<1	15	0.08	0.3	—	—
2s	82926	20/02/83	7.0	187	957	160	10	8	34	289	10	<2	12	523	48	<1	39	0.07	0.1	—	—
2i	82507	26/10/83	7.6	8.30	4 790	870	410	85	159	1 530	11	<2	500	2 350	386	<1	15	0.33	0.1	—	—
2d	82506	26/10/83	6.8	119	613	120	15	7	25	169	11	<2	18	325	32	<1	35	0.05	0.2	—	—
2p	85530	09/11/84	5.4	123	650	117	12	4	26	180	12	<2	15	345	33	<1	37	0.05	<0.2	21	0.96
3s	82529	01/11/83	7.3	195	1 000	200	17	7	44	291	4	<2	21	549	58	<1	37	0.05	0.1	—	—
3i	82528	02/11/83	7.1	23.1	140	15	9	1	3	32	6	<2	11	56	—	<1	27	<0.05	0.1	—	—
3d	82527	01/11/83	6.3	92	501	86	9	5	18	130	16	<2	11	238	44	<1	44	0.05	0.2	—	—
4s	82927	4/84	7.2	281	1 570	540	265	137	48	372	13	<2	323	670	146	<1	21	—	0.3	—	—
4i	82505	12/09/83	7.8	388	2 170	780	267	194	73	482	13	<2	326	990	228	<1	23	0.11	0.3	—	—
4d	82504	12/09/83	7.1	145	745	180	54	20	32	200	12	<2	66	377	42	<1	29	0.07	0.2	—	—
5s	82928	22/02/84	2.9	251	1 290	460	<2	100	50	188	11	<2	<2	236	663	<1	40	—	0.2	—	—
5i	82503	17/10/83	3.0	304	1 680	580	<2	130	63	248	13	<2	<2	295	—	<1	37	0.41	0.1	—	—
5d	82502	17/10/83	7.6	39.7	228	51	84	9	7	49	20	<2	102	58	20	<1	14	0.05	0.3	—	—
6s	82993	8/84	6.1	87.2	470	73	30	8	13	140	11	<2	37	201	71	1	7	0.1	<0.1	—	—
6i	82546	23/11/83	6.7	241	1 210	210	10	8	46	383	5	<2	12	689	58	<1	19	—	<0.1	—	—
6d	82545	23/11/83	7.5	78.1	419	78	57	8	14	113	11	<2	69	178	33	<1	27	0.05	0.2	—	—
7s	82539	24/11/83	7.4	29.8	154	26	11	4	4	49	<1	<2	13	71	12	<1	7	0.07	<0.1	—	—
7i	82543	23/11/83	6.9	32	173	27	7	1	6	48	1	<2	9	68	12	22	10	0.05	<0.1	—	—
7d	82542	23/11/83	7.3	99.7	496	96	16	4	21	139	13	<2	19	265	27	<1	17	0.06	0.1	—	—
8s	82994	8/84	7.6	123	720	85	347	11	14	247	9	<2	423	170	44	<1	13	0.1	0.3	—	—
8d	82540	25/11/83	7.6	69.3	390	45	28	5	8	114	9	<2	34	170	28	<1	39	0.05	<0.1	—	—
9s	82538	02/12/83	7.7	3 800	24 500	2 600	393	232	483	8 550	189	<2	479	14 000	772	<1	22	—	0.8	—	—
9i	82537	02/12/83	7.3	378	1 950	290	67	44	45	613	30	<2	82	1 120	33	1	22	—	0.5	—	—
9d	82544	05/12/83	6.6	61.7	323	50	53	7	8	87	14	<2	65	141	13	<1	20	0.06	0.4	—	—
10s	82548	06/12/83	7.4	105	544	72	27	4	15	172	<1	<2	33	266	47	<1	23	0.06	<0.1	—	—
10i	82929	22/02/84	4.7	363	1 870	360	2	9	81	559	10	<2	2	1 050	129	<1	26	—	<0.1	—	—
10d	82547	05/12/84	6.5	264	1 330	370	7	23	77	353	11	<2	9	772	65	<1	26	—	0.1	—	—
10p	85524	31/10/84	5.9	243	1 260	336	19	21	69	343	12	<2	23	716	58	<1	28	0.08	0.2	29	0.22
11s	82996	23/11/83	6.4	97.5	580	189	35	28	29	125	5	<2	43	116	245	1	10	0.05	<0.1	—	—
11i	82549	28/11/83	6.8	274	1 420	240	40	8	54	450	<1	<2	49	761	88	<1	32	—	0.2	—	—
11d	82559	28/11/83	7.2	60.1	329	89	54	11	15	74	10	<2	66	136	18	<1	32	0.87	0.2	—	—

12s	82889	8/84	4.3	38.1	210	38	<2	2	8	53	6	<2	<2	84	44	<1	16	0.28	<0.1	—	—
12i	82997	8/84	4.3	153	790	105	<2	4	23	252	4	<2	<2	397	78	<1	32	0.05	<0.1	—	—
12d	82550	12/84	7.3	54.5	304	73	39	11	11	67	10	<2	47	121	26	<1	34	0.05	0.2	—	—
13s	82999	8/84	5.8	90.4	520	47	4	4	9	155	1	<2	5	194	97	10	45	0.05	<0.1	—	—
13d	82541	25/11/83	7.5	48.9	269	34	11	2	7	72	8	<2	14	125	16	<1	32	0.05	<0.1	—	—
14s	82930	22/03/84	7.6	2 040	12 200	4 300	177	556	707	3 060	26	<2	216	6 890	815	<1	15	—	<0.1	—	—
14i	82931	22/03/84	8.2	256	1 330	280	168	45	40	400	19	<2	205	615	97	<1	16	—	0.4	—	—
14d	82932	22/03/84	8.0	58.9	322	120	112	25	13	64	11	<2	137	105	14	<1	21	0.15	0.3	—	—
15s	85501	21/03/84	6.6	183	960	184	33	11	38	286	3	<2	40	469	107	<1	21	0.18	0.1	—	—
15i	83000	21/03/84	7.0	58.5	320	91	61	15	13	68	10	<2	74	126	19	<1	34	0.08	0.2	—	—
15d	82933	23/03/84	7.8	60.8	341	150	125	43	10	53	9	<2	152	102	11	<1	37	0.07	0.2	—	—
15p	85518	10/10/84	7.2	58	340	153	120	45	10	51	8	<2	146	101	11	<1	39	0.07	0.2	—	—
16s	82934	15/03/84	8.2	239	1 260	280	195	56	34	361	14	<2	238	548	93	11	20	—	0.3	—	—
16i	82935	15/03/84	8.2	90.4	508	31	173	6	4	178	7	<2	211	157	22	<1	28	0.16	0.6	—	—
16d	82936	15/03/84	8.6	2 330	13 600	4 200	40	713	591	3 470	135	9	31	8 000	689	<1	10	—	<0.1	—	—
17s	82937	19/03/84	7.4	1 290	7 500	2 200	264	418	271	2 060	18	<2	322	4 030	513	2	23	—	0.1	—	—
17i	85502	8/84	7.7	128	670	182	154	35	23	180	10	<2	188	273	28	1	21	0.1	0.2	—	—
17d	82938	08/02/84	7.2	39.5	225	58	62	10	8	47	10	<2	76	73	11	<1	28	0.06	0.3	—	—
19s	85504	8/84	12.0	308	530	605	594	241	1	70	13	<2	<2	165	16	1	2	—	<0.1	—	—
19i	82941	13/02/84	7.5	53.9	312	57	84	8	9	83	6	<2	102	105	18	<1	33	0.08	0.3	—	—
19d	82942	13/02/84	7.0	45.8	253	63	48	7	11	56	9	<2	58	100	15	<1	26	0.06	0.3	—	—
20s	85505	8/84	6.4	2 150	13 300	2 800	50	68	639	3 990	4	<2	61	7 270	1250	<1	21	—	0.6	—	—
20i	82943	14/02/84	3.7	640	3 430	840	<2	32	186	980	17	<2	<2	1 970	204	<1	45	—	<0.1	—	—
20d	82553	13/12/83	6.3	41.5	250	40	34	3	8	56	12	<2	42	91	15	<1	44	<0.05	0.1	—	—
21s	85506	8/84	5.8	59.3	320	61	34	3	13	80	10	<2	41	136	17	<1	36	0.05	0.2	—	—
21i	82944	13/02/84	6.3	64.6	347	57	22	3	12	91	10	<2	27	165	17	<1	35	0.05	0.1	—	—
21d	82561	30/04/84	7.3	64.3	373	100	97	19	13	80	11	<2	118	129	12	<1	50	0.06	0.2	—	—
22s	85531	14/11/84	5.9	89.5	490	69	9	3	15	142	8	<2	11	247	31	<1	34	0.06	0.1	—	—
22d	82552	07/12/83	6.9	63.4	352	58	34	5	11	94	9	<2	41	148	29	<1	35	0.06	0.2	—	—
23s	82945	20/03/84	6.8	57.2	303	35	18	4	6	87	10	<2	22	138	27	<1	20	0.09	<0.1	—	—
23i	82946	20/03/84	6.8	46.2	256	32	20	3	6	65	11	<2	25	110	19	<1	29	0.06	0.1	—	—
23d	82947	20/03/84	8.0	74.3	410	99	154	23	10	109	11	<2	—	101	47	<1	15	0.20	0.4	—	—
24s	85507	8/84	5.4	59	290	42	2	2	9	95	1	<2	3	152	24	<1	6	0.05	<0.1	—	—
24i	82948	26/03/84	6.1	110	564	140	22	14	25	146	8	<2	27	294	35	<1	28	0.08	0.3	—	—
24d	82949	26/03/84	8.1	49.7	283	85	140	24	6	67	6	<2	171	58	16	<1	20	0.11	0.2	—	—
25s	82950	27/03/84	6.6	55.5	302	62	36	5	12	79	8	<2	44	130	16	<1	30	0.06	0.1	—	—
25i	82951	27/03/84	6.3	45.5	254	49	32	3	10	62	9	<2	39	105	13	<1	32	0.05	0.1	—	—
25d	82952	27/03/84	8.1	51.1	285	100	135	22	11	59	9	<2	165	68	13	<1	—	0.13	0.1	—	—
26s	82953	01/03/84	6.6	559	3 210	510	15	22	111	1 030	3	<2	18	1 770	244	<1	23	—	0.2	—	—
26i	82954	01/03/84	4.4	153	757	140	<2	9	29	226	7	<2	<2	415	45	<1	25	0.06	0.3	—	—
26d	82955	02/03/84	7.7	55.1	309	59	78	9	9	80	6	<2	95	108	19	<1	30	0.07	0.5	—	—

TABLE 3. CHEMICAL ANALYSES OF WATER SAMPLES (mg/L)—continued

Bore No.	GSWA Sample No.	Date sampled	pH	Conductivity mS/m at 25°C	TDS	TH	TA	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	NO ₃	SiO ₂	B	F	Fe	Mn
27s	—	—	—	—	(1 340)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
27i	82956	28/02/84	6.1	122	620	120	14	5	27	178	7	<2	17	333	36	<1	25	0.06	0.1	—	—
27d	82957	29/02/84	7.3	42.1	243	43	59	4	8	63	6	<2	72	83	13	<1	30	0.06	0.3	—	—
27p	85521	23/10/84	6.7	43.9	250	39	57	4	7	66	6	<2	69	89	15	<1	29	0.05	0.4	14	0.15
28s	85508	8/84	7.7	364	2 080	589	557	124	68	570	8	<2	680	754	189	<1	23	—	0.4	—	—
28i	82958	15/02/84	7.2	147	752	140	45	7	29	227	7	<2	55	384	46	<1	24	0.06	0.1	—	—
28d	82959	28/02/84	7.6	72.2	382	82	43	8	15	97	11	<2	52	179	14	<1	32	0.06	0.4	—	—
29s	85510	8/84	6.0	72	390	63	20	2	14	111	8	<2	25	185	25	<1	31	0.05	0.1	—	—
29i	82960	16/02/84	7.5	59.2	318	50	25	2	11	85	7	<2	30	148	17	<1	33	0.06	<0.1	—	—
29d	85509	8/84	6.8	36.6	220	34	30	2	7	48	11	<2	37	76	13	<1	40	<0.05	0.1	—	—
30s	85511	8/84	7.2	110	650	70	145	15	8	210	6	<2	177	110	135	2	12	0.6	0.1	—	—
30i	82961	28/03/84	6.5	44.3	250	51	25	4	10	57	8	<2	30	106	14	<1	36	0.08	0.2	—	—
30d	82962	28/03/84	8.1	44	251	110	138	30	8	44	8	<2	168	45	10	<1	22	0.08	0.1	—	—
31s	85512	8/84	6.7	55.9	310	73	81	11	11	81	6	<2	99	98	33	<1	18	0.25	0.1	—	—
31i	82963	29/03/84	6.6	32.3	195	30	32	2	6	44	9	<2	39	73	9	<1	32	0.06	0.1	—	—
31d	82964	16/03/84	6.2	38.9	230	34	36	2	7	54	10	<2	44	86	12	<1	37	0.05	0.1	—	—
32s	85513	8/84	6.2	690	3 840	668	25	27	146	1 220	5	<2	31	—	388	<1	21	—	0.2	—	—
32i	82965	30/03/84	6.3	267	1 350	250	26	12	54	415	7	<2	32	747	68	<1	26	—	0.3	—	—
32d	82966	29/03/84	7.6	75.1	407	82	85	5	17	111	7	<2	104	159	23	<1	33	0.07	0.5	—	—
33s	82967	13/03/84	7.2	31	174	19	16	1	4	50	2	<2	19	61	30	1	15	0.05	0.1	—	—
33i	82968	13/03/84	7.3	34.4	192	26	23	2	5	51	6	<2	28	79	11	<1	24	0.06	<0.1	—	—
33d	82969	10/03/84	7.0	40.5	226	44	30	3	9	54	8	<2	37	93	13	<1	27	0.06	0.2	—	—
34s	85514	8/84	6.6	41.1	220	17	12	2	3	75	1	<2	15	96	21	4	6	0.05	<0.1	—	—
34i	82970	12/03/84	6.4	52.6	285	53	11	3	11	67	11	<2	14	137	15	<1	34	0.06	0.2	—	—
34d	82971	29/02/84	6.8	36.9	196	26	17	2	5	55	4	<2	21	89	13	<1	17	0.05	<0.1	—	—
35s	85515	8/84	5.9	31.7	160	39	7	4	7	41	4	<2	8	68	18	13	3	0.05	<0.1	—	—
35d	82972	3/84	7.1	35.9	209	30	26	2	6	49	9	<2	32	82	12	<1	33	0.06	0.1	—	—
36s	82973	14/03/84	6.3	22.3	121	26	10	2	5	29	3	<2	12	49	10	8	9	0.06	<0.1	—	—
36d	82974	14/03/84	6.8	39.8	248	65	56	8	11	44	11	<2	68	79	13	1	47	0.06	0.3	—	—

Chemical analyses carried out by Government Chemical Laboratories, Perth.

TDS — Total dissolved solids by calculation at 180°C

TH — Total hardness as calcium carbonate

TA — Total alkalinity as calcium carbonate

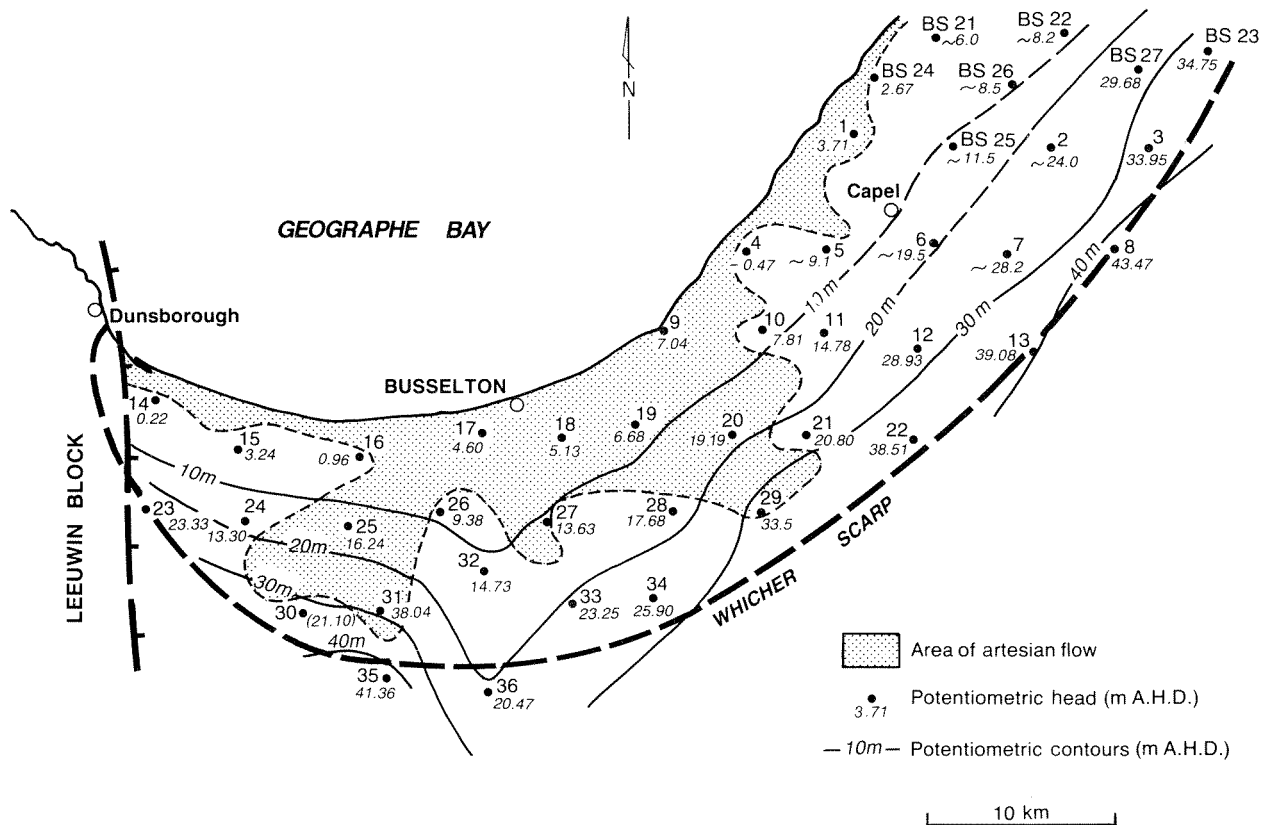


Figure 12. Potentiometric head in the Leederville Formation (11/3/85)

GSWA 23598

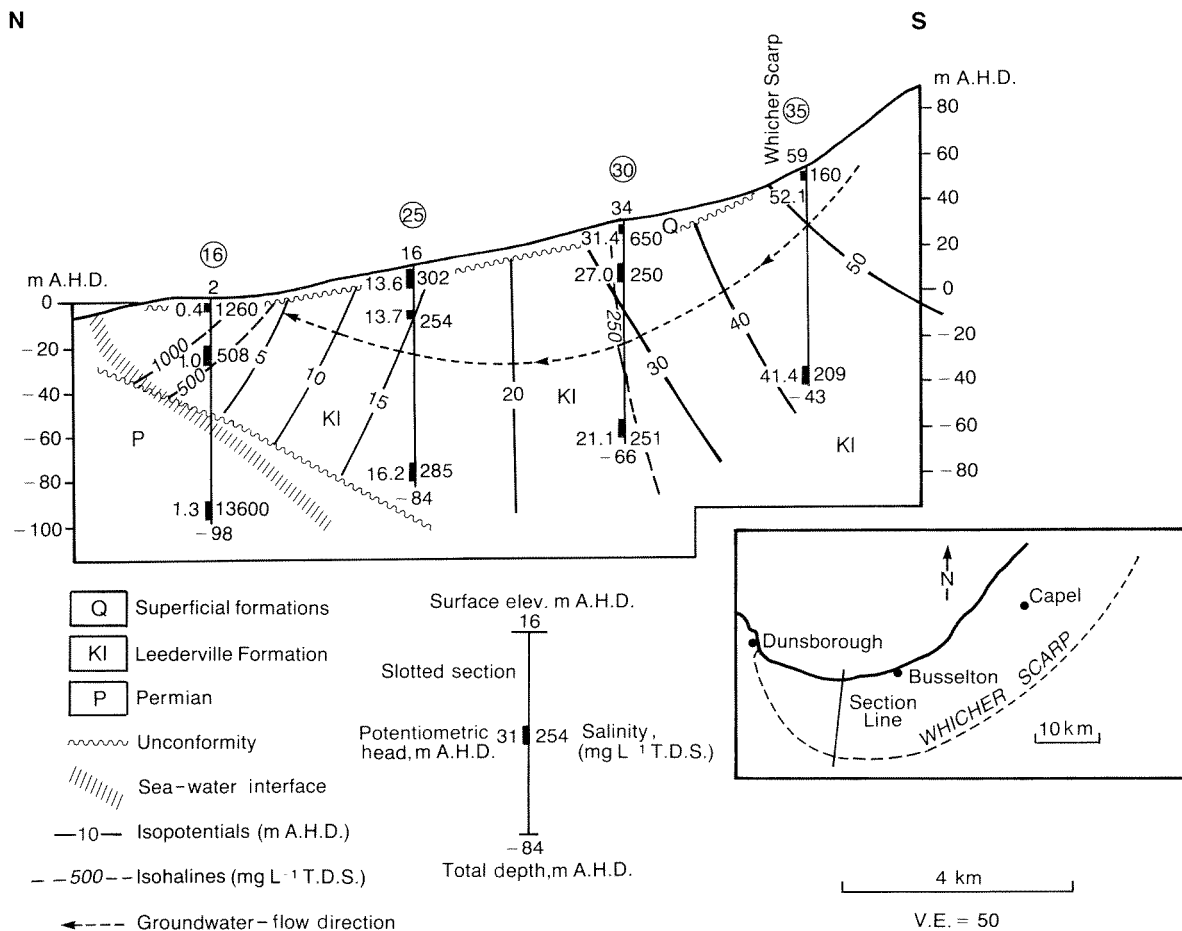


Figure 13. Hydrogeological cross-section—Leederville Formation

GSWA 23598

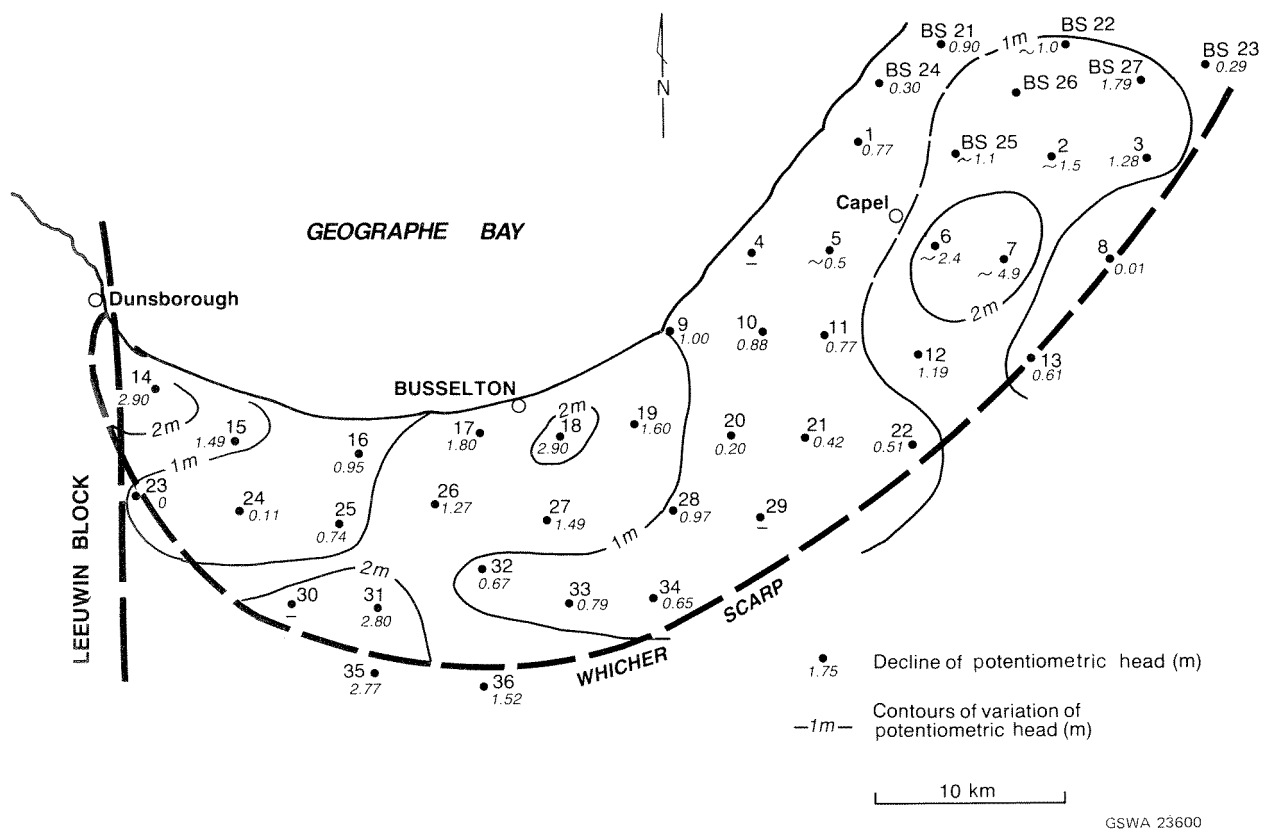


Figure 14. Seasonal variation in potentiometric head in Leederville Formation

The average proportion of saturated sands was derived from data from the Quindalup Line and the lithological and geophysical logs of the Busseton Shallow program. The hydraulic gradient was obtained from the plan of the potentiometric contours (Fig. 12). Throughflow was calculated across the 10 m potentiometric contour.

The following values were used:

Vasse Shelf	Bunbury Trough
K=2 m/d	K=6 m/d
i=0.003	i=0.0025
b= 50 m	b=100 m
l=15 000 m	l=28 000 m
Q=4 500 m ³ /d	Q=42 000 m ³ /d

The annual throughflow for the Vasse Shelf area is therefore of the order of 1.6×10^6 m³, or 0.11×10^6 m³/L, and for the Bunbury Trough in the order of 15×10^6 m³, or about 0.5×10^6 m³/km.

For the Leederville Formation east of the Darradup Fault, on the Capel Anticline, data are insufficient for a throughflow calculation. In this area the formation is relatively thin, and throughflow is probably small.

Groundwater quality

The groundwater salinity in the upper 100 m of the Leederville Formation is shown in Figure 15. With the exception of bore BN 10d, the salinity is less than 500 mg/L T.D.S. The salinity increases gradually in the direction of groundwater flow.

The groundwater is again of the sodium chloride type (Table 3). Iron and manganese values were determined for the pumping bores and were found to be high, with maxima of 29 mg/L and 0.5 mg/L, respectively. Silica is present in generally greater than normal background concentrations: the maximum is 50 mg/L. None of the other parameters exceeds background values.

TABLE 4. RESULTS OF PUMPING TESTS

Site	Pumping rate (m ³ /d)	Final drawdown (m)		Transmissivity (m ² /d)	Hydraulic conductivity (m/d)	Storage coefficient	Aquifer
		Pumping Bore	Deep Obs. Bore				
BN 2	337	20.4	0.47	49	8	2.1×10^{-4}	Juy
BN 10	220	15.1	3.1	34	6	2.7×10^{-4}	KI
BN 15	280	23.2	5.8	12	2	1.4×10^{-4}	KI
BN 27	450	15.1	7.2	39	7	0.9×10^{-4}	KI

KI—Leederville Formation

Juy—Yarragadee Formation

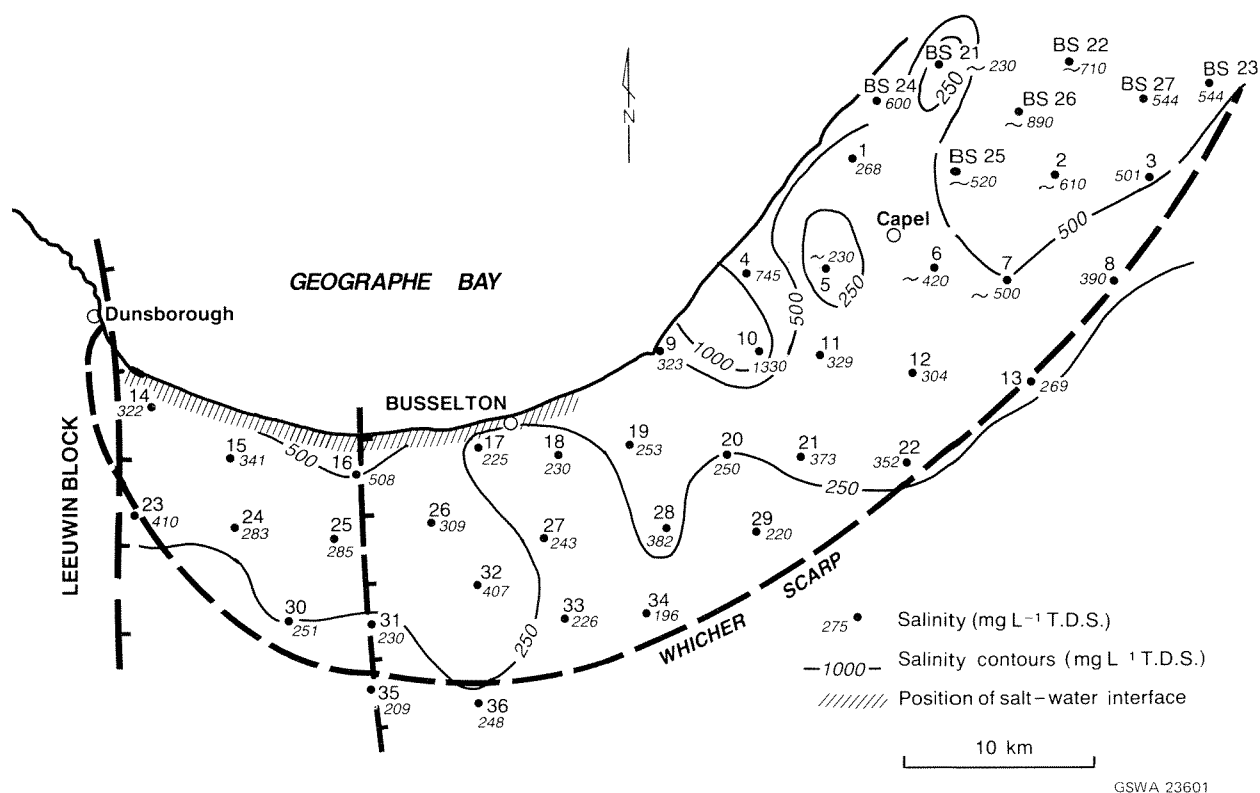


Figure 15. Salinity in the Leederville Formation

Development

The Leederville Formation west of the Darradup Fault is being used extensively for private and municipal water supplies, and about 400 bores with a depth of more than 50 m are on record with the Geological Survey. Annual abstraction from the formation is estimated to be about $5 \times 10^6 \text{ m}^3$.

YARRAGADEE FORMATION

Extent and lithology

The Yarragadee Formation occurs only in the Bunbury Trough. It was intersected in five of the Busselton shallow bores, in an area from Capel northeastwards, along the Capel Anticline (Fig. 12).

The formation is predominantly sandstone. Individual sandstone sections are typically 20 m or more thick, and are separated by shale beds generally up to 10 m thick.

Recharge

Recharge to the Yarragadee Formation is assumed to be by downward leakage from the Leederville Formation, particularly over the northern half of the Blackwood Plateau south of the investigation area, and in the region of the Capel Anticline, northeast of Capel.

Groundwater flow

Groundwater flow is thought to be from the Blackwood Plateau towards the coast, and the flow pattern in the Capel area is probably similar to that in the Leederville Formation.

Discharge

Discharge from the formation is likely to occur offshore, also by upward leakage into the Leederville Formation near the coast where the hydraulic gradient is upward, e.g. Quindalup Line bores Q 4 and Q 10 (Wharton, 1981).

Throughflow

The pumping test carried out at site BN 2 indicates that the Yarragadee Formation has a higher hydraulic conductivity than the Leederville Formation (Table 4), although when compared with values derived for the Yarragadee Formation elsewhere, e.g. BS 10 (Commander, 1984), it still appears to be relatively low.

A throughflow calculation along the 10 m potentiometric contour was done for the top 500 m of the Yarragadee Formation in the area east of the Darradup Fault, using Darcy's equation (1) and the following parameters:

$$K=8 \text{ m/d}$$

$$i=0.004$$

$$b=350 \text{ m (assumed 70% of saturated sandstone)}$$

$$l=5000 \text{ m (between the Darradup Fault and bore BS 22)}$$

$$Q=56000 \text{ m}^3/\text{d}$$

The annual throughflow for this area is therefore in the order of $20 \times 10^6 \text{ m}^3$, or about $4 \times 10^6 \text{ m}^3/\text{km}$.

Groundwater quality

The salinity of the groundwater encountered in the Yarragadee Formation is in the range of 230

mg/L to 900 mg/L T.D.S., with an apparent increase towards the northeast. The percentages of the major ions are similar to those in the Leederville Formation (Table 3), suggesting a close relationship between the two aquifers. Iron and manganese values in the pumping bore BN 2P are high, at 21 mg/L and 0.96 mg/L, respectively.

Development

The water supplies for the Township of Capel, and for the heavy-mineral sand processing in this region, are drawn from the Yarragadee Formation. Total annual abstraction is estimated to be about $4 \times 10^6 \text{ m}^3$.

In view of the calculated throughflow, and the substantial thickness of the formation, there appears to be potential for further development, particularly of the lower sections of the Yarragadee Formation.

SUE COAL MEASURES

The top portion of this formation consists predominantly of sandstone and interbedded minor beds of shale.

Recharge is likely to occur by downward leakage from the Leederville Formation, but there are insufficient data to determine the direction of groundwater flow.

Indications from bores into this formation are that the groundwater salinity is generally low (PWD bores 2/82 and 3/82, and Sumich bore). Near the coast, the formation has been intruded by salt water, as indicated by the high salinity of bore BN 16 d. The water from this bore also has above normal concentrations of calcium, magnesium, potassium and sulphate.

CONCLUSIONS

The Busselton shallow-drilling project has provided new information on the hydrogeology of the superficial formations, the upper parts of the Leederville and Yarragadee Formations, and the Sue Coal Measures.

The unconfined groundwater is only of minor importance in this region because of the limited thickness and predominantly clayey nature of the superficial formations. It is commonly too saline for domestic use.

The Leederville Formation constitutes the main aquifer. Its thickness ranges from about 50 m in the west and on the Capel Anticline to about 500 m in the centre of the Bunbury Trough. Annual throughflow ranges from about $0.1 \times 10^6 \text{ m}^3/\text{km}$ in the Vasse Shelf area to about $0.5 \times 10^6 \text{ m}^3/\text{km}$ in the Bunbury Trough. The salinity is generally less than 500 mg/L T.D.S.

In the region of the Capel Anticline, northeast of Capel, the Yarragadee Formation is close to the surface and constitutes the major groundwater source. Annual throughflow for the upper 500 m of the formation is about $4 \times 10^6 \text{ m}^3/\text{km}$. The salinity is generally slightly higher than in the Leederville Formation.

In the western part of the Vasse Shelf, the Leederville Formation is underlain at shallow depth by the Sue Coal Measures. So far, very few bores have been drilled into this formation, but they indicate that the salinity is generally low. The formation has the potential to become the major groundwater source in this area.

The percentages of the major ions in groundwater from the different aquifers are similar, indicating hydraulic connection between the aquifers. Along the coast, the aquifers are intruded by a salt-water wedge.

All confined aquifers have the potential for further development, particularly at greater depths than are being exploited at present.

Monitoring of the bores has provided data on seasonal changes of the potentiometric head in the aquifers, and these results will assist in the future management of the groundwater resources in this region.

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HYDROGEOLOGY OF THE SUPERFICIAL FORMATIONS BETWEEN LANCELIN AND GUILDERTON

by J. S. Moncrieff and M. Tuckson

ABSTRACT

Drilling at 22 sites on the Swan Coastal Plain between Guilderton and Lancelin, during 1976 and 1980, has extended knowledge of the stratigraphy, structure and hydrogeology of the Late Tertiary to Quaternary superficial formations. The bores intersected a predominantly shallow-water marine and eolian sequence which has been successively deposited in bands subparallel to the coast. The sediments consist of calcarenite and sand along the coast, sand further east, clay over sand in the southeast, and an underlying Pliocene limestone. The superficial formations average about 50 m in thickness and overlie eroded and weathered Cretaceous sediments of the Leederville Formation, the Osborne Formation and the Lancelin beds.

The sediments contain a mainly unconfined groundwater flow system which receives rainfall recharge in all areas, except where surface clay is present in the southeast. Direct rainfall recharge is about 7% of average annual rainfall, and a subordinate amount of recharge originates from runoff onto the coastal plain in the east. The water table reaches an elevation of just over 70 m in the Regans Ford Area in the northeast, from where groundwater flows westward and southward to discharge to the sea and Gingin Brook. The Moore River is mainly a gaining stream but at times of high-river stage there is groundwater recharge from the river between Karakin and Bidaminna Lakes. Groundwater discharge occurs as leakage to the Leederville Formation in the northeast, under a downward hydraulic-head gradient, and there is minor upward leakage from the Leederville Formation in the southeast.

Groundwater storage in the superficial formations is estimated to be $8 \times 10^9 \text{ m}^3$. A large, undeveloped resource of fresh, unconfined groundwater has been found in the Regans Ford Area from where the annual throughflow past the 50 m water-table contour is estimated to be $16 \times 10^6 \text{ m}^3$.

More than half of the area contains groundwater of less than 750 mg/L TDS. The groundwater is of the sodium chloride type and contains high concentrations of dissolved iron in many places. There are areas of higher salinity groundwater, exceeding 1000 mg/L TDS, near Karakin and Bidaminna Lakes, due to recharge from the Moore River, and in the southeast, which is an area of groundwater discharge. A salt-water wedge occurs at the base of the flow system along the coast.

Current abstraction is estimated to be about $5 \times 10^6 \text{ m}^3/\text{year}$. This includes the town-water supplies for Lancelin, Ledge Point and Guilderton.

INTRODUCTION

LOCATION

The area of study extends over about 1200 km² of the coastal plain between Lancelin and Guilderton, about 90 km north from Perth (Fig. 1). This area was informally known as the Salvado region and falls within the Gingin Groundwater Area which is administered by the Water Authority of Western Australia.

PURPOSE

The project was carried out by the Geological Survey of Western Australia (GSWA) with the following purposes: to investigate the hydrogeology of the superficial formations*; to identify the

underlying Mesozoic formations; to assess the groundwater resources of the area; and to provide a network of groundwater observation bores.

The project was jointly funded by the Commonwealth and State Governments as part of a long-term program to evaluate the groundwater resources of the Perth Basin.

CLIMATE AND LAND USE

The area has a Mediterranean climate characterized by hot, dry summers and cool, wet winters.

The average annual rainfall decreases from just over 700 mm in the south to 623 mm in the northwest, at Lancelin. Rainfall exceeds potential evaporation only during May to August.

About 40% of the land has been cleared of native vegetation, mainly for pastoral purposes,

* 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).

although some intensive market gardening, floriculture and fodder-crop production are undertaken.

Lancelin, Ledge Point, Seabird and Guilderton are small fishing and holiday resorts. Gingin, to the southeast, is a centre for the local agricultural and grazing activities.

PREVIOUS WORK

Groundwater occurrence around Lancelin was investigated for the town-water supply by Morgan (1964) and drilling confirmed the existence of fresh groundwater in the Quaternary sediments just east of the town. Lancelin 2B also penetrated about 14 m into the underlying Cretaceous sequence.

The hydrogeology of the superficial formations of the coastal plain south of the study area has been described by Allen (1976). Exploratory drilling for the Cataby Shallow Drilling Project extends to the north of the area described here, and was commenced by the GSWA in 1985. The GSWA has also undertaken drilling to evaluate the deep groundwater resources along the Gingin Brook Line (Sanders, 1967) in the south and the Gillingarra Line (Moncrieff, in press) in the north.

PHYSIOGRAPHY

Landforms

The area lies on the Swan Coastal Plain (Playford and others, 1976) which is separated from the Dandaragan Plateau to the east by the Gingin Scarp, a former shoreline. The coastal Plain is

about 38 km wide and may be subdivided into three main geomorphological units: The Coastal Belt; the Bassendean Dunes; and the Pinjarra Plain (Playford and others, 1976) These closely correspond with the major geological units (Fig. 5).

The Coastal Belt consists of the Quindalup Dunes formed by the Safety Bay Sand, along the coast, and the Spearwood Dunes which are coextensive with the Tamala Limestone. The Bassendean Dunes are formed by the Bassendean Sand. The Pinjarra Plain is underlain by the Guildford Formation and is locally termed the Beermullah Plain, west of Beermullah Lake.

Drainage

The Moore River and its tributary Gingin Brook are the major drainages. The Moore River rises on the Darling Plateau, 35 – 80 km east to northeast of the area. It flows across the Dandaragan Plateau and reaches the coastal plain at Regans Ford; it discharges to the ocean at Guilderton. The river-water salinity on the coastal plain ranges from fresh to saline (560 – 9800 mg/L), with the highest salinity during winter when salinized areas, to the east, contribute to the runoff. Gingin Brook and the small Red Gully Creek rise on the Dandaragan Plateau. They contain fresh to brackish water.

Surface flow mainly ceases during summer and recommences in response to winter rainfall. Permanent pools and small baseflows in the Moore River and Gingin Brook are maintained during summer by groundwater discharge.

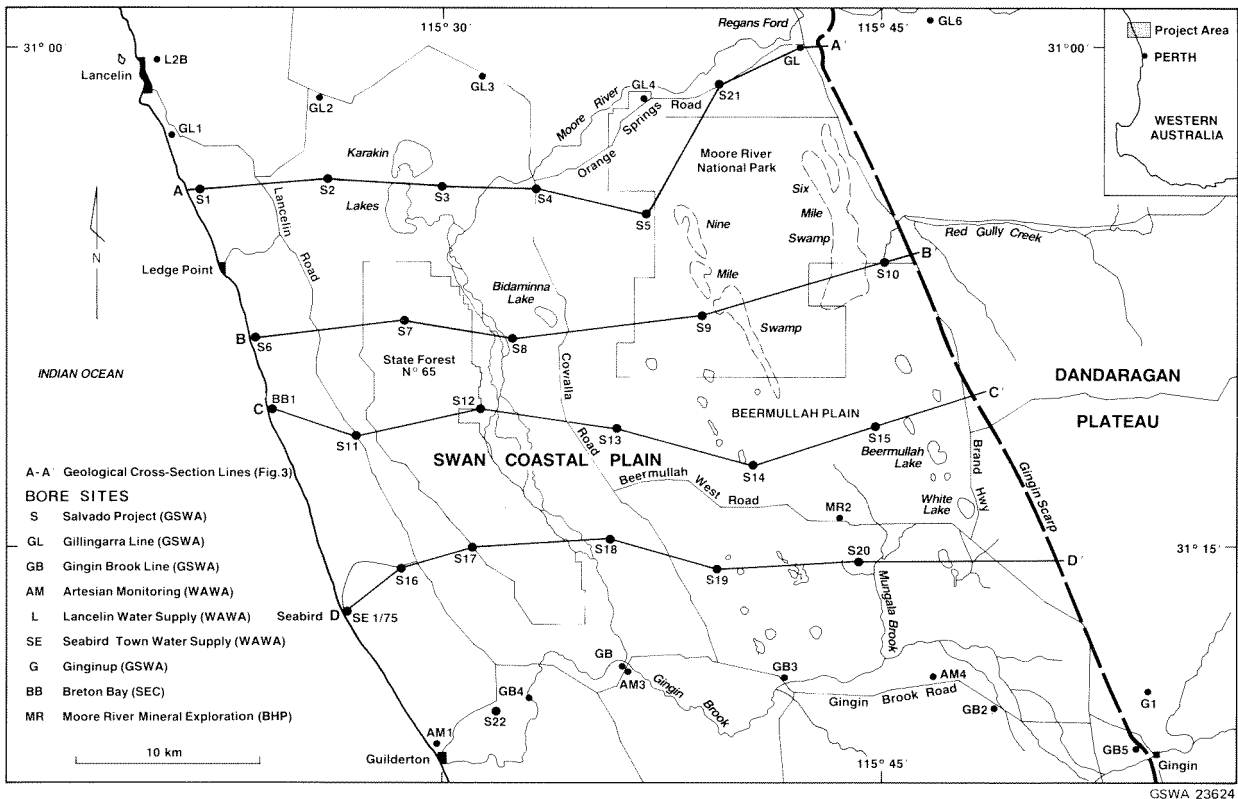


Figure 1. Location map

Numerous lakes and swamps occupy an aggregate area of about 15 km². These occur mainly in interdunal depressions of the Bassendean Dunes (Six Mile and Nine Mile Swamps) or on the Pinjarra Plain (Beermullah and White Lakes). Karakin Lakes lie within the Spearwood Dunes and Bidaminna Lake is at the boundary between the Spearwood and Bassendean Dunes. An estimated area of 60 km², on and north of the Pinjarra Plain, becomes partially inundated for periods of up to several days after heavy winter rain. The lakes are seasonal or ephemeral and range from fresh (less than 1000 mg/L TDS) to saline (10 000–15 000 mg/L TDS). How (1978) has reported significant diurnal variations in the chemistry and fauna of Lake Beermullah during November 1978.

INVESTIGATION TECHNIQUES

Drilling and bore construction

Thirty-one bores, between 19.2 m and 127.0 m deep, were constructed at 22 sites along four, roughly east-west, lines across the coastal plain (Fig. 1). An observation bore was drilled at each site and an accompanying test-production bore at 9 sites. The aggregate depth drilled was 2437 m. Bore-completion data are summarized in Table 1.

Initially three observation bores were drilled in 1976 by the Public Works Department (S11, S16, S22) using a cable-tool percussion rig, but these did not penetrate the entire Cainozoic section. The bores are completed with 203 mm mild-steel casing and 152 mm stainless steel, 0.7 mm aperture, continuous slot, telescopic screens without a gravel pack.

The remainder of the bores were drilled during 1980 by the Mines Department Drilling Section using mud-flush or air-flush rotary techniques. The observation bores are cased with 100 mm PVC which is slotted over selected intervals. The test-production bores contain 203 mm A.W.W. casing and are screened with 152 mm stainless steel, 0.5 mm aperture, continuous-slot screens over the same interval as the slots in the observation bore at each site. Both observation bores and test-production bores are packed with graded sand.

Sampling, logging and testing

Ditch cuttings, collected at 3 m intervals during drilling, were lithologically logged; they are now stored at the GSWA core library. After the completion of drilling, natural-gamma, 16-inch and 64-inch normals resistivity logs were run in the observation bores. Sidewall cores were collected at 18 of the sites for palynological and petrological examination. Temperature logs were later run in some bores.

All the bores were developed using a combination of surging, swabbing or jetting, and airlifting. Test pumping was conducted at the sites with test-production bores. The test-pumping procedure consisted of step-drawdown tests, to check bore development and to determine bore efficiencies, and an eight-hour constant-rate test. The results of the constant-rate testing are summarized in Table

2. Pumped or airlifted water samples were collected from each bore and submitted to the Government Chemical Laboratories for chemical analysis. The results are presented in Table 4. Airlifting was unsuccessful at site 17 and the salinity was derived by conductivity logging over the slotted interval. The bores were levelled to Australian Height Datum (AHD) by the Surveys and Mapping Division of the Department of Mines. Monitoring of water levels in the observation bores was carried out at approximately monthly intervals after the completion of drilling for two to three years (depending on the site).

GEOLOGY

SETTING

The project area is in the central part of the Perth Basin within the Dandaragan Trough, a structural subdivision of the basin, which is thought to contain over 15 000 m of sediments (Playford and others, 1976). Sediments of Cretaceous, Late Tertiary and Quaternary age were intersected during drilling (Table 3).

STRUCTURE

The Cretaceous sediments form an eroded basement on which the Cainozoic sediments are deposited. The surface of this basement slopes towards the coast from 100 m near Brand Highway, east of S10, to about -25 m along the coast (Fig. 2). The gradient is steep near the Gingin Scarp but flattens substantially to the west within about 8 km of the scarp.

The Cainozoic superficial formations are thin and flat-lying (Fig. 3). Their deposition and structure were controlled by eustatic changes in sea level, accompanied by reworking of pre-existing and contemporaneous sediments.

STRATIGRAPHY

CRETACEOUS

Leederville Formation

The Leederville Formation (Cockbain and Playford, 1973) was intersected at 4 sites. It occurs below the superficial formations in the east (Fig. 2). In the west it is apparently disconformably overlain by the Osborne Formation; however, part of the contact may be faulted (Playford and others, 1976) but no evidence was found for this.

The formation consists of interbedded sandstone, siltstone and shale. Spores and pollen indicate a late Neocomian to Aptian age and a non-marine to nearshore-marine depositional environment (Backhouse, unpublished reports listed in Moncreiff and Tuckson, 1987). The base of the formation was not penetrated.

Osborne Formation

The Osborne Formation (McWhae and others, 1958) was intersected at 5 sites but was not fully penetrated. It forms subcrops below the superficial formations in the central part of the coastal plain (Fig. 2). It is disconformably overlain by the

TABLE 1. BORE DATA TABLE

Bore	<u>Grid ref. AMG zone 50</u>		<u>Commenced</u>	<u>Completed</u>	<u>Elevation (m AHD)</u>		<u>Total depth (m)</u>	<u>Slotted/screened interval (m bns)</u>		<u>Formation screened</u>	<u>Head (m AHD) 17-20/3/81</u>	<u>Salinity TDS by calculation (mg/L)</u>	<u>OB TO PB</u>		<u>Base of super-ficial formations RL (m)</u>	<u>Top of Ascot Beds RL (m)</u>	<u>Status</u>
	<u>Easting</u>	<u>Northing</u>			<u>surface</u>	<u>top of casing</u>							<u>distance (m)</u>	<u>direction</u>			
42	1A	343750	6561330	4/7/80	7/7/80		4.261	37.5	18.12	– 24.08	Tamala	0.321					OB
	1B			18/8/80	21/8/80	3.009	3.269	28.2	18.02	– 24.13	Tamala						PB
	2A			4/6/80	10/6/80			42.0									Aband
	2B			11/6/80	13/6/80			102.0									Aband
	2C			13/6/80	23/6/80			91.0									Aband
	2D	350330	6561850	23/6/80	30/6/80	87.064	88.080	127.0	94.04	– 100.00	Ascot	10.951			-12.9	-1.9	OB
	3A	356800	6561660	8/2/80	12/2/80	45.234	46.428	75.0	38.00	– 50.00	Ascot	37.628			-6.9	5.1	OB
	4A	362080	6561380	5/2/80	6/2/80	53.903	54.644	75.0	37.00	– 55.00	Ascot	49.529	34.30	216°	-2.7	13.8	OB
	4B			25/9/80	30/9/80	53.888	54.413	59.0	38.51	– 57.02	Ascot						PB
	5A	368160	6560210	15/2/80	20/2/80	65.790	66.962	69.0	32.15	– 44.15	Guildford	54.522	30.05	245°	-0.2	25.3	OB
	5B			20/9/80	21/9/80			41.0									Aband
	5C			22/9/80	25/9/80	65.775	66.054	45.0	31.77	– 44.02							PB
	6A			19/5/80	20/5/80			15.0									Aband
	6B			19/5/80	20/5/80			15.4									Aband
	6C			20/5/80	23/5/80			30.0									Aband
	6D	346650	6553260	26/5/80	30/5/80	3.586	4.488	57.0	12.04	– 18.00	Tamala	-0.042	31.10	219°	—	-23.9	OB
	6E			22/8/80	26/8/80	4.188	4.436	19.2	11.19	– 17.40	Tamala						PB
	7A	354750	6554280	8/7/80	9/7/80	59.946	60.730	114.0	64.68	– 76.08	Ascot	6.591			-16.6	-24.1	OB
	8A	360750	6553380	6/2/80	8/2/80	38.163	38.870	66.6	34.00	– 52.00	Ascot	34.185			-10.8	3.7	OB
	9A			20/2/80	22/2/80			54.0									Aband
	9B			22/2/80	26/2/80			78.0									Aband
	9C	371050	6554850	6/2/80	5/3/80	64.669	65.389	56.0	30.00	– 42.00	Guildford	52.884	30.60	145°	0.5	17.5	OB
	9D			17/9/80	19/9/80		64.642	43.0	29.89	– 42.19	Guildford						PB
	10A	381180	6557730	13/2/80	15/2/80	69.703	70.873	72.0	18.00	– 24.00	Yoganup	66.778	31.20	032°	—	43.7	OB
	10B			15/9/80	16/9/80		69.966	25.0	17.78	– 24.06							PB
	12A	359050	6549480	17/7/80	22/7/80	33.518	34.295	59.5	40.1	– 46.01	Ascot	14.545			-13.2	-5.2	OB
	13A	366520	6548510	5/3/80	10/3/80	70.691	71.817	90.0	57.4	– 75.4	Ascot	46.357	32.80	247°	-4.3	-27.2	OB
	13B			1/9/80	3/9/80	68.130	68.305	79.0	56.92	– 75.68							PB
	14A	374110	6546540	28/3/80	8/4/80	52.221	53.032	73.0	39.00	– 51.00	Ascot	49.622			1.0	11.0	OB
	15A	380720	6548740	12/3/80	14/3/80	49.599	50.879	60.0	6.00	– 36.00	Guildford	49.279			—	13.1	OB
	17A	358800	6541970	24/7/80	1/8/80	57.740	58.366	83.0	49.50	– 67.50	Ascot	3.426			-13.6	-1.6	OB
	18A	366100	6542610	10/3/80	12/3/80	38.139	39.466	60.0	35.00	– 47.00	Ascot	24.291			-8.8	9.7	OB
	19A			9/4/80	15/4/80			31.5			Ascot						Aband
	19B	372130	6540860	16/4/80	29/4/80	52.425	53.135	60.0	36.00	– 56.00	Ascot	44.190	30.00	303°	-2.8	27.2	OB
	19C			4/9/80	6/9/80			30.0									Aband
	19D			8/9/80	11/9/80	52.332	52.673	56.0	35.82	– 54.29	Ascot						PB

20A	379770	6541500	14/3/80	18/3/80	45.612	46.690	54.0	27.00	–	39.00	Guildford -Yoganup	44.790	1010	26.3	355°	—	8.6	OB
20B			15/9/80	16/9/80	45.811	46.376	41.0	26.75	–	39.12	Guildford -Yoganup		1080					PB
21A	372170	6567350	12/2/80	13/2/80	74.389	75.573	81.0	51.00	–	63.00	Guildford -Yoganup	69.608	350			—	13.3	OB
1/76	352210	6547900	1/3/76	2/4/76	17.95	18.249	37.0	26.40	–	29.78(c)	Tamala	1.154	1090(b)					OB
2/76	360000	6533070	6/4/76	2/5/76	38.321	38.535	57.3	45.87	–	50.31(c)	Tamala	1.170	530(b)					OB
3/76	354670	6540800	13/5/76	4/6/76	29.13	29.516	47.5	38.34	–	44.66	Tamala	0.416	520(b)					OB

OB Observation bore (a) from salinity logging
PB Pumping bore (b) by evaporation
Aband Abandoned bore (c) below top of casing

TABLE 2. CONSTANT RATE TEST PUMPING RESULTS

Observation bore	Formation screened	Length of screen in pumping bore (m)	Pumping rate (m ³ /day)	Maximum drawdown (m) (after 480 min)		Method of Analysis	Transmissivity (m ² /day)	Hydraulic conductivity (m/day)	Storage coefficient	Specific yield	Boulton delay index (days)
1A	Tamala	6.0	1070	0.29	0.02	Type-curve match not available					
4A	Ascot	18.5	1183	10.36	0.65	Boulton Theis	251 251	14 14	1.6 x 10 ⁻⁴		
5A	Guildford -Ascot	12.2	891	4.08	0.61	Theis Theis	886 865	73 71	3.4 x 10 ⁻⁴		
6D	Tamala	6.12	1071	1.42	0.02	Type-curve match not obtainable					
9C(a)	Guildford	12.3	952	—	0.68	Boulton Theis	224 286	18 23	3.9 x 10 ⁻⁴	—	—
9C(a)	Guildford	12.3	957	3.78	0.81	Boulton Theis	311 234	25 19	4.3 x 10 ⁻⁴	1.8 x 10 ⁻²	1
10A	Yoganup	6.3	237	5.83	0.41	Boulton Theis	153 104	24 17	8.3 x 10 ⁻⁴	—	—
13A	Ascot	18.8	1072	7.68	3.12	Theis Theis	150 194	8 10	5.2 x 10 ⁻⁴		
19B	Ascot	18.5	445	10.75	0.97	Boulton Theis	93 84	5 5	2.6 x 10 ⁻⁴	1.5 x 10 ⁻²	2.1
20A	Guildford	12.4	1345	3.25	0.91	Theis Theis	918 897	74 72	4.6 x 10 ⁻⁴		

(a) Test repeated.

Lancelin beds. The formation consists of interbedded, soft, black to green, silty and sandy glauconitic shale. It is of early Albian to early Cenomanian age and was deposited under shallow-marine conditions (Backhouse, unpublished reports).

Lancelin beds

The Lancelin beds (Edgell, 1964) were intersected at 10 sites, but were not fully penetrated. The unit was first described from Lancelin No. 2B bore (Fig. 1) but is poorly known. It is unconformably overlain by the Ascot beds or the Tamala Limestone. The unit consists of grey-green to white, silty and sandy, soft, glauconitic calcilutite and subordinate chalk. Fragments of the bivalve *Inoceramus* are common in some sections, and traces of mica and some phosphatic nodules occur. A light-brown weathered zone may be present at the top.

The age of the Lancelin beds is Coniacian or early Santonian to late Campanian in the project

bore (Backhouse, unpublished reports); and extends into the late Maastrichtian in Breton Bay No. 1 (Fig. 1). The unit was deposited during transgressive-regressive marine phases (Marshall, 1984).

TERTIARY

Ascot beds

The Ascot beds (Playford and others, 1976) were intersected at 13 sites and occur in a north-trending subsurface ridge beneath the central part of the coastal plain (Fig. 4). They are more extensive than to the south. In the bores of the Gingin Brook Line, Sanders (1967) indicated that the Tamala Limestone extends inland nearly to Gingin. However, the part east of Cowalla Road and some of the lower section west of Cowalla Road are probably Ascot beds.

The Ascot beds are usually 10 – 15 m thick, with a maximum thickness of 31.5 m in S13A. They are overlain by the Yoganup or Guildford Formations in the east and by the Tamala Limestone in the

TABLE 3. STRATIGRAPHIC SUCCESSION

	<i>Age</i>	<i>Formation</i>	<i>Maximum thickness penetrated (m)</i>	<i>Lithology (c)</i>
QUATERNARY	Holocene	Alluvium, lake and swamp deposits	3	sand, clay
		Safety Bay Sand	6	sand, (limestone)
		Becher Sand	9	sand
	Late Pleistocene	Bassendean Sand	9	sand
		Muchea Limestone	(a)	limestone
		Tamala Limestone	89	sand, limestone
	Pleistocene	Guildford Formation	46	sand, clay
TERTIARY	Pliocene	Yoganup Formation	21	sand, (clay)
		Ascot beds	31.5	limestone, sand
UNCONFORMITY				
CRETACEOUS	Late	Lancelin beds	(b)	calcareous mudstone, (greensand)
	Early-Late	Osborne Formation	(b)	shale, siltstone sandstone
UNCONFORMITY				
	Early	Leederville Formation	(b)	sandstone, siltstone, shale

(a) Not intersected.
(b) Not fully penetrated.
(c) Subordinate lithologies in brackets.

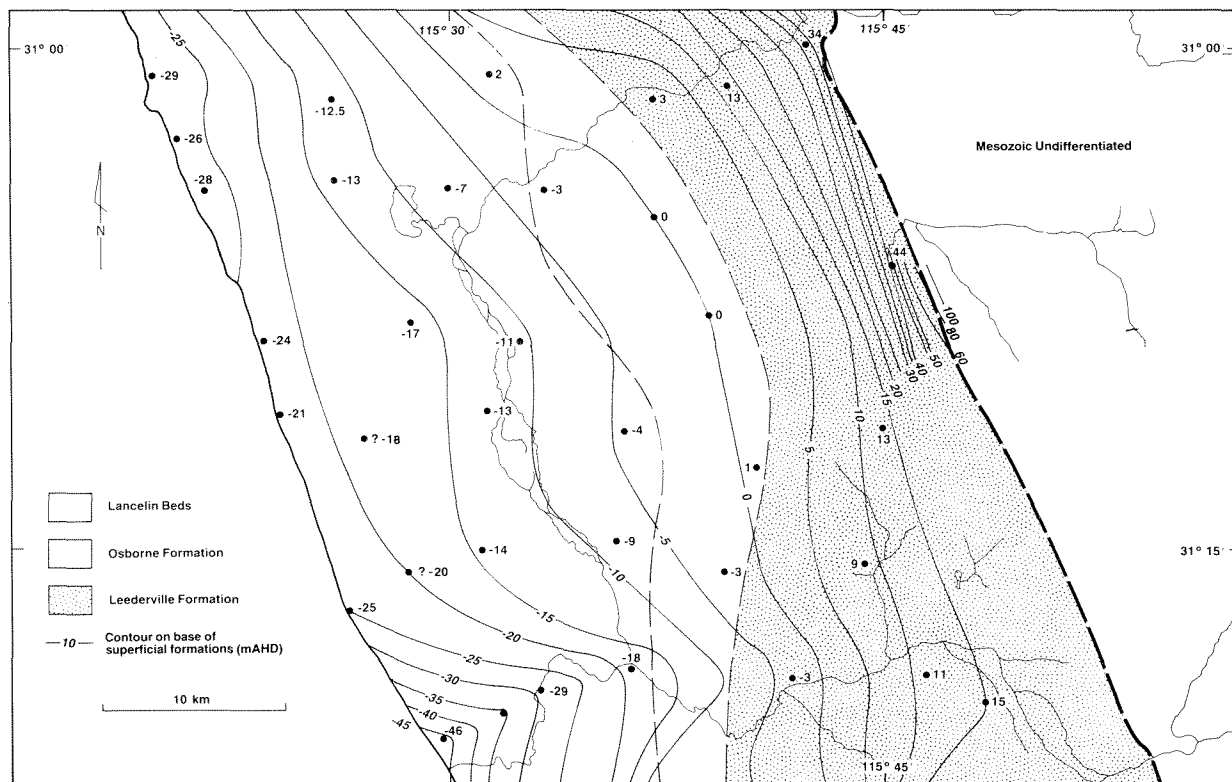


Figure 2. Subcrop map

west; the contacts with the Guildford Formation and the Tamala Limestone are unconformable. Baxter and Hamilton (1981) believed the Ascot beds to be a facies equivalent of the Yoganup Formation but the drilling suggests that they are overlain by the Yoganup Formation in the project area.

The Ascot beds consist of light-grey to cream or light brown, hard to friable calcarenite which is commonly interbedded with sand. They are cavernous in places. In the sand, quartz is the dominant mineral, but quartz usually constitutes less than 10% of the calcarenite. The sand is fine grained to granule sized, moderately to very well sorted, and angular to well rounded. In places the sand contains a rich assemblage of mollusc shells. Traces of glauconite and phosphate-rich nodules near the base of the unit are presumed to be derived from Cretaceous strata.

The lithology and fauna indicate a Pliocene age and deposition in a shallow-water, open-marine environment (Kendrick, G. W., 1983, personal communication).

Yoganup Formation

Overlying the Ascot beds and the Cretaceous strata, there is a thin, discontinuous layer of fine to coarse sand which is correlated with the Yoganup Formation (Low, 1971), on the basis of its stratigraphic position and the occurrence of similar sand assigned to the formation elsewhere (Baxter and Hamilton, 1981). The formation was identified at 10 project bore sites and from mineral-exploration bores at the base of the Gingin Scarp (Baxter, 1977, 1982).

The formation is 21 m thick in S10A but elsewhere it is between 2 m and 8 m thick. It is unconformably overlain by the Guildford Formation, the Tamala Limestone, or alluvium and colluvium near the Gingin Scarp.

The quartz sand is light-grey to green-brown, and is clayey in places. Grains are subangular to well rounded, poorly to well sorted, and many are polished. Heavy minerals constitute up to 2% of some samples; accessory glauconite and feldspar are also present. Ferruginous sandstone occurs as a section, which is 8 m thick, in S15A.

The heavy-mineral deposits, correlated with the Yoganup Formation at Gingin, are believed to be of late Tertiary to early Pleistocene age (Baxter, 1982). The Yoganup Formation in the area is possibly of Pliocene age. According to Baxter (1981), the sediments were deposited in a paralic environment.

QUATERNARY

The coastal plain is formed by Quaternary sediments, which conceal the eroded Late Tertiary and Cretaceous strata. The sediments are about 25 m thick at the coast and increase in thickness to about 130 m northwest of Karakin Lakes. They thin to the east and grade into sandy colluvium along the base of the Gingin Scarp. Seven main units have been recognized (Table 3) and six of these crop out (Fig. 5). There is uncertainty about the identification of the base of formations in the subsurface, because of minor lithological changes and down-hole sample contamination. In addition there has been reworking of sediments from the

underlying formations in many places. The formation boundaries cannot be established from natural gamma-ray logs.

Guildford Formation

The Guildford Formation (Low, 1971) occurs in the subsurface in the eastern half of the study area and crops out on the Beermullah Plain. It was intersected at 10 sites and reaches a maximum thickness of 46 m in S21A. The Guildford Formation is unconformably overlain by the Bassendean Sand or the Muchea Limestone. It is possibly overlain by the Tamala Limestone along its western margin. The formation has a quartzose sandy facies and a clayey facies. The clay facies is restricted to parts of the Beermullah Plain where clay overlies sand and interfingers with the sand to the north and west.

The sand is light grey, buff, brown or grey-green, fine to coarse, mainly subangular to rounded and moderately to very well sorted. Grains may be polished or, in some sections, frosted. Accessory feldspar and heavy minerals occur, with traces of carbonate, mica, quartzite, chert, and a few sandstone clasts. The clay is black, light grey, brown, green, yellow or mauve and variably sandy. Weakly cemented ferruginous sandstone ('coffee rock') is developed in a few places near the water table and, sporadically, well below the water table.

The Guildford Formation is of Pleistocene age, based on its stratigraphic position in the bores and on dating of fauna from two thin, marine horizons in the Perth area (Darragh and Kendrick, 1971). The clay facies is considered to be alluvial or estuarine, but the origin of the sand is uncertain. It may represent a shallow-marine deposit, parts of which have been reworked under eolian conditions. Some of the sediment has probably been derived from the Yoganup Formation.

Tamala Limestone

The Tamala Limestone (Playford and others, 1976) occurs in a coastal belt up to 20 km wide, and forms offshore islands and reefs. It was intersected at 12 sites and reaches a maximum thickness of about 140 m, northwest of Karakin Lakes. The formation is disconformably overlain by the Becher Sand, the Safety Bay Sand and sandy alluvium, along the Moore River and Gingin Brook. The Tamala Limestone consists of about two-thirds sand and one-third quartz calcarenite or calcareous sandstone, with minor clay and calcilutite. The proportion of sand increases towards the east. The limestone is variably indurated, and its surface is usually calcretized and may feature pinnacles. Caverns occur in the subsurface.

The formation is cream to light grey or light yellow-brown although red-brown ferruginized zones, 1 m to 15 m thick, occur above the water table in the east. The limestone contains variable amounts of quartz and carbonate skeletal fragments. The quartz grains are fine to coarse, moderately to very well sorted and angular to rounded. Many are frosted, but polished grains are common in the basal part of some of the bores near the

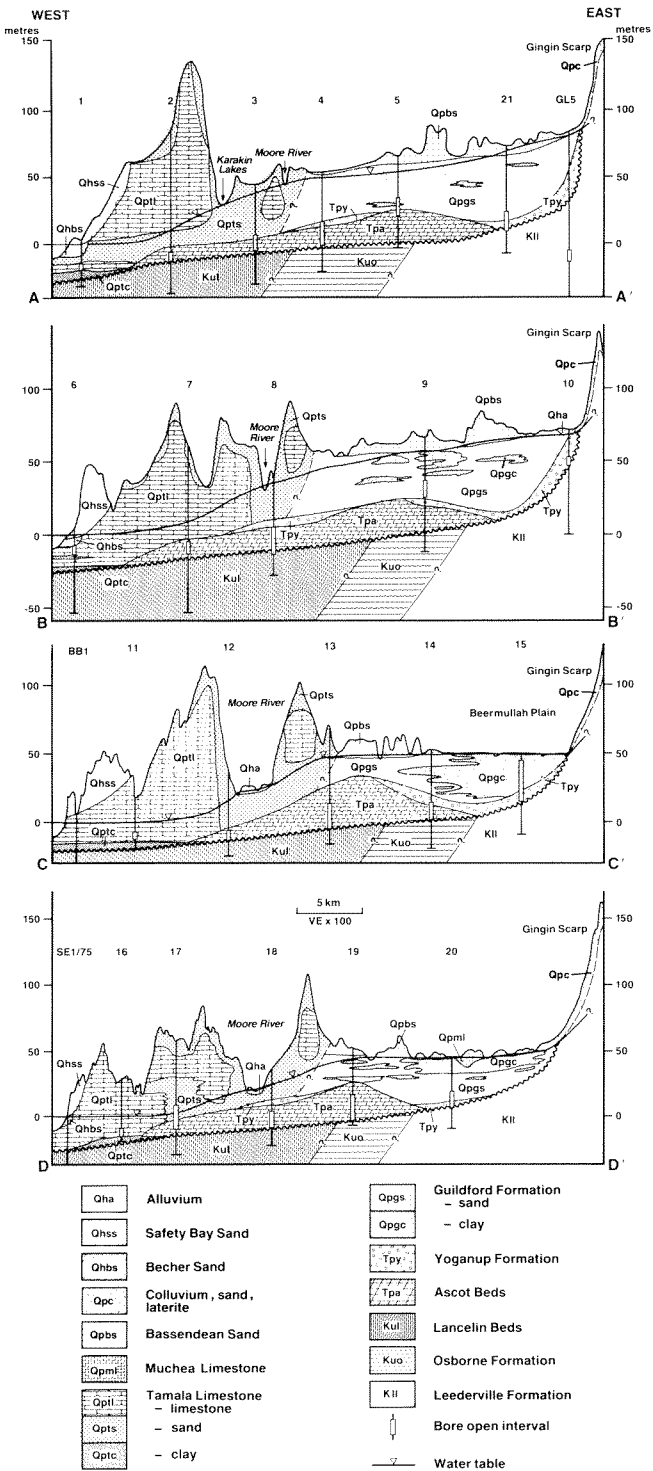
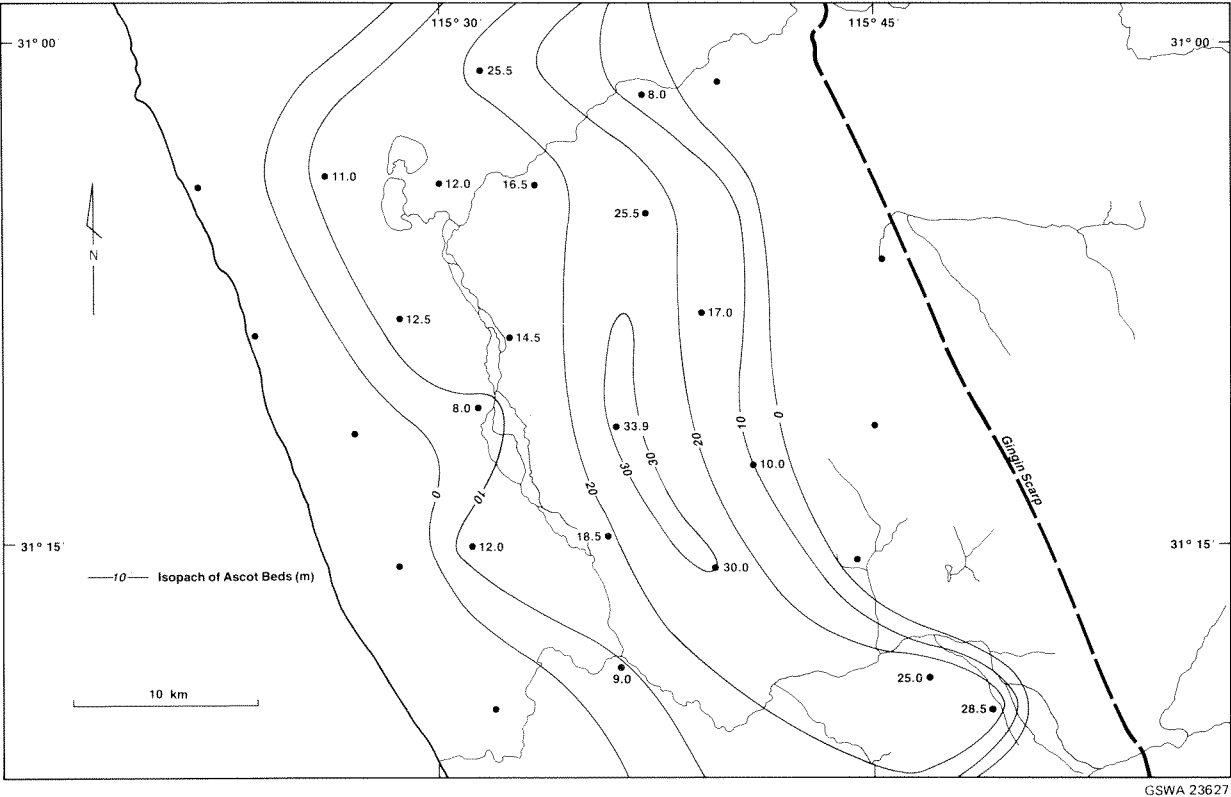
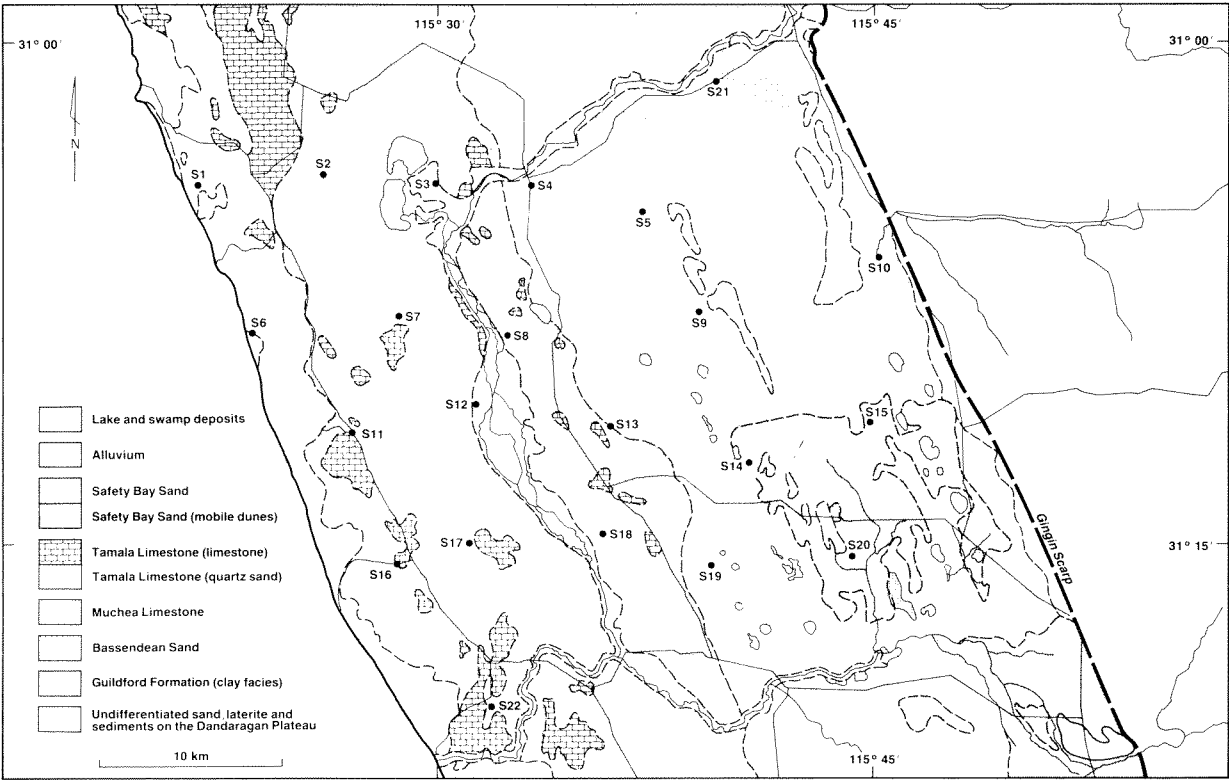


Figure 3. Geological cross-sections



GSWA 23627

Figure 4. Isopachs of the Ascot beds



GSWA 23628

Figure 5. Surface geology

coast. Traces of feldspar and glauconite, and phosphate-rich nodules near the base, were probably derived from Cretaceous strata.

Heavy minerals usually constitute less than 1%, but a sidewall core taken 7 m above the base of the formation in S6D (RL -15.4 m AHD) contained about 5% heavy minerals.

The basal 7 m of the formation in S1A and thinner sections in S11 and Seabird 1/75 consist of creamy grey, sandy calcilutite containing up to 30% of very fine, carbonate skeletal fragments.

The Tamala Limestone is of late Pleistocene age (Playford and others, 1976). The upper part is eolian, whereas the basal part contains marine, littoral or lagoonal sections. More extensive and detailed study may allow subdivision of the formation.

Muchea Limestone

The Muchea Limestone (Fairbridge, 1953) is known from outcrop, from shallow excavations and from several private and mineral-exploration bores on the Pinjarra Plain. Limestone occurrences to the east of S14 (Kendrick, 1978) are here assigned to the formation.

The formation is generally less than 2 m thick, although shells believed to be from the formation have been collected 13.7 m below the ground surface (Kendrick, 1978) and a thickness of 11 m is indicated by drill cuttings from MR2, a mineral-exploration bore 3 km northwest of S20 (Fig. 1). While the apparent thickness of these sections may be exaggerated due to down-hole contamination by drill cuttings, they could indicate substantial thickening of the formation at these localities.

The Muchea Limestone consists of soft to hard, cream to yellowish brown, sandy, marly and locally fossiliferous limestone. It is, at least in part, overlain disconformably by the Bassendean Sand.

Kendrick (1978) has described gastropods from the formation which indicate a fresh-water environment of deposition. He suggests that extensive lakes may have occupied the area at the time of deposition. The fossils are non-diagnostic for age, and Fairbridge (1953) has recorded extant snail species from the formation. The limestone was probably deposited during the late Pleistocene or possibly early Holocene, mainly in a lacustrine environment and around springs.

Bassendean Sand

The Bassendean Sand (Playford and Low, 1972) was intersected at six bore sites. Its thickness varies greatly, depending on the topography, and reaches a maximum of about 40 m between S5 and S21.

The formation consists of light-grey to light grey-brown, mainly frosted quartz sand, which is fine to medium, well sorted, and subangular to subrounded. Traces of feldspar, heavy minerals and carbonate occur. A few sections are slightly clayey. Where the water table occurs within the formation there may be a thin layer of ferruginized sand ('coffee rock'). Several types of dune are present, which probably indicate different periods of dune building during the late Pleistocene to Holocene.

Becher Sand

The Becher Sand (Semeniuk and Searle, 1985) was identified at S1 and S6, and Seabird 1/75. It is conformably overlain by the Safety Bay Sand and does not crop out onshore.

The formation consists of light grey and light grey-brown, fine to coarse, subrounded to well rounded, well sorted, (and in places polished) quartz sand with subordinate carbonate sand. Locally some of the sand may be coloured dark brown-grey by adhering plant fibre. Fawn coloured, calcareous mudstone which is at least 2 m thick occurs in Seabird 1/75. The Becher Sand is mainly a submarine seagrass-bank sequence of Holocene age and is still being deposited in places (Semeniuk and Searle, 1985).

Safety Bay Sand

The Safety Bay Sand (Playford and Low, 1972; Semeniuk and Searle, 1985) occurs along the coast in a belt up to 5 km wide. From S6 northwards, active parabolic dunes and blowouts form a significant proportion of the area of outcrop. The formation was intersected at two sites where it is up to 6 m thick; it is probably thicker elsewhere.

The formation consists of cream to buff, calcareous sand which is weakly to moderately cemented at depth. It generally contains more than 50% carbonate grains; mainly shell and some bryozoan fragments. The quartz is fine to medium grained, well sorted and angular to rounded. Traces of heavy minerals occur. The Safety Bay Sand is of Holocene age and is still being deposited.

Alluvium, lake and swamp deposits

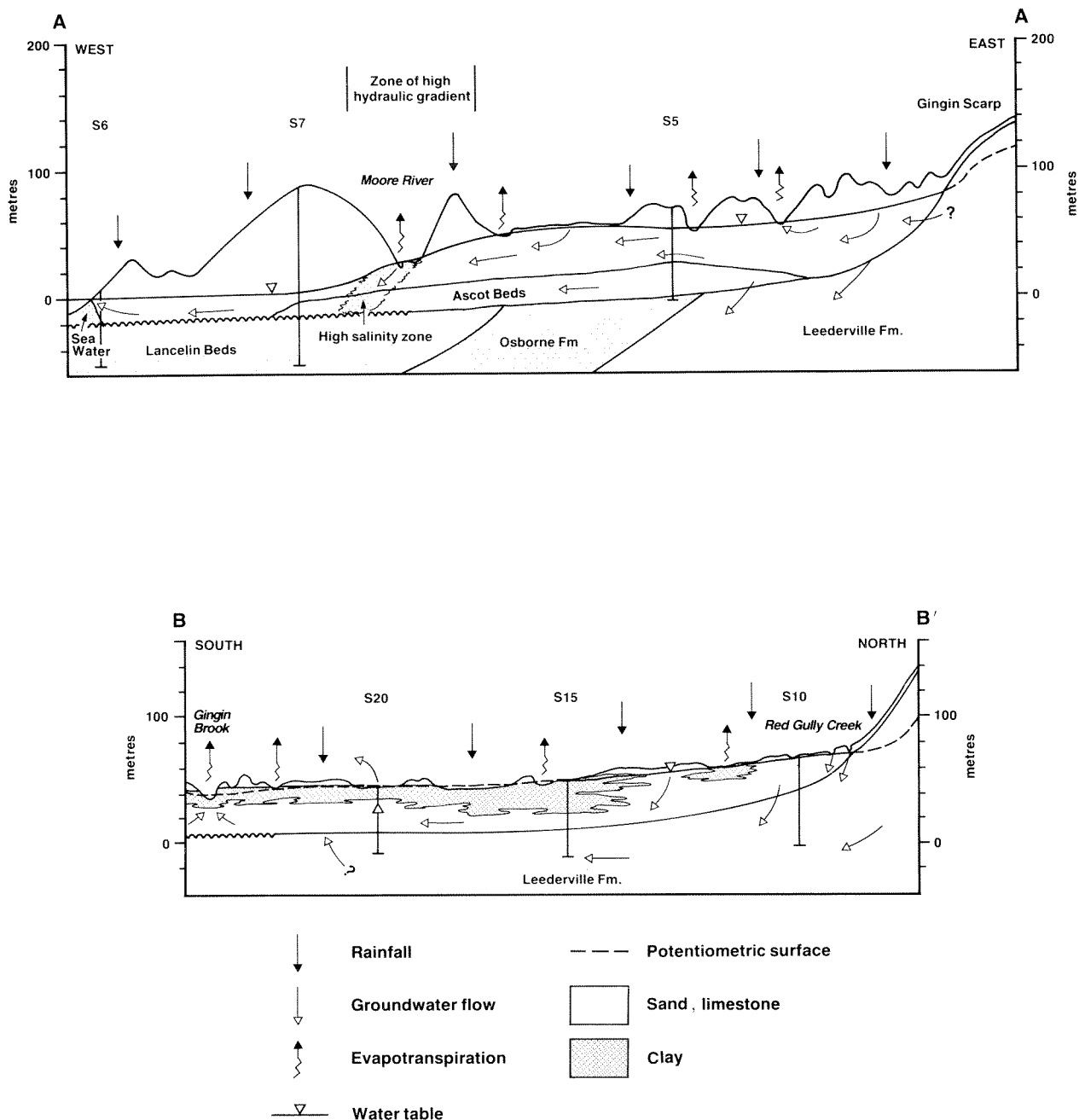
Sandy alluvium occurs along the Moore River, Gingin Brook and Red Gully Creek. Thin lacustrine and swamp deposits are associated with the lakes and swamps. They are sandy but may contain clay, thin lenses of peat and some diatomite.

HYDROGEOLOGY

FLOW-SYSTEM

The superficial formations contain a predominantly unconfined regional groundwater flow-system which is bounded to the north by the Moore River (with an arbitrary extension westwards to the coast at Lancelin) to the south by Gingin Brook, to the east by the Gingin Scarp, and to the west by the sea. Below the Coastal Belt, the

flow system extends north of the project area. In the east, there is downward hydraulic connection between the unconfined flow system and the underlying Leederville Formation (Fig. 6). In the west, the unconfined flow system overlies impermeable Osborne Formation and Lancelin beds. Locally, under the Beermullah Plain, the flow system is confined by the clayey facies of the Guildford Formation, and the potentiometric surface is above the ground.



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Figure 6. Diagrammatic sections showing groundwater flow

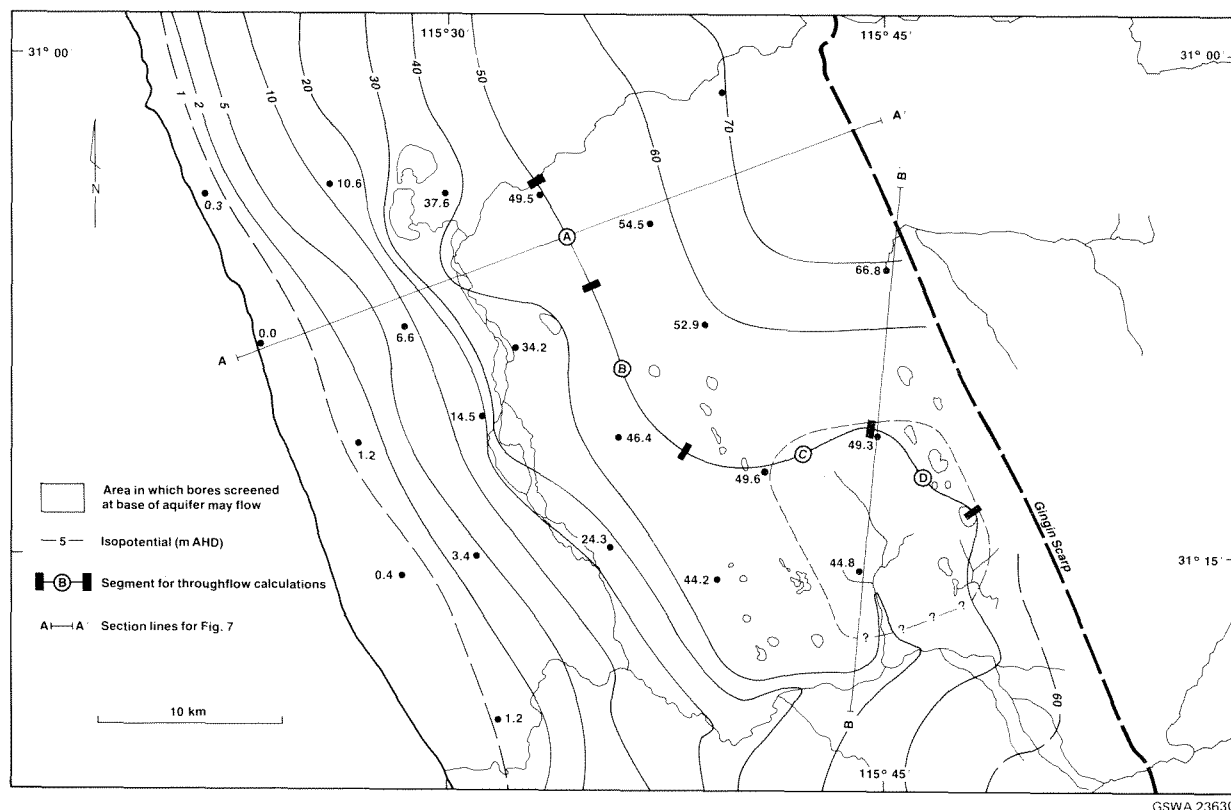


Figure 7. Water-table contours (March 1981)

Test pumping has shown the average hydraulic conductivity of the sand in the Ascot beds to be about 8 m/day and of the sand in the Guildford and Yoganup Formations to be about 30 m/day. The average hydraulic conductivity of the Tamala Limestone could not be ascertained from the test pumping.

Water-table configuration

The water table slopes westward and southward from an elevation of about 70 m in the northeast, in an area including the highest part of the Bassendean Dunes (Fig. 7). In the east it is generally close to the surface, with swamps and lakes in interdunal areas, whereas in the west beneath the coastal belt, it is deep and is unrelated to topography.

For the purpose of throughflow calculations the area in the northeast, where the water table is above 50 m, is termed the Regans Ford Area. Groundwater flows from this area towards the major hydraulic discharge boundaries: the sea and Gingin Brook. The Moore River is a losing stream between Karakin Lakes and Bidaminna Lake, and a gaining stream elsewhere, but its role alternates in some sections depending on river stage. The hydraulic gradient is low in the southeast and in the west, but a steep gradient zone (about 12 km wide) occurs within the Tamala Limestone

approximately beneath the north-south reach of the Moore River. This zone may reflect a low hydraulic conductivity due to cementation or finer grained sediment.

A perched water table, which may cause surface flooding to persist for periods of more than a week after prolonged or heavy rainfall, is seasonally present over much of the Beermullah Plain.

There is a downward hydraulic-head gradient of about 11 m, over a depth of 40 m from just below the base of the superficial formations to the base of the Leederville Formation, at Gillingarra Line site 5 (Moncrieff, in press). This suggests that there may be significant downward leakage from the superficial formations to the Leederville Formation in the northeast (Fig. 6).

Recharge

Recharge is by direct infiltration of rainfall with subordinate amounts from runoff. Seasonally, groundwater recharge occurs from the Moore River between Karakin and Bidaminna Lakes, and from Red Gully Creek and other small streams which flow from the Dandaragan Plateau and dissipate across the coastal plain.

At AM4 (Fig. 1) there is an upward hydraulic-head gradient of about 5 m over an interval of 200 m from the Leederville Formation to the base of the superficial formations. Thus, there is

potential for upward leakage from the Leederville Formation in the southeast (Fig. 6). Recharge occurs mainly during winter and early spring through the permeable surface sand and limestone. On the Pinjarra Plain, rainfall gives rise to locally derived surface runoff from the clayey soils.

Hydrographs show that the water levels fluctuate in response to rainfall (Fig. 8); lowest levels are mainly during March to May and the highest levels mainly during August to October. Water-level rises were also recorded in S14A, S15A and S20A due to heavy rainfall in January 1982. Other water-level fluctuations were observed due to ocean tides in S1A and S6A and nearby pumping in S12A. The smallest annual water-level changes occur west of the Moore River where the flow system is dominated by the high transmissivity of the Tamala Limestone. The largest changes, of over 1 m, occur under the Beermullah Plain, where the flow system is confined and where there may be some influence from head changes in the Leederville Formation, and near Red Gully Creek, where runoff provides variable amounts of recharge.

The hydrographs (Fig. 8) also show that water levels have generally risen since the beginning of 1980. This has coincided with three years of near average rainfall following a very dry year in 1979. Also, there may be some effects of land clearing, resulting in increased infiltration.

In the northeast, where recharge is solely by rainfall, net recharge, expressed as a percentage of rainfall, can be estimated using chlorinity data. The average chlorinity of the rainfall, estimated from data for Yanchep, 60 km to the south, and Boothendarra, 80 km to the north (Hingston and

Gailitis, 1977), is about 9 mg/L. The chlorinity of the groundwater, averaged from S5A, S9D and S21A, is 135 mg/L (Table 4). This represents a recharge rate of about 7% of rainfall.

Estimates of recharge from runoff are more difficult to make because there is no river gauging. Public Works Department spot-estimates of the flow in Red Gully Creek past the Brand Highway, each March between 1969 and 1978, varied between zero and $22 \times 10^3 \text{ m}^3/\text{day}$. During March 1981, it was observed to be flowing 'quite fast' past the same spot but it was not flowing past S10. The amount of recharge from the creek would be at least as variable as the flow. Estimates of the recharge from the Moore River have not been attempted because the river is not gauged where it flows across the coastal plain. Recharge by upward leakage from the Leederville Formation is restricted to the southeast, but this cannot be calculated because neither the vertical hydraulic conductivity nor the area over which leakage takes place are known.

Throughflow

The throughflow from the Regans Ford Area across the 50 m water-table contour (Fig. 7; A-D) has been calculated using the Darcy equation as $16 \times 10^6 \text{ m}^3/\text{year}$ (Moncrieff and Tuckson, 1987).

Net recharge, averaged over the area contributing to flow (380 km^2) is therefore about 43 mm/year or about 6% of the average annual rainfall (approximately 680 mm). It is probably an underestimate because there is groundwater discharge to the underlying Leederville Formation in the northeast.

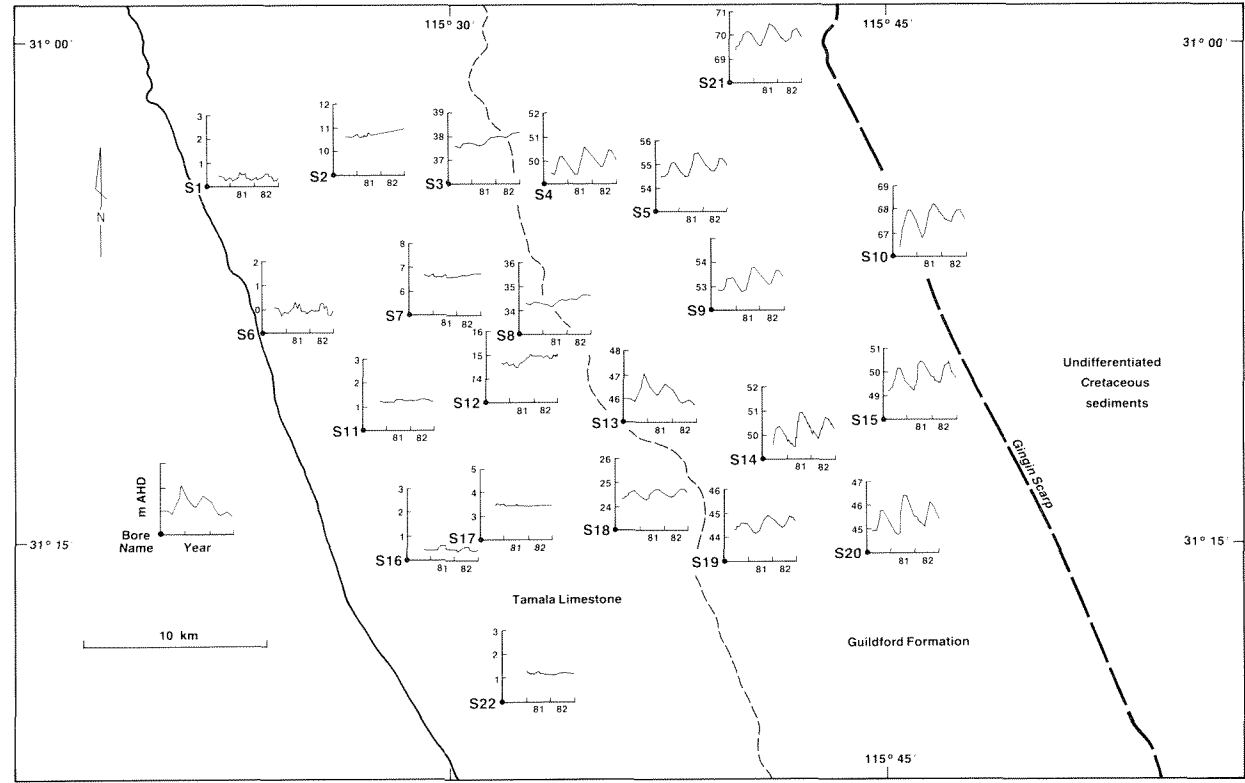


Figure 8. Hydrographs 1981-82

TABLE 4. CHEMICAL ANALYSES (mg/L unless otherwise indicated)

Bore no.	GWSA sample no.	Sample date	Sampling stage (b)	pH	Conductivity (c)	TDS (f)	TH (g)	TA (h)	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	NO ₃	SiO ₂	B	F	Fe (total)	Formation				
1A	12463	14/08/80	A	7.5	85	440	194	150	58	12	89	3	nil	183	153	15	1	16	<0.05	0.1	0.06	Tamala				
1B	12475	19/11/80	T	8.1	98	500	234	200	72	13	93	3	nil	244	164	16	2	16	<0.05	0.2		Tamala				
1B	12471	19/11/80	N	7.3	90.6																	Tamala				
2D	12452	30/06/80	A	7.4	140	780	271	195	72	22	182	6	nil	238	281	78	3	18	0.09	0.2		Ascot				
3A	12431	28/02/80	A	7.4	290	1450	418	110	85	50	391	10	nil	134	761	67	<1	19		0.1		Ascot				
4A	12432	27/02/80	A	7.7	109	580	200	160	57	14	137	5	nil	195	247	2	<1	19	0.05	0.1		Ascot				
4B	12476	20/10/80	T	8.2	117	590	210	165	61	14	142	5	nil	201	250	2	<1	20	<0.05	0.1		Ascot				
5C	12477	11/11/80	T	7.9	40	220	78	65	23	5	45	2	nil	79	74	6	<1	21	0.05	<0.1		Guildford				
5C	12472	11/11/80	N	7.0	46.2																2.6	Guildford				
6D	12453	3/06/80	A	7.5	742	4300	927	225	124	150	1270	43	nil	274	2220	345	<1	14		0.3		Tamala				
6E	12478	24/11/80	T	8.3	1030	5800	1185	220	130	209	1700	57	nil	268	3090	462	2	14		0.2		Tamala				
6E	12469	24/11/80	N	7.1	692																0.10	Tamala				
7A	12464	13/08/80	A	7.5	228	1140	390	195	100	34	282	7	nil	238	516	59	1	26		0.1		Ascot				
8A	12433	29/03/80	A	7.7	325	1630	416	270	94	44	456	11	nil	329	825	18	<1	22	0.1	0.1		Ascot				
9C	12434	27/03/80	A	8.1	79	430	166	155	47	12	94	3	nil	189	154	2	<1	19	0.1			Guildford				
9D	12479	14/11/80	T	8.6	93	490	214	190	61	15	102	4	12	207	170	5	2	20	0.05	0.1		Guildford				
10A	12454	28/02/80	A	7.7	119	630	99	19	7	20	192	6	nil	23	330	28	<1	36	0.09	0.1		Yoganup				
10B	12466	31/10/80	N	6.1	133										376						0.33	Yoganup				
11	12402	31/03/76	A	7.2		1090(e)	380	236	116	22					391		1			0.1		Tamala				
12A	12465	18/08/80	A	7.5	136	730	233	168	62	19	176	5	nil	205	295	40	<1	27	0.05	0.2		Ascot				
13A	12455	19/03/80	A	7.6	100	540	208	184	60	14	123	4	nil	224	203	4	<1	24	0.05	0.2		Ascot				
13B	12467	22/10/80	N	7.4	104										211						3.9	Ascot				
14A	12460	30/04/80	A	7.9	102	560	216	215	57	18	123	4	nil	262	197	4	2	25	0.05	0.1		Ascot				
15A	12461	19/07/80	A	8.1	153	850	192	121	34	26	231	9	nil	148	383	47	<1	42	0.05	0.2		Guildford				
16	12406	3/06/76	A	7.5		520(e)	211	158	63	13					199		2			0.1		Tamala				
18A	12456	20/03/80	A	7.8	97	530	203	204	58	14	116	4	nil	249	187	3	<1	19	0.05	0.1		Ascot				
19B	12462	29/04/80	A	7.7	123	670	240	231	68	17	159	4	nil	281	247	15	<1	22	0.05	0.2		Ascot				
19D	12480	24/10/80	T	7.9	118	590	191	170	47	18	151	4	nil	207	240	4	<1	22	0.08	0.1		Ascot				
19D	12470	24/10/80	N	7.3	120																	Ascot				
20A	12457	18/03/80	A	8.4	190	1010	242	130	36	37	280	11	18	122	504	31	<1	36		0.2		Guildford				
20B	12481	28/10/80	T	8.4	219	1080	339	236	78	35	278	11	6	275	472	31	<1	35		0.3		Guildford				
20B	12468	28/10/80	N	7.0	199										503							Guildford				
21A	12458	26/03/80	A	7.1	64	350	47	12	4	9	105	6	nil	15	162	41	<1	19		<0.1		Guildford				
22	12404	1/05/76	A	7.4		530(e)	247	200	81	11					171		8			<0.1		Tamala				
Rain (a)																										
Yanchep									0.72	0.68	5.6	0.54				0.70	10.88	1.80								
Rain (a)									average 31/01/73 to 12/07/74																	
Boothendarra									0.54	0.46	3.6	0.27				0.66	7.01	1.48								

Analyses by Government Chemical Laboratories, Perth

(a) Supplied by F. V. Hingston.

(b) A = airlift, T = end of test pumping (8 hours), N = non aerated, sampled 4 hours after start of test pumping.

(c) m S/m at 25°C.

(d) By calculation.

(e) By evaporation.

(f) TDS = total dissolved solids

(g) TH = total hardness as CaCO₃(h) TA = total alkalinity as CaCO₃

Throughflow calculations have not been attempted for the area west of the north-south reach of the Moore River because of the presence of karst features in the Tamala Limestone, and the hydraulic conductivity of the unit could not be obtained from the test-pumping program.

The two estimates of recharge above the 50 m water-table contour, about 7% of average rainfall using chlorinity data and about 6% from the throughflow calculations, are in good agreement. The higher figure (7%) is adopted because of the probable underestimation of recharge from the throughflow calculations.

Discharge

Groundwater discharges mainly to the sea and to Gingin Brook. Discharge to the sea occurs above a salt-water wedge along the coast; the wedge was intersected in S6A.

Groundwater also discharges to two sections of the Moore River, between Regans Ford and Karakin Lakes and from Bidaminna Lake to the coast, and to small drainages in the southeast. Discharge occurs to lakes and swamps, where the water is lost by evaporation. Water loss also occurs through evapotranspiration from vegetation where the water table is shallow. There is downward leakage to the Leederville Formation in the northeast.

Storage

The specific yield could not be obtained from the test pumping program but it is assumed to be

0.2, based on average values used for the superficial formations by Cargeeg and others (1987).

By planimetry and calculation, using a map showing the saturated aquifer thickness (Fig. 9), the volume of saturated sediments, excluding the Guildford Formation clay facies, is estimated to be $40 \times 10^9 \text{ m}^3$. This represents a volume of groundwater in storage of $8 \times 10^9 \text{ m}^3$ using the assumed specific yield, which is equivalent to about 140 years recharge over the area at the adopted rate of 7% of average rainfall. For comparison, similar calculations of the volume of groundwater in storage in the superficial formations in the northern Perth area have yielded $65 \times 10^9 \text{ m}^3$ and for the southern Perth area $5 \times 10^9 \text{ m}^3$ (Allen, 1976).

GROUNDWATER QUALITY

Water samples collected from the bores, either during constant-rate test pumping or airlifting, were analyzed by the Government Chemical Laboratories (Table 4). Only partial analyses were conducted on the samples from S11, S22 and S16, while no sample could be obtained from S17A.

Salinity

The salinity of the groundwater is less than 750 mg/L TDS over more than half the area (Fig. 10). The lowest salinity, (<250 mg/L) occurs around S5A in the Regans Ford Area. Higher salinity groundwater (>1000 mg/L) occurs in the southeast, near the Moore River in the vicinity of Karakin and Bidaminna Lakes, and at S6.

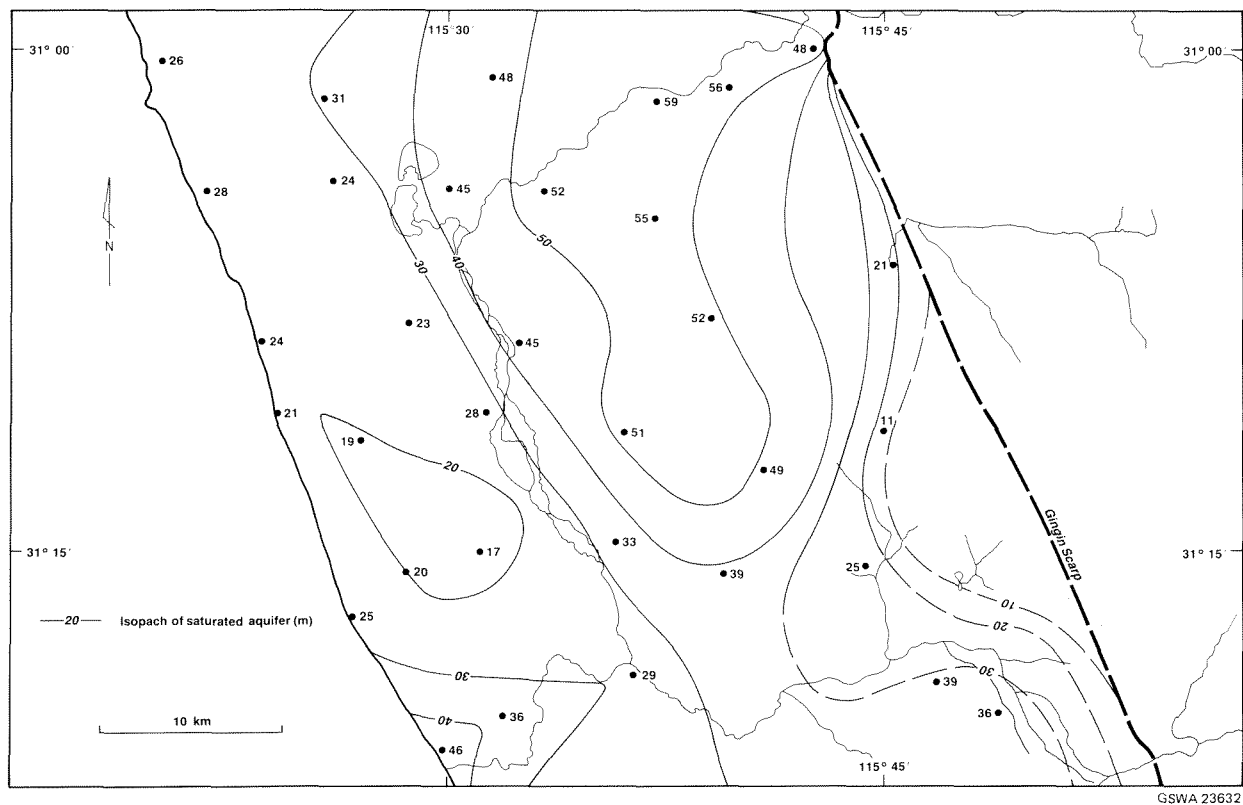


Figure 9. Saturated-aquifer thickness

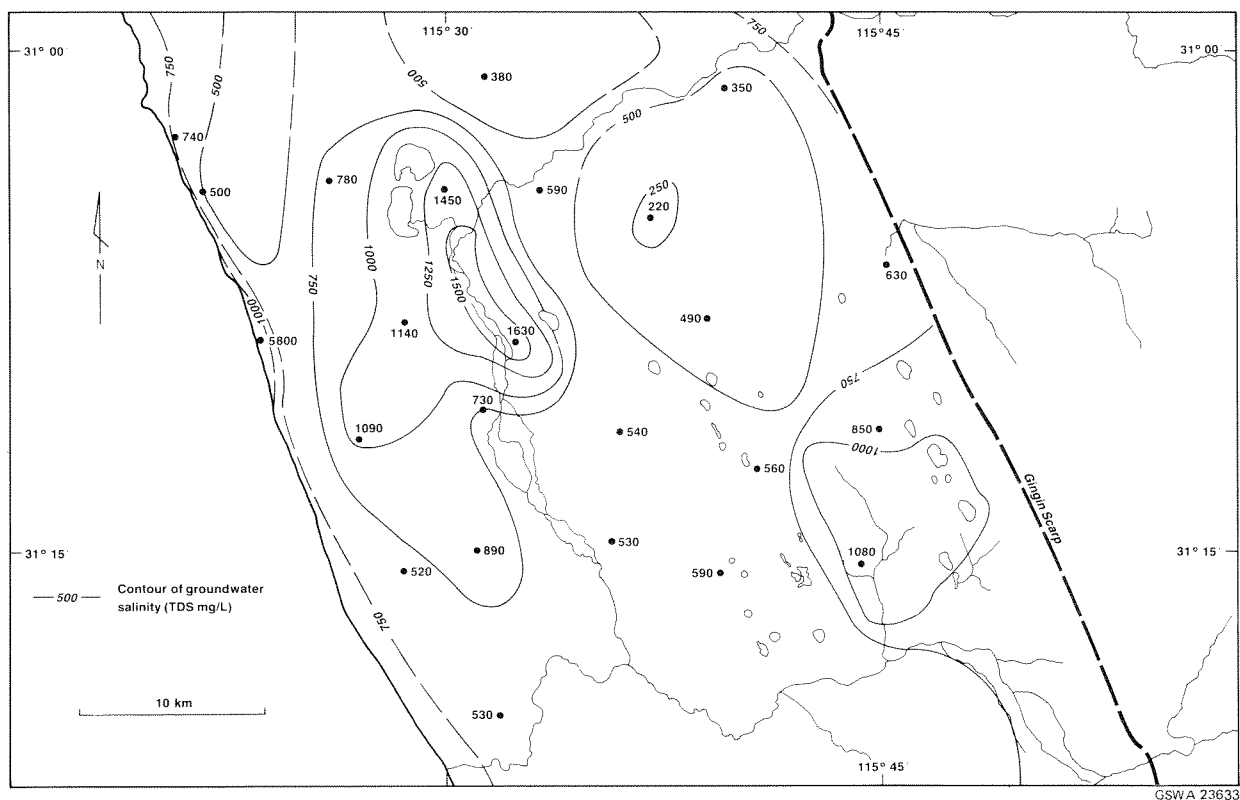


Figure 10. Groundwater salinity

In the southeast the groundwater salinity at the base of the superficial formations reaches at least 1080 mg/L (S20B). This is probably due to upward leakage of marginal to brackish groundwater from the Leederville Formation. The salinity of the groundwater in the top of the Leederville Formation, calculated from resistivity logs, is about 1100 mg/L.

High soil salinities are also prevalent in the southeast. The shallow water table, poor drainage, numerous lakes and swamps, and episodic winter flooding facilitate the concentration of dissolved salts near the surface by evapotranspiration. Also, the low hydraulic gradient and upward hydraulic head preclude rapid flushing of the salts.

The groundwater salinity is around 1 500 mg/L TDS near the Moore River in the vicinity of Karakin and Bidaminna Lakes. This is probably caused by recharge from the Moore River during periods of high-river stage. Evapotranspiration from the shallow water table and from lakes could also contribute to the high salinity of groundwater in the area.

The high-salinity groundwater at S6 (5 800 mg/L) is from the coastal salt-water wedge.

Hydrochemistry

The major ions from the chemical analyses are plotted on trilinear diagrams in Figure 11 and presented graphically in Figure 12. In Figure 11, the analyses plot in the sodium chloride field with a linear range towards some which are transitional to the calcium bicarbonate field. This is shown diagrammatically in Figure 12 by a range of pat-

terns between one representative of the sodium chloride type groundwater (S21A) and one of groundwater transitional between sodium chloride type and calcium bicarbonate type (S1B).

Groundwater of sodium chloride type occurs in the east where the aquifer is siliceous. The patterns (Fig. 12) are similar to that of rainfall and probably of runoff from the east.

Groundwater of transitional composition is found in bores screened in, or immediately above, the Ascot Beds. Exceptions are the analyses from S6D, where there is seawater intrusion, and S3A and S8A, where there is groundwater recharge from the Moore River.

The linear zonation of the plot (Fig. 11) and the range of patterns between two end-members (Fig. 12) suggest hydrochemical evolution (from sodium chloride type towards calcium bicarbonate type) which is caused by dissolution of carbonate within the aquifer type.

High concentrations of iron, up to 4.5 mg/L, occur at four (S5C, S13B, S19D and S20B) of the seven sites where non-aerated water samples were collected. The concentration of boron does not exceed 0.09 mg/L and of fluoride 0.3 mg/L.

Temperature

The temperature of the groundwater in the superficial formations is generally between 18°C and 19°C. Beneath the Beermullah Plain the groundwater is 1°C to 2°C warmer (S14A, S15A, S20A), possibly due to the insulating effect of the surficial clay or due to upward leakage of warm Leederville Formation groundwater.

GROUNDWATER DEVELOPMENT

There are about 350 private bores in the area that draw water from the superficial formations. The water is used for stock and domestic purposes, and increasingly for irrigation. The estimated annual abstraction is $5 \times 10^6 \text{ m}^3$. This is about one third of the estimated throughflow from the Regans Ford Area alone and leaves potential for further development.

Town-water supplies for Lancelin, Ledge Point and Guilderton are drawn from the Tamala Limestone, while Seabird and Gingin obtain groundwater from the Leederville Formation.

There is a large groundwater resource in the Regans Ford Area that may be suitable for devel-

opment for public-water supply. However, much of the area lies within the Moore River National Park where a lowering of the water table will affect wetlands. It is also an area of recharge for the Leederville Formation.

Groundwater for irrigation is drawn from both the superficial formations and the Leederville Formation in the area. Irrigation may cause increases in recharge and the return water may lead to local increases in the salinity of groundwater in the superficial formations. On the Beermullah Plain, which is underlain by clay and where drainage is poor, irrigation should be avoided because of the likelihood of increased soil salinity.

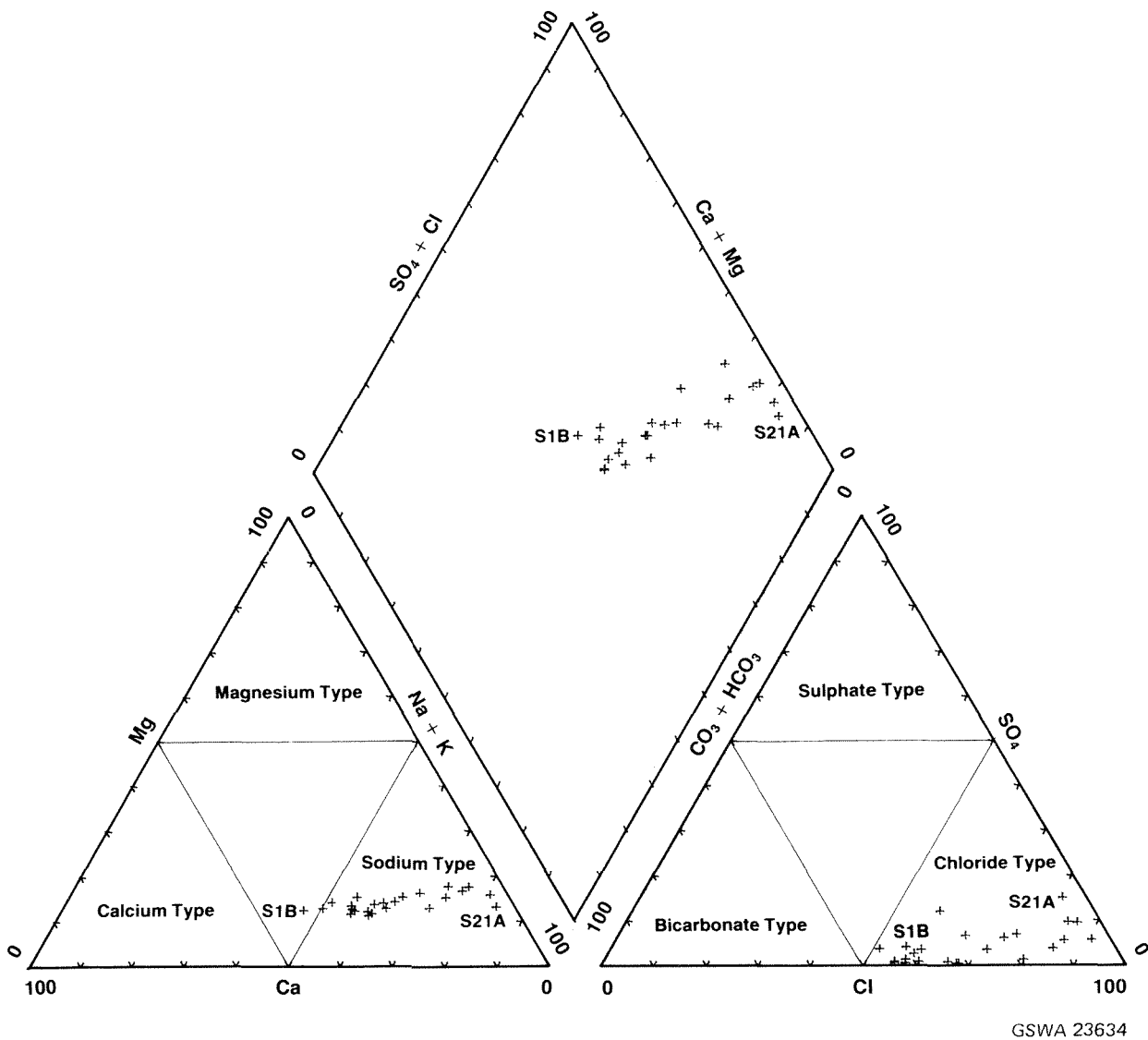


Figure 11. Piper trilinear diagram

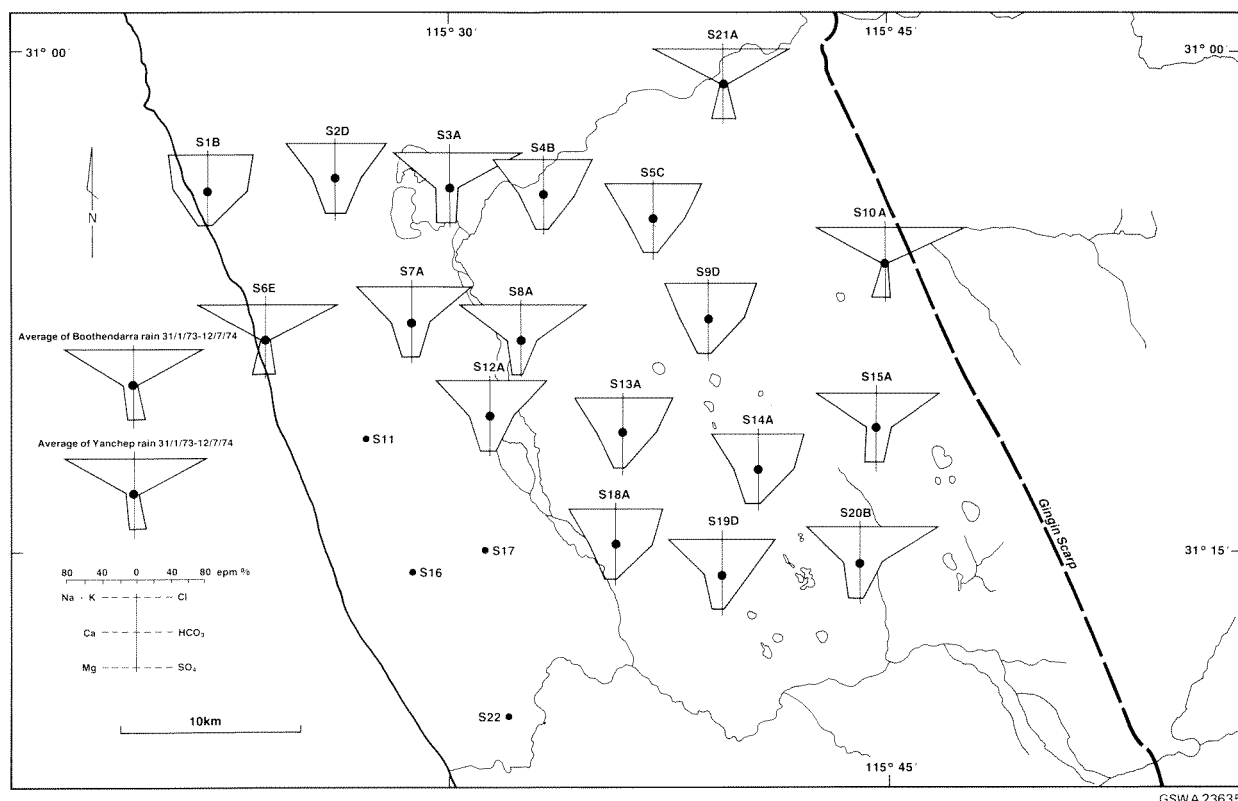


Figure 12. Diagrammatic representations of chemical analyses

CONCLUSIONS

The investigation has provided new information on the lithology and the extent of the Cainozoic superficial formations, the distribution of the underlying Leederville Formation, Osborne Formation and Lancelin beds and the configuration of the erosional unconformity at the top of these Cretaceous formations. The Ascot beds have been shown to be more extensive than further south, and the thickest known section of 31.5 m was penetrated.

A large, undeveloped resource of unconfined groundwater has been found in the Regans Ford Area centered beneath the Moore River National Park. Throughflow past the 50 m water-table contour is estimated to be $16 \times 10^6 \text{ m}^3/\text{year}$, of less than 750 mg/L TDS. Development of this resource may be restricted because lowering of the water table will affect wetlands and the area is a source of fresh groundwater recharge to the Leederville Formation.

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STRUCTURE OF KALGOORLIE GREENSTONES — REGIONAL DEFORMATION HISTORY AND IMPLICATIONS FOR THE STRUCTURAL SETTING OF THE GOLDEN MILE GOLD DEPOSITS

by Cees Swager

ABSTRACT

Four regional deformation phases are recognized in the greenstone sequence at Kalgoorlie. D₁ thrusting and recumbent folding have resulted in repetition of the greenstone sequence, implying large distances of transport. A northwest to southwest movement direction is tentatively suggested. D₂ regional folding about northwest-trending axes is followed by progressive D₃ deformation. The latter involved major northwest-trending sinistral wrench faults (Boulder-Lefroy Fault) with subhorizontal displacements in the order of 10 km, in addition to regional northeast-southwest shortening with the development of a steep southwest-dipping S₃ foliation. The wrench faults are associated with diagnostic *en echelon* folds which are at an angle to the regional F₂ and F₃ folds. North-northeasterly trending D₄ dextral faults, with subhorizontal displacements ranging from tens of metres up to 1 km, are possibly related to shear reversal along the major faults. Weak post-D₄ cross folding took place about northeast-southwest axes.

The Kalgoorlie gold mineralization events are related to the D₃ (Golden Mile lodes) and D₄ (Mount Charlotte stockworks) deformation events. The Golden Mile lode structures suggest largely concurrent D₃ wrenching and regional shortening. The steep "main lode system" is largely restricted to the massive Golden Mile Dolerite and defines a sinistral-shear fracture system related to the D₃ wrench faulting. "Flat lodes", including the Oroya hanging-wall and footwall shears, are restricted to the layered Paringa Basalt or its contact with the dolerite, and are developed as shallow-dipping fault zones or shear zones along planes of weakness during D₃ northeast-southwest shortening. The Oroya Shoot formed in a dilational jog, in the overlap between off-stepping footwall and hanging-wall shears. Several stages of extensional features (cross lodes, veins, fractures) indicate minor but constant subhorizontal northwest-southeast tension throughout the syn-D₃ alteration history. The "Mount Charlotte stockworks" are defined by two sets of quartz veins that can be related to the D₄ dextral Charlotte and Reward faults.

The regional wrench faults probably played a crucial role in both the regional and detailed setting of the gold deposits in the Kalgoorlie greenstone belt.

INTRODUCTION

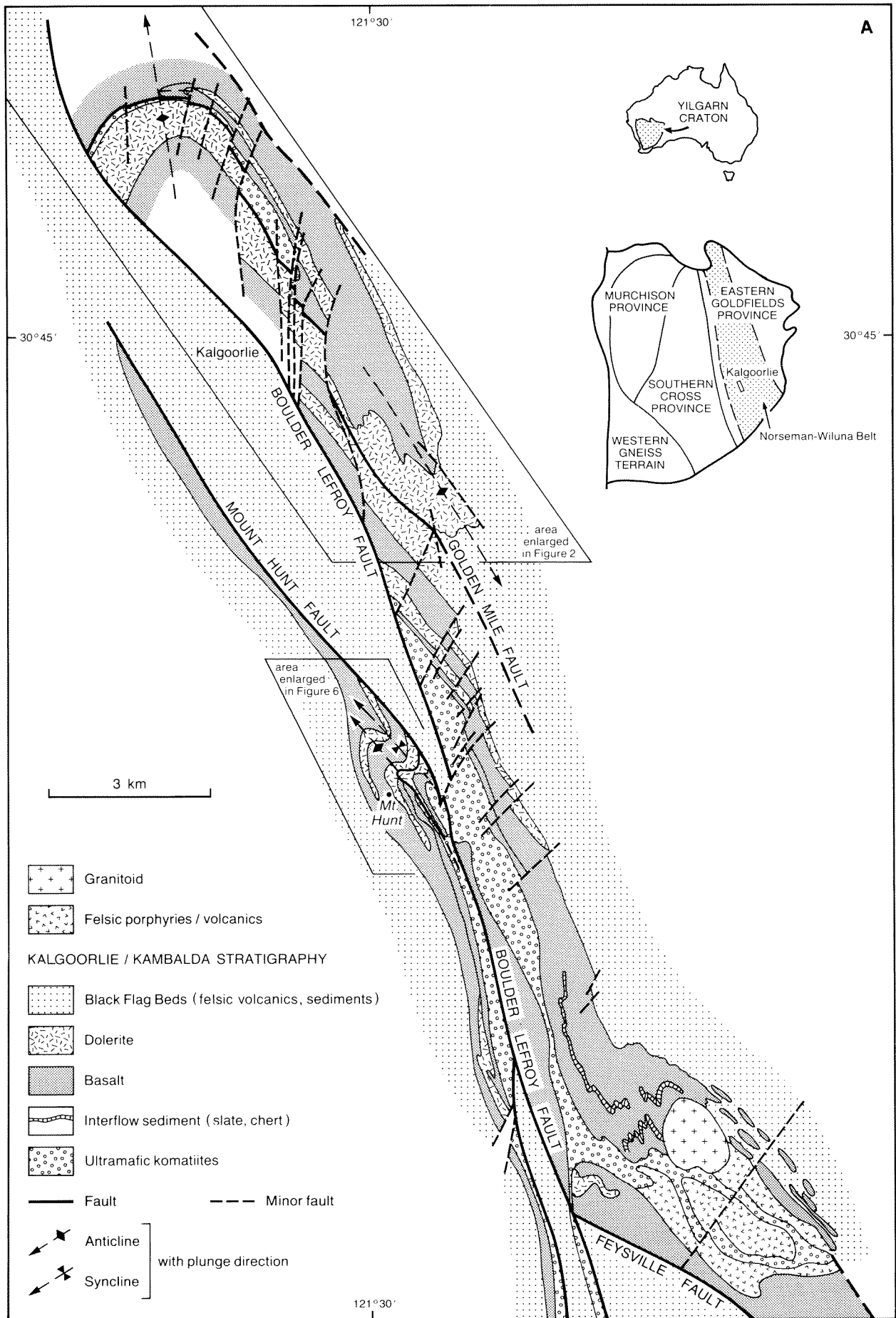
The importance of structural controls on the localization of the Kalgoorlie gold deposits (total output > 1 250 tons; Keats, 1987) in the greenstones of the Archaean Yilgarn craton, was recognized early in the area's long mining history (Larcombe, 1912). The recent upsurge in gold mining and exploration has been accompanied by renewed research, particularly centred on operating mines. Most studies have dealt with geochemical aspects and local structural controls of the alteration processes associated with mineralization (Clark, 1981; Boulter and Phillips, 1985). A current model for gold deposition involves the channelling of auriferous metamorphic fluids, with possible mantle contributions via fractures, faults and shear zones, into chemically receptive host rocks, during the later stages of regional metamorphism and deformation (Groves and others, 1984; Perring and others, 1987).

The structural framework for these studies in the Kalgoorlie mining area is based on the work of Woodall (1965) and Travis and others (1971)

which in turn draws on many earlier contributions (Woodall, 1965; p. 77-79). Recent regional mapping by the Geological Survey of Western Australia in the Kalgoorlie-Kambalda area (Keats, 1987; Griffin, 1988) has provided the basis for a study of the regional structural setting of the mining area. This paper discusses the deformation history of the Kalgoorlie-Kambalda greenstone belt, which is then used as the framework for the definition of the structural controls and relative timing of the Golden Mile deposits. Detailed data for this paper were collected from the field, from drill core, and from several underground levels of the North Kalgurli Mine, as well as from literature on the Kalgoorlie gold mines.

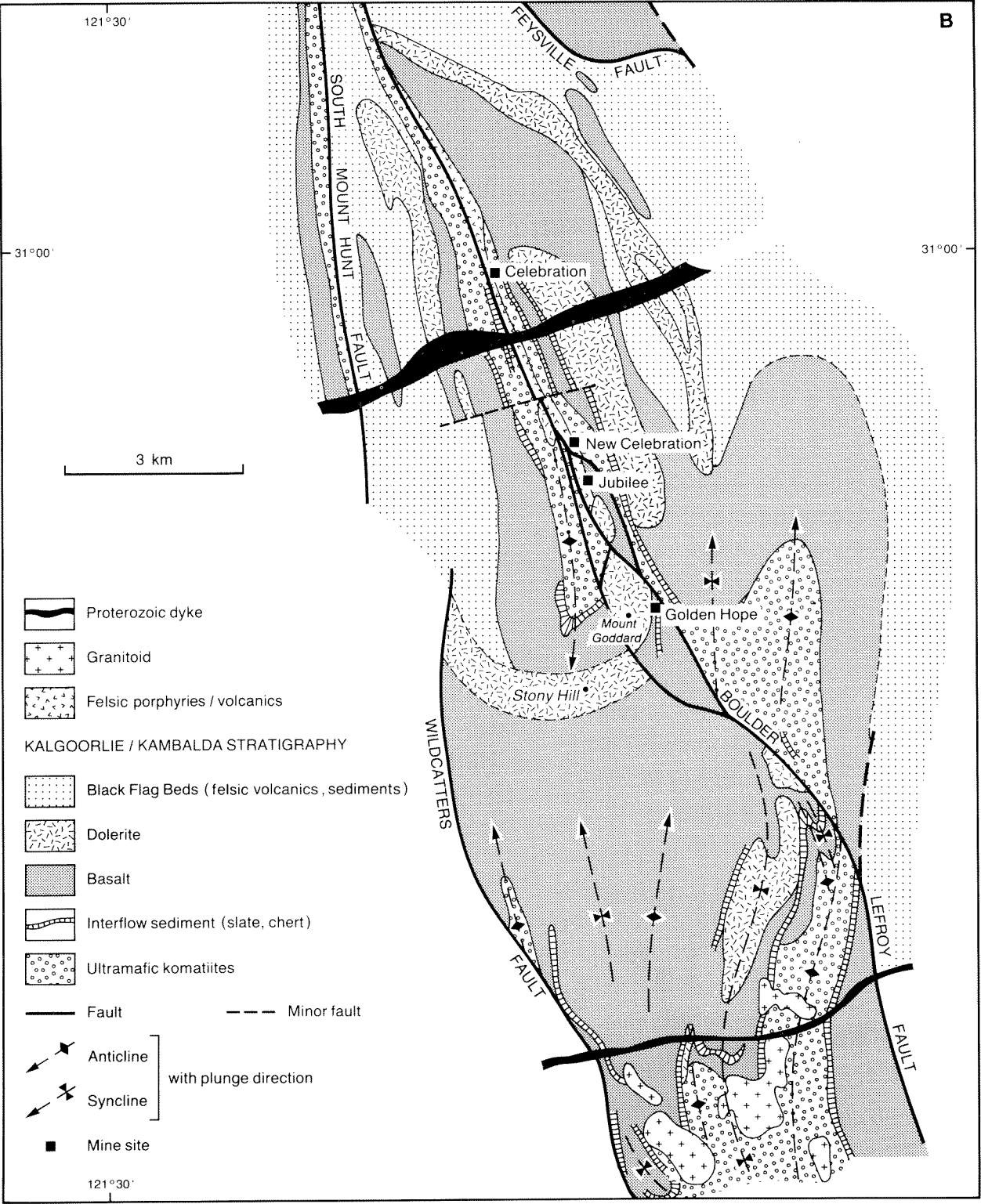
GEOLOGICAL SETTING

The Kalgoorlie gold-mining area occurs in a low-grade metamorphic domain of the Norseman-Wiluna greenstone belt (Fig. 1; Binns and others, 1976) which has been interpreted as a central, linear, rift zone in the Eastern Goldfields Province of



the Yilgarn craton (Gee and others, 1981; Groves and Batt, 1984; Hallberg, 1986). The granite-greenstone belt is 600 km long and is characterized by a strong, northwest, structural trend, dominated by major fault zones and shear zones which can be traced over hundreds of kilometres.

The faults have sliced up the volcano-sedimentary greenstone sequence into elongate domains with more or less coherent internal stratigraphies. Correlation of the sequences across the major faults has proved to be difficult, and is hindered by intensely weathered lithologies and their poor ex-



GSWA 23692

Figure 1 (A and B). Regional geology of the Kalgoorlie-Kambalda greenstone belt, compiled from Keats (1987) and Griffin (1988). Inset in Figure 1A shows location within the Yilgarn Craton.

posure. Some authors have proposed multicyclic deposition of ultramafic and mafic-to-felsic volcanics and sediments (Williams, 1970; Gemuts and Theron, 1975), whereas others have pointed out the likelihood of structural repetition within the greenstone belts (Archibald and others, 1981; Griffin and others, 1983).

With the availability of information from extensive mining and exploration, the stratigraphy of the Kalgoorlie area is now well established (Travis and others, 1971), and it is correlated with that of the Kambalda and Victory areas to the south (Gresham and Loftus-Hills, 1981; Clark and others, 1986; Table 1). All rocks are metamorphosed to greenschist facies, but, for brevity in this paper, the prefix 'meta' is omitted. The generally well-preserved primary structures allow the original rock types to be interpreted with some confidence. Figure 1 shows an interpretation map of the Kalgoorlie-Kambalda area compiled from recent detailed mapping by the Geological Survey of Western Australia (Keats, 1987; Griffin, 1988).

The first map of the Kalgoorlie mining area dates back to Campbell (1902). Since then, as Finucane (1965) stated "knowledge has been progressive and cumulative". The present-day under-

standing of the overall geometry is still largely based on the work by Woodall (1965) and Travis and others (1971). Figure 2, showing the major structural elements discussed in this paper, is based on the recent 1:25 000 GSWA map of the mining area (Keats, 1988). The main structures are the near-vertical Golden Mile Fault (GMF) and the upright Kalgoorlie Anticline which plunges gently to the southeast. The Brownhill Syncline and Paringa Anticline are parasitic folds on the western limb of the Kalgoorlie Anticline, and they die out quickly with depth (Woodall, 1965). The GMF has been interpreted as a major strike fault in the so-called Kalgoorlie Syncline (Gustafson and Miller, 1937; Campbell, 1953) with a vertical movement estimated to be several kilometres (Travis and others, 1971). The narrow, but persistent sliver of Black Flag Beds, west of the GMF, is extensively intruded by felsic porphyry (hence the early name 'Boulder Dyke'). A prominent set of north-northeasterly trending dextral faults offsets the GMF and the Kalgoorlie Anticline. The Boulder-Lefroy Fault, one of the prominent, regional, strike faults, has brought the Kalgoorlie mafic sequence into contact with the Black Flag Beds to the west. Woodwall (1965) suggested a vertical displacement (west block down) along the Boulder-Lefroy Fault.

TABLE 1. STRATIGRAPHY OF THE REGIONAL GREENSTONE SEQUENCE AT KALGOORLIE, KAMBALDA AND VICTORY (20 KM SOUTHEAST OF KAMBALDA).

<i>KALGOORLIE</i> <i>(Woodall, 1965)</i>	<i>KAMBALDA</i> <i>(Gresham and</i> <i>Loftus-Hills, 1981)</i>	<i>KAMBALDA-VICTORY</i> <i>(Clark and others, 1986)</i>
Black Flag Beds (felsic volcanics, sediments) 3000 m	—	—
Golden Mile Dolerite 300-750 m	—	Condenser Dolerite
Paringa Basalt 300-900 m	Kambalda Hangingwall Basalt —upper member	Paringa Basalt
Williamstown Dolerite 150-300 m	—	Defiance Dolerite
Kapai Slate 3 m	Sediment-intrusive complex	Kapai Slate
Devon Consols Basalt 60-150 m	Kambalda Hangingwall Basalt —lower member	Devon Consols Basalt
Hannan Lake Serpentinite 300-900 m	Kambalda Ultramafics	Tripod Hill Formation Silver Lake Peridotite
—	Kambalda Footwall Basalt	—

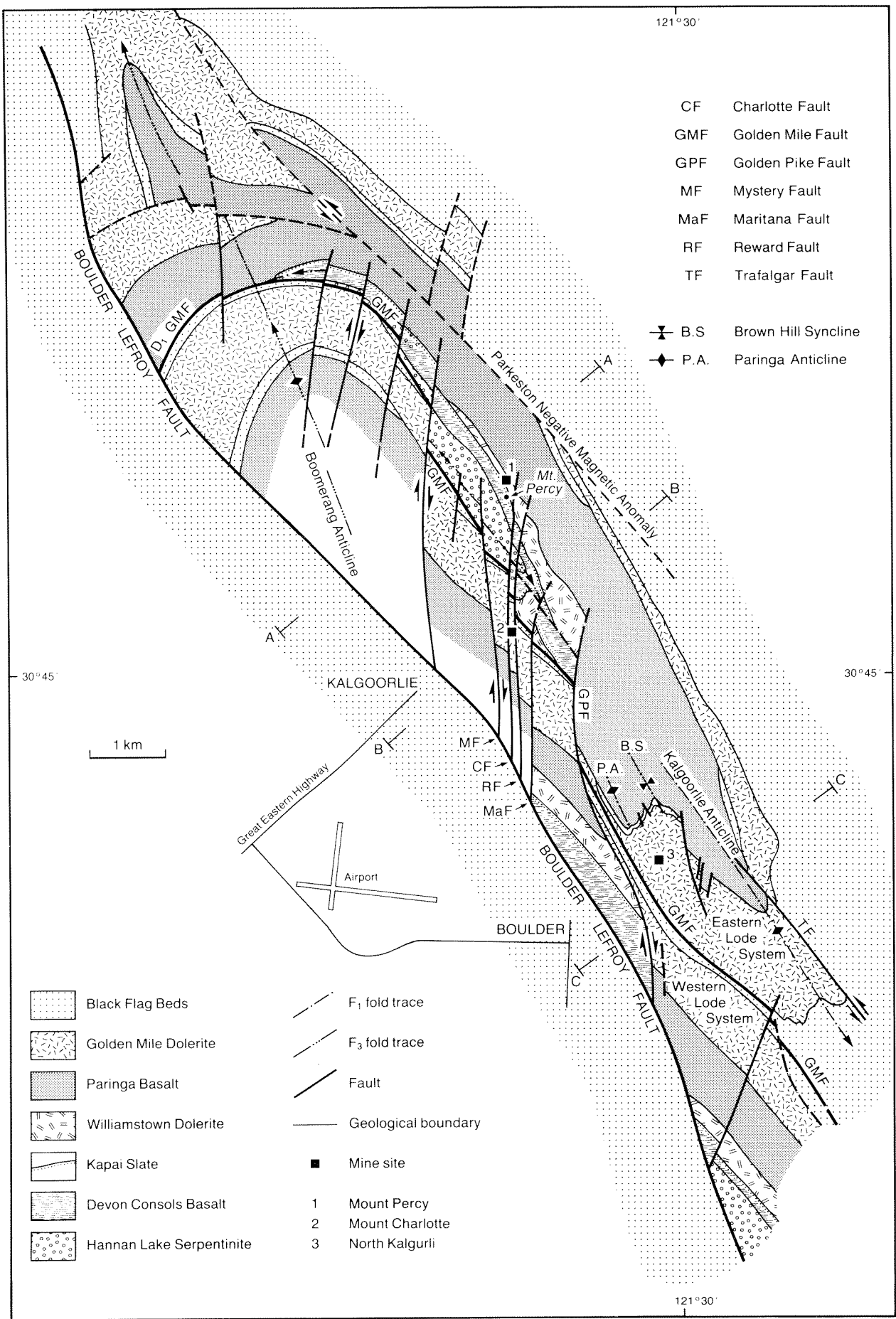


Figure 2. Schematic geological map of the Kalgoorlie mining area. After Keats (1987).

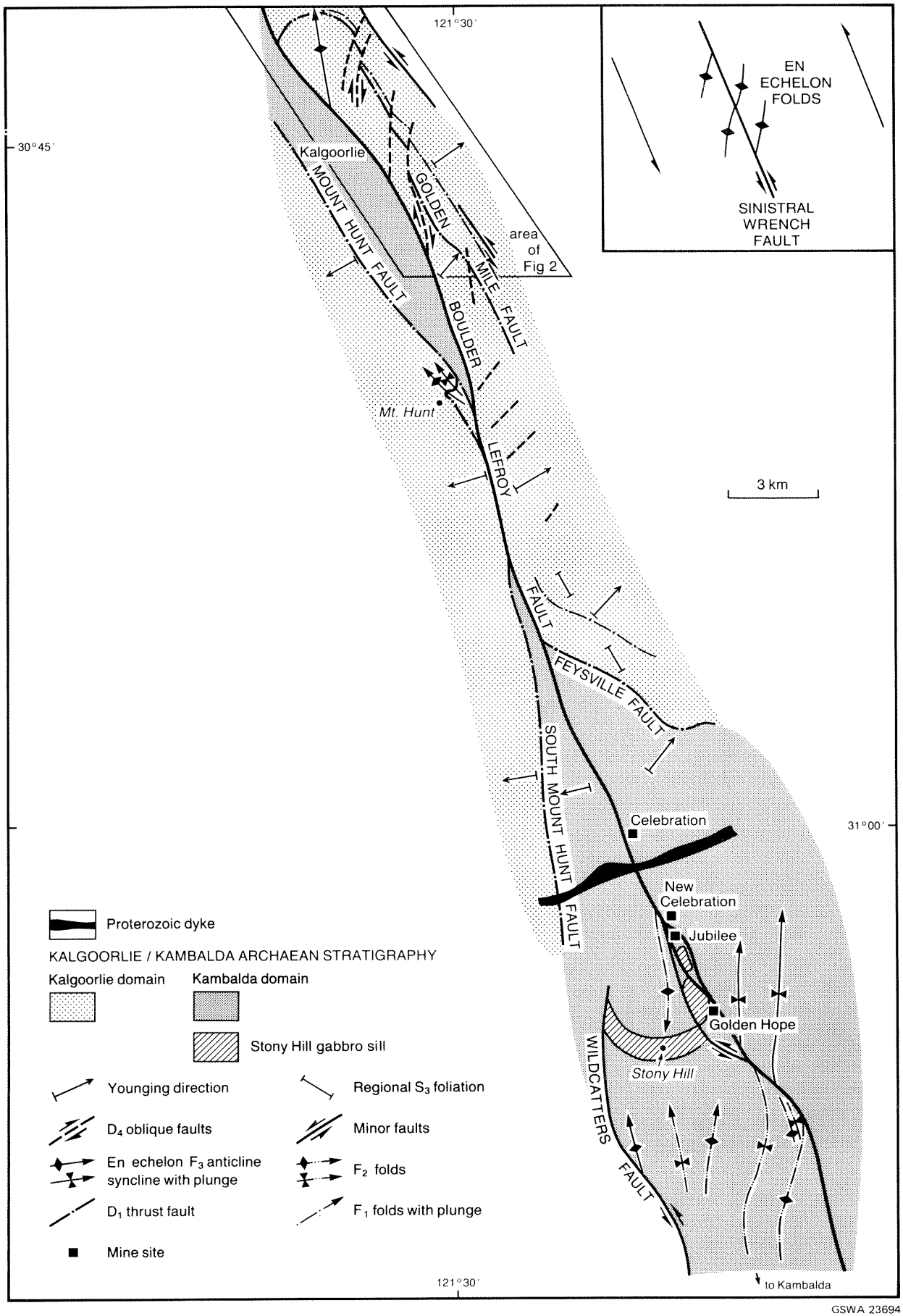


Figure 3A. Schematic geological map showing the Kalgoorlie and Kambalda 'domains' of the regional sequence, and the BLF wrench fault with *en echelon* fold traces. Inset shows geometric relation of *en echelon* folds in a sinistral wrench regime. After Wilcox and others (1973), and Sylvester and Smith (1976).

The bulk of the gold production in Kalgoorlie is from the Golden Mile area (*i.e.* the area east of the Golden Pike Fault in Figure 2). Numerous steeply dipping pyritic siliceous lodes ("Main lode system") contain extensive carbonate and sericite alteration haloes (Phillips, 1986) in the Golden Mile Dolerite, and, to a lesser extent, in the Paringa Basalt. These lodes are divided into a Western and an Eastern lode system, on either side of the GMF (Fig. 2). Rich shallow-dipping, gold-telluride lodes (including the Oroya Shoot) are found along and below the dolerite-basalt contact; they commonly occur where interflow sediments

are present within the basalt. All these lodes are generally interpreted to have formed by replacement along fractures and shears (Larcombe, 1912; Finucane, 1965; Phillips, 1986), with the exception of Tomich (1986) who favoured a volcanogenic origin. Woodall (1965) suggested that the fracture systems were present before the mineralization, whereas Boulter and Phillips (1985) argued that the Main lode system developed as ductile shear zones, during the upright-folding event, with simultaneous introduction of hydrothermal fluids. However, Gustafson and Miller (1937) had already argued that the shear fracture pattern 'on both sides of the Kalgoorlie Syncline' (*i.e.* the Western and Eastern lode systems) is essentially the same, and therefore was imposed on an already folded sequence.

The "Mount Charlotte quartz-vein stockworks", which form the second major source of production, are controlled by the Charlotte and Reward 'oblique' faults and are largely restricted to the granophyric unit in the Golden Mile Dolerite (Clark, 1981). Woodall (1965) proposed that the stress system responsible for the oblique faults also controlled the Golden Mile "Main lode system". However, Boulter and Phillips (1985) stated that the Golden Mile lodes predated the oblique faults and their associated "Mount Charlotte stockworks".

Other gold deposits are present in the Mount Percy area. The Union Club orebody occurs in the Devon Consols Basalt, generally close to and (in places) within the Kapaï Slate, where the Charlotte Fault passes through this stratigraphic contact. The Mystery orebody occurs in and along felsic porphyry that intrudes the Hannan Lake Serpentine (Sund and others, 1983).

This paper focuses only on the structures of the two major gold mineralization types and their relationships to the regional deformation history.

STRUCTURAL HISTORY OF THE KALGOORLIE GREENSTONE BELT

The dominant structure in the Kalgoorlie belt is the northwesterly striking Boulder Fault, which can be traced into the Kambalda area as the Lefroy Fault. The geometrical relationships of this Boulder-Lefroy Fault (BLF) with other major fault structures and fold structures form the basis for the proposed deformation history of the Kalgoorlie greenstones. The most important features (Fig. 3A) are:

- The stratigraphic sequences on either side of the BLF are the right way up and dip away from the BLF. Therefore, the BLF occurs in the axial plane of a regional antinormal structure, here interpreted as D_2 , and called the Celebration Anticline (Norris, 1987). Southwards, the BLF is to the east of the antinormal hinge, which is preserved as the Kambalda Anticlinorium. In other words, the BLF only occupies the D_2 fold hinge, northwards from the Golden Hope mine (Fig. 1).

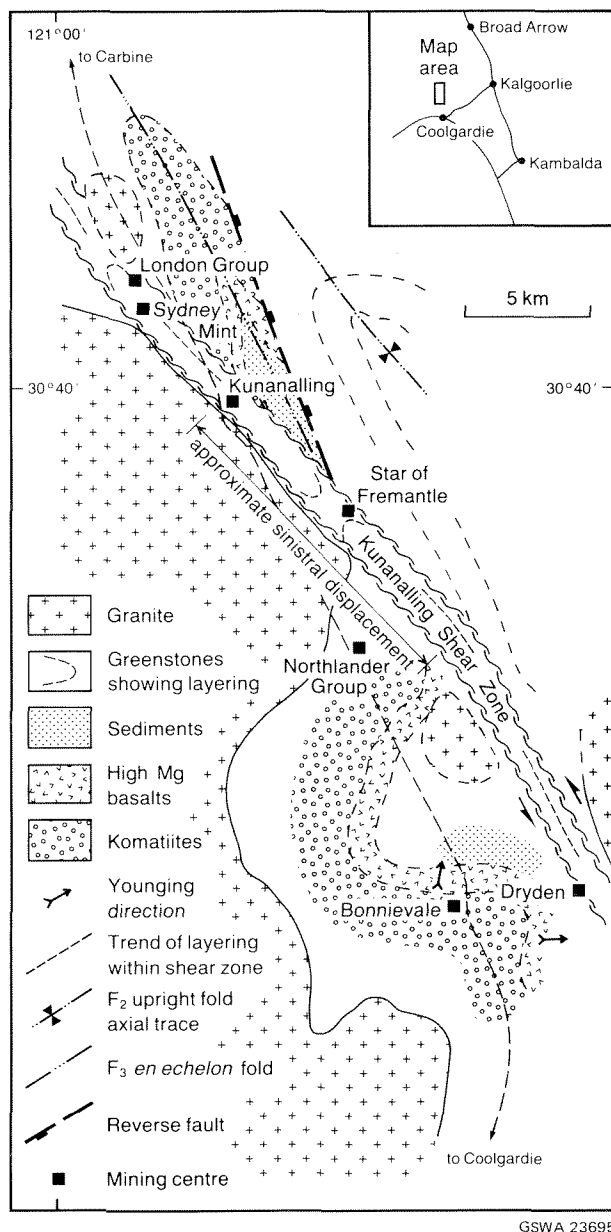


Figure 3B. Schematic geological map of the Bonnievale-Kunanalling area, after Hunter (1988). The sinistral D_3 Kunanalling shear zone offsets upright F_2 folds, with characteristic *en echelon* F_3 fold and associated reverse fault, developed east of the shear zone. Displacement is at least 10 km. The irregular east-west trending cross folds probably developed during granite emplacement.

TABLE 2. DEFORMATION HISTORY OF KALGOORLIE GREENSTONES, AND CORRELATIONS WITH OTHER REGIONAL STRUCTURAL STUDIES

	<i>KALGOORLIE-KAMBALDA</i> <i>This paper</i>	<i>AGNEW</i> <i>Platt and others, 1978;</i> <i>Platt, 1980</i>	<i>KAMBALDA</i> <i>Gresham and Loftus-Hills,</i> <i>1981</i>	<i>WIDGIEMOOLTHA-NORSEMAN,</i> <i>Archibald and Bettenay, 1977</i> <i>Archibald and others, 1978</i>	<i>LAKE DUNDAS</i> <i>Spray, 1985</i>
	—	—	S ₄ Open, upright folds, south-plunging poorly developed	S ₄ Crenulation cleavage located along granitoid domes	—
post-D ₄	Very weak, approximately E-W crossfolding, small scale, localized	—	Open folds ENE-NE trending axial surface causing F ₂ -F ₃ domal structure	—	D ₄ Open, upright folds sub-horizontal plunge, Sub-vertical ENE-trending S ₄ causing F ₃ + F ₄ domal structure; domes coinciding with 'diapirs'
D ₄	North-trending dextral faults; west-dipping (Mount Charlotte Fault) displacement up to several 100 m, locally 1 km; shear reversal along major wrench faults	—	—	—	—
	Regional NE-SW shortening, regional foliation S ₃ , subvertical, locally multiple foliations (?); folding on various scales; plunges variable NW to SE	—	—	D ₃ Open to tight folds; regional NNW-trending S ₃ ; synmetamorphic faults between domains; initiation of synkinematic granite doming	D ₃ Main regional event; sub-vertical plunge; close-tight steep NNW-trending S ₃ ; large transcurrent faults active
D ₃	Regional, sinistral wrench faults, NNW-trend, very steep, displacement major faults 10 km (Boulder-Lefroy Fault) displacement minor faults 100 m to	Waronga shear zone, N-trending dextral ductile shear zone	Major NNW-trending faults	—	—

1 km (Trafalgar Fault): 'en echelon' folds oblique to wrench fault (Boomerang Anticline)	D ₂	Major tight folds, steep to vertical plunge, steep NNW-trending S ₂ ; quartz lineation subhorizontal (pre-D ₂ leucogranite)	D ₂	Main regional event; open, close, upright folds NNW-trending axial surface	D ₂	Macroscopic-mesoscopic folds regional N to NNW trending S ₂	D ₂	Large-scale folds; weak NNE-trending S ₂ refolded by D ₃
S ₂ Regional folding, large wavelength (N)NW - (S)SE axes. Little fabric development in mafic volcanics								
D ₁ Subhorizontal shortening; direction NE to SW recumbent folds to fold nappes (GMF; Kalgoorlie Anticline) large thrust sheets? (Feysville Fault; Mount Hunt Fault?)	D ₁	Mesoscopic-macroscopic, isoclinal folds originally recumbent or inclined, regional subhorizontal S ₂ ; with associated tectonic slides	D ₁	Small-scale localized, tight-isoclinal, recumbent and napped fold; Weak S ₁	D ₁	Macroscopic isoclinal recumbent folds; no mesoscopic folds; no microscopic fabrics; only found in 'static' domains	D ₁	Steep mylonitic S ₁ , intrafolial folds; S ₁ originally shallow-dipping; restricted to shear zones between greenstones and gneisses

- (b) Axial traces of several regional folds (e.g. Boomerang Anticline) show a remarkably constant geometrical relationship with respect to the BLF. This geometry is compatible with the asymmetrical relationships between *en echelon* folding and the regional-fault trace in a left-lateral (sinistral) wrench or strike-fault system (Wilcox and others, 1973). Sinistral displacement along the BLF is supported by other observations, such as the curving of minor fold-axial traces towards the fault (e.g. northern Kambalda Anticlinorium), and the displacement of the Stony Hill – Mount Goddard dolerite (Fig. 1) which has been segmented into two strike-slip duplexes (Woodcock and Fisher, 1986). The BLF is thus interpreted as a D₃ sinistral wrench or strike-slip fault. The BLF must have developed after the regional D₂ anticline, because the wrench faulting cannot explain the change in younging direction across the fault.
- (c) The greenstone sequence is repeated across the Feysville and Mount Hunt Faults which occur, respectively, on the east and west side of the BLF. Both faults are largely bedding-parallel, and the sequence shows the same younging direction across each fault, whereby older rocks everywhere overlie younger rocks (Fig. 3). The Feysville and Mount Hunt Faults are interpreted here as D₁ thrust faults, possibly representing an equivalent D₁ structure, folded and offset by the D₂ Celebration Anticline and the D₃ BLF.

The deformation history is summarized in Table 2, and features of each deformation phase are described and discussed below.

D₁ — RECUMBENT FOLDING AND THRUSTING

Kalgoorlie area

The Golden Mile Fault (GMF) occurs on the eastern limb of the D₂ Celebration Anticline (Figs 2 and 3). To the west of the GMF there is a simple, near-vertical sequence, which is younging uniformly to the east. The fault plane is virtually parallel to bedding, at a constant stratigraphic level just above the Golden Mile Dolerite – Black Flag Beds (Figs 2 and 4). To the east of the fault there is a sequence folded by the Kalgoorlie Anticline, with the fault plane transgressing the stratigraphy. Contrary to suggestions on published cross-sections in Woodall (1965) and Travis and others (1971), there is no recorded synclinal closure at depth west of the GMF (Hopkins, 1983).

Both the GMF and the Kalgoorlie Anticline are folded by the Boomerang Anticline (Fig. 2). The Kalgoorlie Anticline, though best preserved east of the Golden Pike Fault, can be followed northwards, despite later complex faulting, around the Boomerang Anticline (Fig. 2), where recent drilling (M. Schwabe, personal communication, 1986) suggests a west-plunging anticline just north of and

subparallel to the GMF. Thus the plunge direction of the Kalgoorlie Anticline changes going northwards, from shallow southeast in the Golden Mile, through subhorizontal to shallow northwest in the hinge region of the Boomerang Anticline (Fig. 2).

Campbell (1953) and Woodall (1965) interpreted the GMF as a major strike fault, in the axial plane of an upright Kalgoorlie Syncline, with a vertical displacement in the order of 3 km. However, major volume problems are implied by such a fault movement. The stratigraphy of Hannan Lake Serpentinite and Golden Mile Dolerite is sheared out on the western limb of the Kalgoorlie anticline southwards of Mount Percy, whilst the GMF retains a constant and bedding-parallel attitude with respect to the sequence west of the fault

(Fig. 4A – C). Northwards from Mount Percy the western limb of the Kalgoorlie Anticline partly reappears (Fig. 2), with the GMF still at the same bedding-parallel attitude with respect to the western sequence.

Restoration to a pre-D₂ configuration (by removing the effects of D₂ and D₃ tilting and folding) results in a flat-lying GMF parallel to bedding in the underlying sequence (*i.e.* west of the fault), overlain by a repetition of the sequence in a recumbent anticlinal structure (Fig. 4E). This geometry is explained by D₁ thrusting of the ‘eastern’ over the ‘western’ sequence. At the Golden Mile and southwards, where the inverted limb of the recumbent Kalgoorlie Anticline is present, the eastern sequence shows a fold-nappe geometry

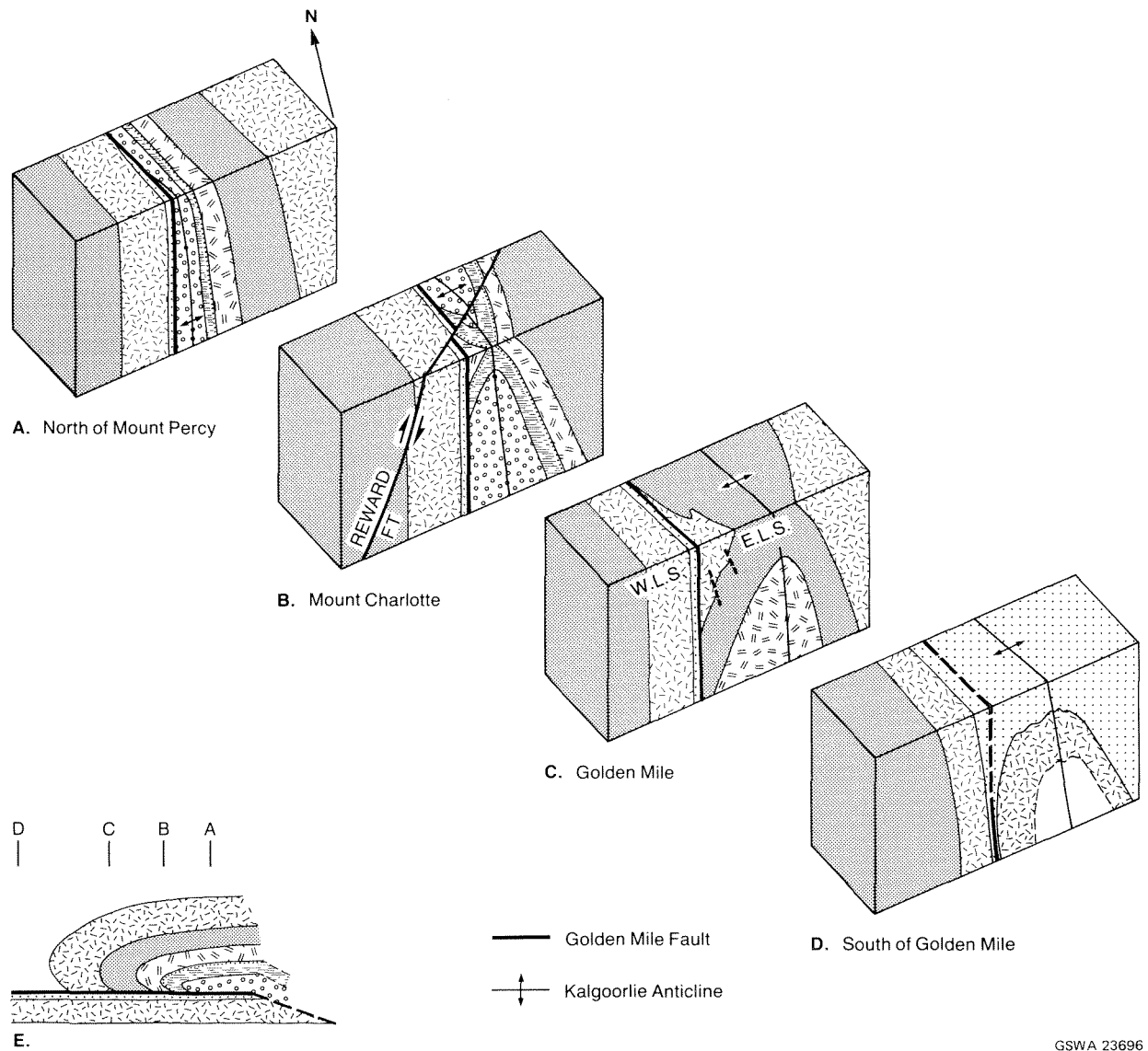


Figure 4. Simplified cross-sections from the Kalgoorlie mining area. Adapted from Travis and others (1971), Hopkins (1983) and Keats (1987). Stratigraphy legend as in Figure 2.

(A) North of Mount Percy
 (B) Mount Charlotte
 (C) Golden Mile
 (D) South of Golden Mile
 (E) Idealised section through D₁ thrust geometry with suggested ramp. The approximate positions of cross-sections A-E are indicated.

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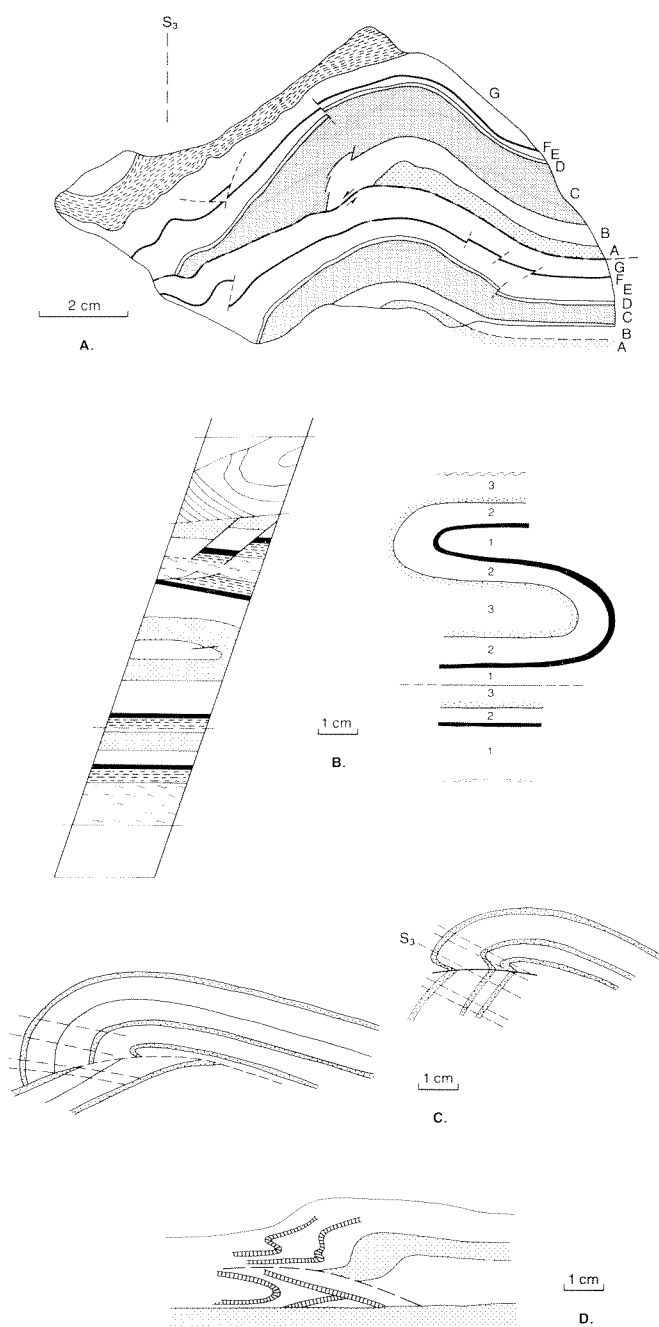


Figure 5. Small-scale D₁ structures.

(A) Thrust in interflow slates within Paringa Basalt. From hinge area of F₃ fold, Croesus North open pit.

(B) Repeated stratigraphy and intrafolial fold in Black Flag Beds at footwall of Golden Mile Fault, (i) drill core North Kalgurli Mine, (ii) interpretation as profile section.

(C) Sheared recumbent D₁ fold in Kapai Slate, south of Golden Mile. Two sections are 7 cm apart.

(D) Intrafolial folding, low-angle reverse fault (ramp) and thrust in Kapai Slate, south of Golden Mile.

(McClay, 1981). At Mount Percy, where the inverted limb is largely sheared out, the eastern sequence is a thrust nappe (McClay, 1981). The simplest interpretation is that these changes in geometry (exposed because of the F₁ fold plunge) represent sections through the D₁ thrust geometry, approximately parallel to the D₁ transport direction (Fig. 4E). However, the widely spaced sections may also indicate lateral differential movement (*i.e.* at right angles to the transport direction) resulting in changes from a sheared recumbent fold to a thrust-nappe geometry, similar to the nappes that die out laterally, as described in various Cenozoic fold-and-thrust belts (*e.g.* Dahlstrom, 1970).

The GMF is thus interpreted as a D₁ thrust fault and the Kalgoorlie Anticline as a D₁ recumbent fold. The latter developed either early in D₁ and was subsequently sheared along the GMF, or relatively late in D₁ as the thrust sheet moved over its footwall (Fig. 4E). The thin sliver of Black Flag Beds directly below the GMF indicates that the decollement horizon developed just above the contact with the Golden Mile Dolerite. That contact marks the transition from the massive mafic volcanics and intrusives to the regularly layered felsic volcanics and sediments. Drill cores from the Golden Mile area suggest that D₁ fabrics in that horizon are largely obliterated by the subsequent porphyry intrusions ('Boulder Dyke') and carbonate alteration. However, the following structures are tentatively interpreted as D₁: zones of intense shearing; intrafolial isoclinal folds; and local repetition of stratigraphy (Fig. 5B), particularly in shale intersections of the Black Flag Beds below the thrust fault.

Minor D₁ structures in sedimentary rocks (Kapai Slate and interflow slates in the Paringa Basalt) include small-scale thrusts and recumbent folds (Fig. 5). These mimic the large structure and low-angle reverse faults, folded during D₂ and D₃ and/or crosscut by the regional foliation S₃. Bedding – S₃ relations on the western limb of the Kalgoorlie Anticline confirm that S₃ has overprinted the anticline.

Mount Hunt area

The Mount Hunt sequence which is directly correlated with, but is generally thinner than, the Kalgoorlie stratigraphy (Travis and others, 1971; Keats, 1987), lies to the west of the BLF, and youngs westward (Figs 1 and 3). The complex geometry of the area (Fig. 6; after Keats, 1987) can be interpreted in terms of a recumbent D₁ anticline-syncline fold pair, of which the very thin overturned east-younging limb was sheared out, and probably attenuated by later shearing (Fig. 7). This D₁ structure, together with the D₁ GMF and Kalgoorlie Anticline (Fig. 3) may be interpreted as lateral equivalents, occurring on either limb of the D₂ Celebration Anticline.

The near vertical plunge of the later fold, and its weak axial-planar foliation, suggest that refolding took place during D₃ regional shortening. In the

hinge of this F_3 fold, the axial-plane foliation overprinted earlier small-scale structures such as asymmetric F_2 folds.

Feysville and Mount Hunt faults

As discussed above, the Feysville and Mount Hunt faults are interpreted as D_1 thrust faults. For example, the Feysville fault is subparallel to bedding in sequences on either side, with older rocks overlying younger rocks in the same younging di-

rection, and is truncated by the BLF and overprinted by the regional foliation. These relationships indicate D_1 repetition of the greenstone sequence. The complex geometry north of the fault indicates an anticline (Keats, 1987) with an axial trace which strikes approximately northwest, parallel to the fault. Northwards, this trace curves towards parallelism with the BLF, and is eventually cut out against the BLF, which is overprinted by S_3 and thus predates D_3 , is tentatively interpreted as a D_1 structure (originally a recumbent anticline?) which developed at the hanging wall of the Feysville fault.

Figure 3A shows schematically the distribution of the 'regional stratigraphic domains' (referred to as the Kalgoorlie and Kambalda 'domains') bounded by these major D_1 thrust faults. The geometry suggests that the entire Kalgoorlie domain is an allochthonous thrust sheet that itself contains D_1 nappe structures, and was folded by the D_2 regional anticline. The movements along these major thrust faults must have been considerably larger than along the GMF, possibly in the order of tens of kilometres.

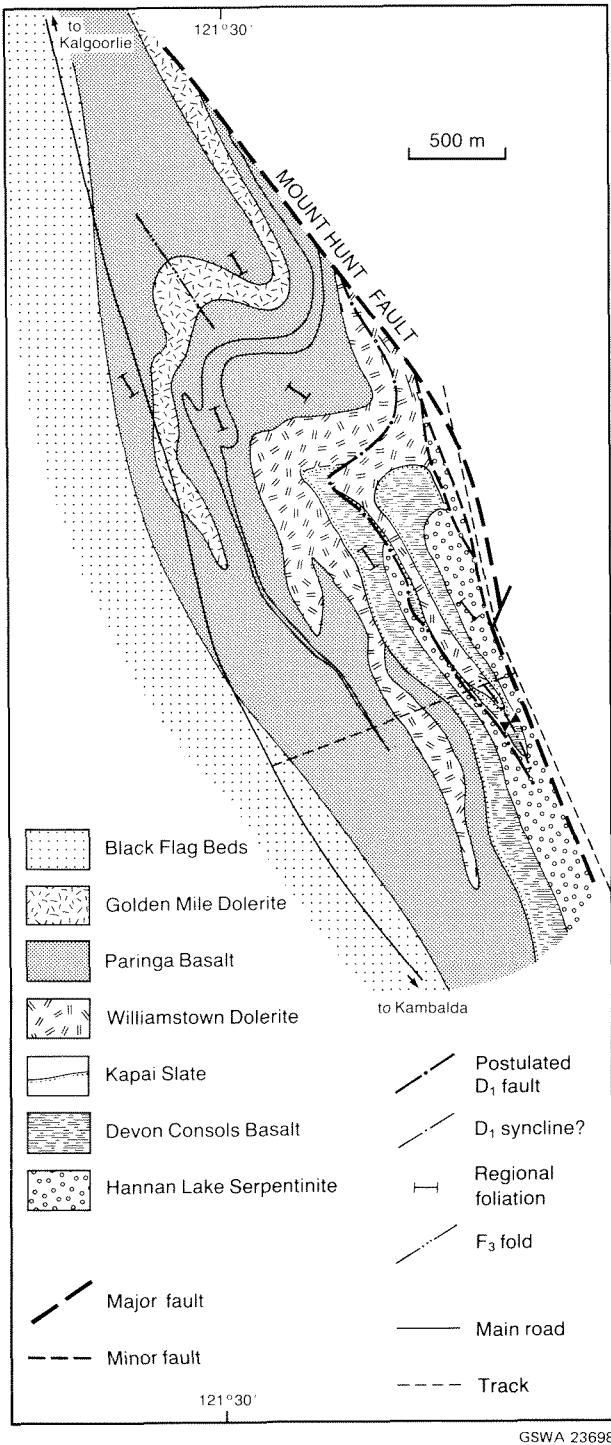


Figure 6. Schematic geological map of Mount Hunt area. Adapted from Keats (1987).

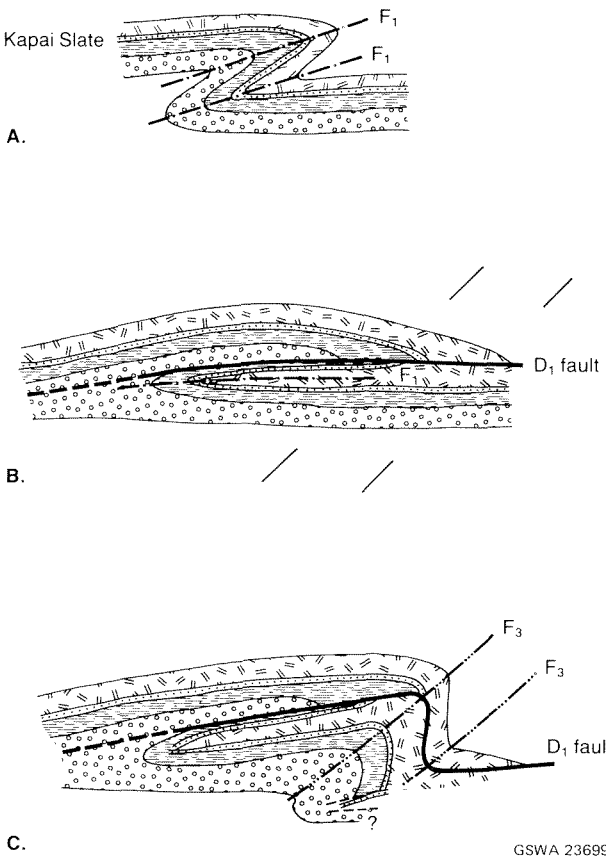


Figure 7. Possible development of Mount Hunt geometry, seen in D_1 profile sections.

- (A) Initial stage of D_1 recumbent folding.
- (B) Partly preserved overturned limb of D_1 recumbent fold. Thinning of limb may have occurred during D_1 or later.
- (C) Asymmetric D_3 refolding, after F_2 tilting of the D_1 structure into steep vertical position on the western limb of the Celebration Anticline.

The Feysville and Mount Hunt faults are temporally and geometrically equivalent structures, but a direct correlation is open to question. For example, the thrust faults may occur at different stratigraphic levels.

D₂ — REGIONAL NORTHWEST-SOUTHEAST FOLDING

Evidence for large-scale D₂ folding along northwest-trending axes is based on the opposite younging direction across the BLF (Fig. 3A). This regional anticline (which was named the Celebration Anticline in the New Celebration mining area by Norris, 1987) must predate the initial development of the BLF along its axial plane, because D₃ wrench faulting by itself cannot explain the pattern of younging directions. The original F₂ fold may have had a shallow northwest plunge, as suggested by the overall younging direction indicated by the disappearance of the mafic lower part of the stratigraphy northwards along the BLF.

Outside the area under consideration, the D₂ deformation has resulted in large-scale, north-northwesterly striking upright folds with a regional S₂ foliation that is best developed in sediments and felsic volcanics.

D₃ — SINISTRAL WRENCH FAULTING AND REGIONAL SHORTENING

The D₃ phase is a complex, progressive event with two distinct modes of deformation, *i.e.* regional northeast-southwest shortening resulting in D₃ folds and S₃ foliation development, together with widely spaced strike or wrench faulting. The Golden Mile structures (discussed separately) provide evidence for the contemporaneity of wrench faulting and regional shortening; they also show that shortening outlasted wrenching. The overall D₃ deformation can be described as transpressional (Sanderson and Marchini, 1984).

Wrench faulting

Wrench faults are expressed as near-vertical strike-slip faults of considerable strike extent, commonly with large subhorizontal displacements (Moody and Hill, 1956; Wilcox and others, 1973). These displacements generate associated compressional and extensional strains which result in characteristic folding and faulting patterns. These include *en echelon* folds (Fig. 3A inset), synthetic and antithetic strike faults (analogous to Riedel and conjugate Riedel Shears), reverse or thrust faults and normal faults or extension fractures (Tchalenko, 1970; Wilcox and others, 1973). Any combination of these structures may occur within a wrench-fault domain on various scales, depending on factors such as superimposed regional compression or extension lithologies and pre-existing structures. The systematic patterns of these various structures (independent of their scale) are the diagnostic features of a wrench-fault regime and define the sense of displacement (Wilcox and others, 1973).

The geometrical evidence for the BLF as a sinistral wrench fault is summarized in Figure 3A and in the introduction to this section. The develop-

ment of the *en echelon* folds, and their distinction from folds formed by D₂ and/or D₃ regional shortening, deserves further attention. As discussed above, the initiation of D₃ wrench faulting post-dates the D₂ regional folding. Because the fault developed along the axial plane of the D₂ Celebration Anticline, the associated wrenching affected an already tilted sequence, and resulted in very steeply plunging attitudes of the *en echelon* folds. In contrast, the regional F₂ folds show more moderate plunges as well as plunge reversals. Furthermore, *en echelon* folds tend to develop at a small angle to the trend of the regional folds (Fig. 3B), and may die out along strike. The steeply plunging Boomerang Anticline at Kalgoorlie is interpreted as a characteristic *en echelon* fold, whereas the Kambalda Anticlinorium probably formed during D₂ regional folding, and was subsequently transected at a small angle by the BLF. This anticlinorium was most likely attenuated during D₃ shortening.

The Kunanalling shear zone in the Coolgardie area (Hunter, 1988) provides further evidence for the local development of *en echelon* folds during wrench faulting (Fig. 3B). Horizontal movement estimated from displacement of the stratigraphy is at least 10 km.

Drill core through the BLF, several kilometres south of Boulder, indicates a wide zone (> 100 m) of highly sheared and brecciated material. Within the contact zone, fragments of Hannan Lake Serpentinite and Devon Consols Basalt are found mixed with Black Flag Beds. A strong mineral lineation, exhibiting shallow to intermediate plunges to the southeast, may reflect only the latest phase of movement (see below: D₄). At New Celebration (Fig. 1), the BLF zone is at least 100 m wide and is extensively intruded by felsic porphyry (Norris, 1987).

The amount of horizontal displacement is difficult to establish because of the lack of markers which can be directly correlated across the BLF. However, displacement of the Stony Hill dolerite west of the fault appears to be at least several kilometres. Total movement is suggested to be in the order of 10 km, comparable to displacement along the sinistral Kunanalling shear zone (Fig. 3B).

Regional shortening

Several observations suggest that regional northeast-southwest shortening accompanied and outlasted D₃ sinistral wrench faulting. Evidence from the Golden Mile is discussed in more detail in a later section (Golden Mile: foliations, lineations and veins). On a regional scale, mesoscopic and macroscopic F₃ folds have overprinted small-scale D₁ structures (Fig. 5A) and possible F₂ folds.

The S₃ axial-plane foliation, mainly observed in various slate horizons, has a constant orientation over the entire area, whereas there are many variations in F₃ fold plunge. This is illustrated several kilometres north of the Feysville fault, where F₃ folds change in plunge direction from steeply northwest to steeply southeast. This reversal takes

place where the overall layering changes from a westerly to a more northerly strike, without any change in S_3 orientation or any evidence for major cross-folding. In the Kalgoorlie area, F_3 axes show an overall trend in plunge from steeply northwest in the north, via shallow to intermediate in the Golden Mile, to steeply southeast at Hannan Lake (Fig. 8).

The variable orientations of F_3 fold axes and lineations, due to S_3 – bedding intersection, are explained as the consequence of a constant regional D_3 shortening event overprinting a stratigraphy already folded during D_2 . On the other

hand, the subhorizontal quartz fibres in subvertical extension veins and fractures (Fig. 8) suggest a minor component of subhorizontal northwest-southeast extension during D_3 .

However, the nearly coaxial orientation of D_2 and D_3 , with both principal shortening directions northeast-southwest, has made it difficult to distinguish between the folding phases and associated foliations. In many areas of the Norseman-Wiluna belt only one regional foliation can be observed, which is commonly related to the regional F_2 folds. Only in areas where the F_2 structures have been reoriented can a separate S_3 foliation be recognized.

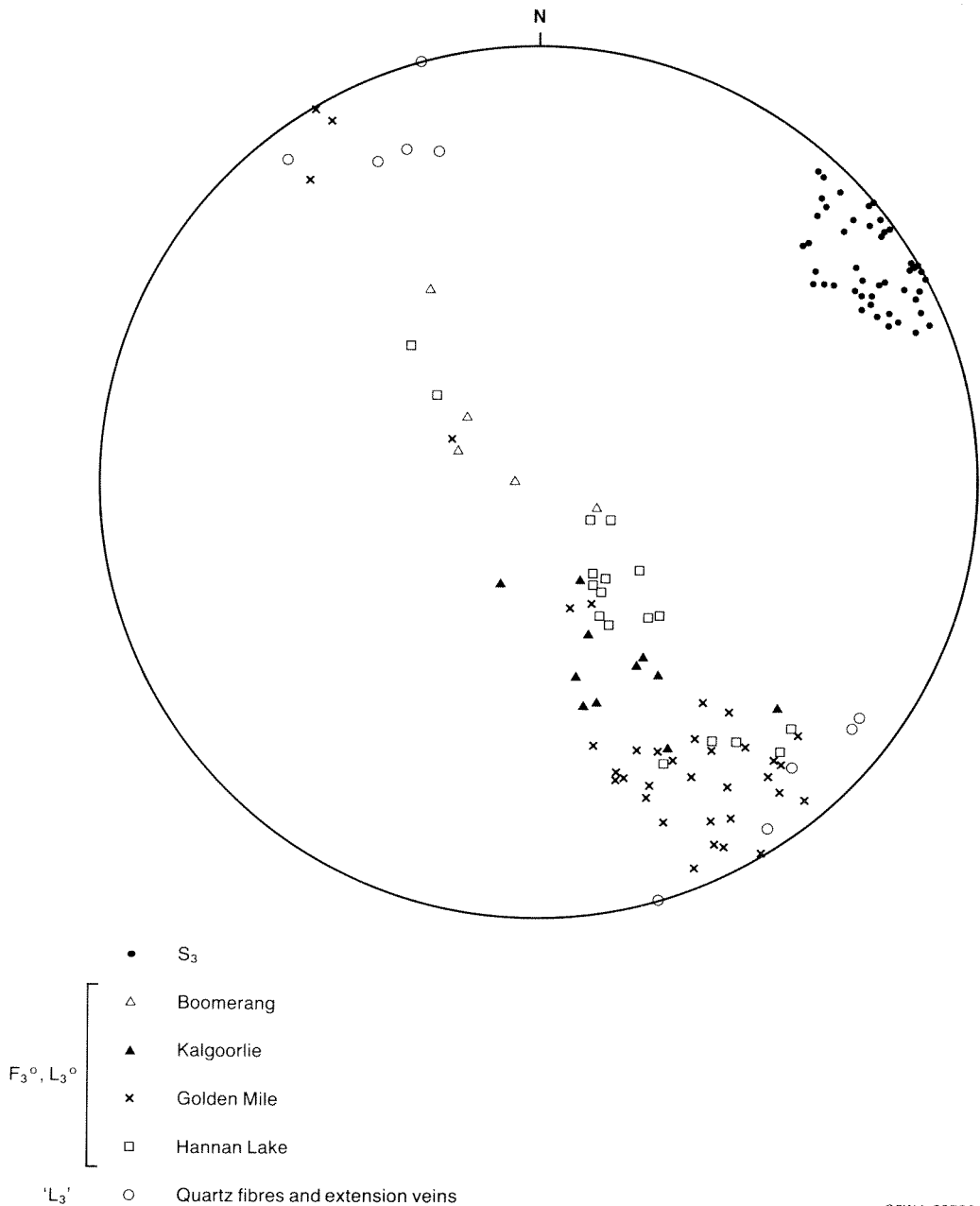


Figure 8. Stereographic projection (equal-area net) of regional S_3 and D_3 elements in metasedimentary rocks from Kalgoorlie mining area and immediate vicinity.

D₄ — OBLIQUE DEXTRAL FAULTING

A prominent set of north-northeasterly striking dextral faults, oblique to the regional trend, has offset all previous structures, although the precise geometry of their interaction with the BLF is not known. These west-dipping faults are well documented in the mining area (Woodall, 1965; Travis and others, 1971), and have also been mapped on a regional scale southwards in the belt (Keats, 1987). The displacements include a dip-slip component with a relative west-block-up movement (Clark, 1981). They vary from several metres to hundreds of metres, but the Golden Pike Fault has a displacement of approximately 1 km (Fig. 2). The faults are characterized by strongly foliated and locally brecciated material (Clark, 1981). Drill core through the Golden Pike Fault in the North Kalgurli Mine lease (where the fault has curved into a strike-parallel orientation) shows a mylonitic foliation in strongly carbonated and sericitized dolerite, having a strong mineral lineation with a shallow plunge to the southeast.

The exact geometrical relationship between the oblique faults and the BLF is not known, although Woodall (1965) suggested that the BLF is deflected at its intersection with the Golden Pike Fault. One possibility is that the oblique faults are secondary

features controlled by a reversal of shear direction, from sinistral to dextral, along the pre-existing wrench fault. The observation that the Golden Pike Fault curves, for a considerable length, from an oblique to a strike-parallel orientation, is an argument in favour of this shear reversal. Even though the oblique faults are regional phenomena, any dextral movement along the BLF must be at least an order of magnitude smaller than the preceding D₃ sinistral displacement.

POST-D₄ CROSS-FOLDING

In the area of Kalgoorlie – Hannan Lake very weak and localized cross-folding and kinking, along northeast-southwest axes, have been observed. This phase of deformation has hardly, if at all, influenced the regional geometry.

REGIONAL CORRELATIONS AND IMPLICATIONS

The deformation history of the Kalgoorlie greenstones can be correlated with those of other studies elsewhere in the region, on the basis of the main structural episodes (Table 2). Table 3 shows the correlation with the detailed deformation history of the Kambalda – Buldania area (Clark and others, 1986; Archibald, 1987) which lies along

TABLE 3. DETAILED CORRELATION OF THE DEFORMATION HISTORY OF THE KALGOORLIE GREENSTONES AND THEIR SOUTHERN CONTINUATION IN THE KAMBALDA-BULDANIA ‘CORRIDOR’ (cf ARCHIBALD, 1987).

<i>Kalgoorlie</i> (This paper)		<i>Kambalda-Victory-Tramways</i> (Clark and others 1986; Archibald, 1987)	
D ₄	Dextral faults, northerly trend oblique displacement, up to 1 km		
	Regional northeast-southwest shortening subvertical S ₃ folding on all scales	D ₄	S ₄ ‘zones of foliation’ east-dipping and west-dipping
D ₃	Sinistral wrench faults with <i>en echelon</i> folds; displacements 10+ km		Regional strike-slip or wrench faults
		D ₃	Open, upright folds, Kambalda ‘dome’
D ₂	Regional folds, upright (north) northwest trend		
		D ₂	Recumbent-inclined folds; isolated, macroscopic associated thrusts
D ₁	Recumbent folds, fold nappes, large thrust sheets	D ₁	Thrust stacking

strike southwards of the Kalgoorlie belt. The main differences are:

- (a) isolated inclined to recumbent F_2 folds have not been distinguished in the Kalgoorlie area:
- (b) early regional upright folding (D_2) is distinguished from the D_3 wrench faulting-regional shortening in this paper. The S_4 'zones of foliation' along distinct shears in the Victory area (Clark and others, 1986) are correlated here with late D_3 shortening (as, for example, the flat faults and associated lodes in the Eastern lode system — see following section).

If anything, Tables 2 and 3 illustrate the progressive nature of the regional deformation after the initial D_1 thrusting event. The D_2 and D_3 regional northeast-southwest shortening are virtually coaxial. They can be viewed as a single continuous event in areas where unequivocal overprinting between F_2 and F_3 folds, or S_2 and S_3 foliations, did not occur.

Most authors have documented early subhorizontal folds and/or foliations on various scales in widely scattered domains of the Norseman-Wiluna belt. It is noteworthy that most large-scale D_1 structures described so far are re-

cumbent folds (Archibald and others, 1978; Platt and others, 1978). This raises the question of how many D_1 thrust sheets have gone unrecognized (Archibald and others, 1981; Griffin and others, 1983).

The debate on the occurrence and extent of early thrusting is not restricted to the Eastern Goldfields: it is very much alive in other Archaean greenstone belts such as the Barberton Mountainland (De Wit, 1982; Lowe and others, 1985; Anhaeusser, 1984). However, if thrusting is unequivocally demonstrated, even in a small area of a belt, the possibility of its widespread occurrence is enhanced. The D_1 recumbent folds, the likely thrust origin of Feysville, Mount Hunt and Golden Mile Faults, and the structural stacking in the Kambalda-Victory area (Archibald, 1987) indicate that structural repetition has taken place in the Kalgoorlie-Kambalda greenstone belt and, possibly, throughout the Norseman-Wiluna belt.

Structural repetition would have major consequences for the model of cyclic deposition of mafic-to-felsic volcanics (Williams, 1970; Gemuts and Theron, 1975; Gee and others, 1981). A typical cycle consists of a komatiitic base giving way to tholeiitic basalts, followed by felsic volcanics and sediments. It should be pointed out that such a model and tectonic repetition by thrusting are not mutually exclusive. However, early thrusting pro-

TABLE 4. PROMINENT LODE AND FAULT SYSTEMS IN THE GOLDEN MILE, AND THEIR INFERRED SEQUENCE OF DEVELOPMENT. DATA INCLUDED FROM FINUCANE (1965) AND WELLS (1964)

LODE OR FAULT SYSTEM	ORIENTATION	OCCURRENCE	MOVEMENTS
1. Main Lode System		Eastern and Western lode systems	
Main lode	315-330°, 80-85°W		minor sinistral
No. 2 lode	300-305°, 70-75°SW	—	—
Caunter lode	280°, 55-70°S	—	minor extension
Cross lode	50°, steep NW and SE	(cross-faults in orientation)	extension
2. Flat faults, lodes		Eastern lode system	
Oroya hanging-wall shear	310-330°, 30-50°SW	along and just below	reverse
Oroya footwall shear	—	Golden Mile Dolerite	reverse
Oroya Shoot	shallow SE plunge		dilation (breccia)
Flat faults	+200°, 15-30°SE	Paringa Basalt contact	reverse
Flat lodes	shallow SE plunge	(intersection flat fault -main lode)	dilation
3. East-dipping strike faults (steep)	+145°, 75-85°NE	Eastern lode system	reverse plus minor sinistral
4. West-dipping strike faults (shallow)	295-360°, 25-50°W	Western lode system	reverse
East-dipping strike faults (shallow to intermediate)	+340°, 50°E		reverse
5. Oblique west-dipping faults	330-350°, 65-80°W	Eastern and Western lode systems	dextral plus minor reverse

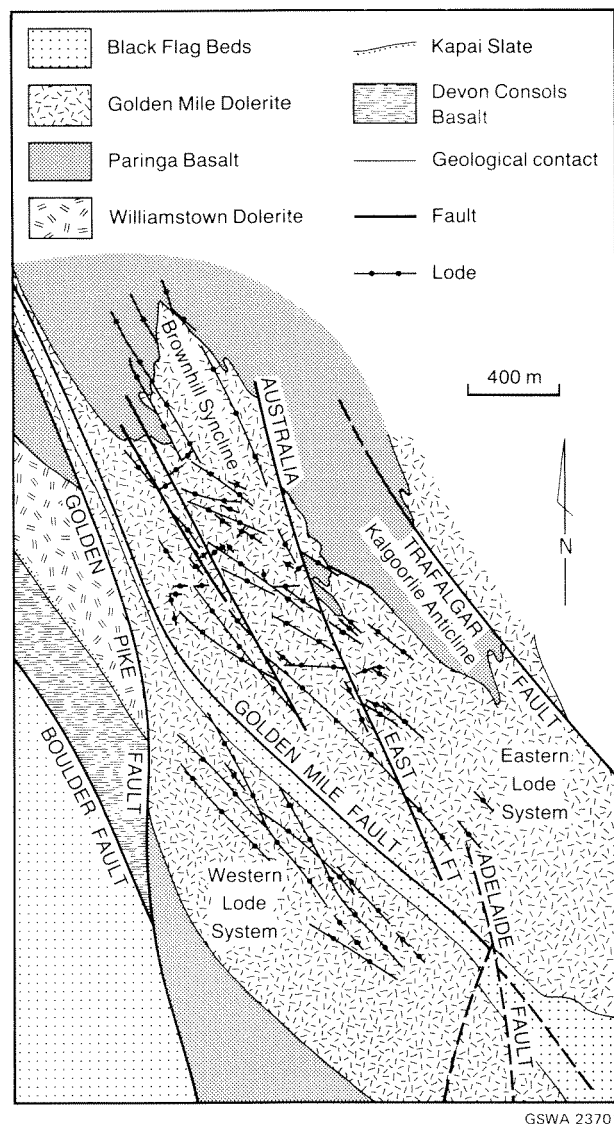


Figure 9. Schematic maps showing lode and fault patterns in the Golden Mile.

(A) Eastern lode system. From Golding (1982).

(B) Shown in next column.

(C) Shown on p. 76.

vides a valid alternative explanation for the repetition of very similar sequences (Griffin and others, 1983) if there is no definite evidence for multicyclic deposition.

An indication of the direction of transport during D_1 must rely on the large-scale geometry, because of the lack of preserved fabrics and the later structural-metamorphic overprints. A possible northeast to southwest thrusting direction may be inferred from the vergence of the Kalgoorlie Anticline when the GMF is rotated to a horizontal position along a northwest-striking axis. However, such simple unfolding does not take into account the complex deformation history.

The regional spacing of the major D_3 wrench faults implies the development of distinct zones dominated by shearing and wrenching, adjacent to domains dominated by regional shortening. These shortening domains are characterized by a constant regional foliation (S_2/S_3), and persistent re-

gional F_2 and/or F_3 folds. The wrench-fault domains show more complex geometries, characterized by major shear zones, strike-slip duplexes, *en echelon* folds and/or secondary fault systems. The interaction of wrench faulting with regional shortening (*i.e.* transpression) has further complicated movement patterns within these domains (Sanderson and Marchini, 1984).

STRUCTURAL CONTROLS ON KALGOORLIE GOLD DEPOSITS

GOLDEN MILE: LODGE AND FAULT PATTERNS

The Golden Mile mining area contains numerous shears, faults and fractures, that are called lodges where they are mineralized. Their relative

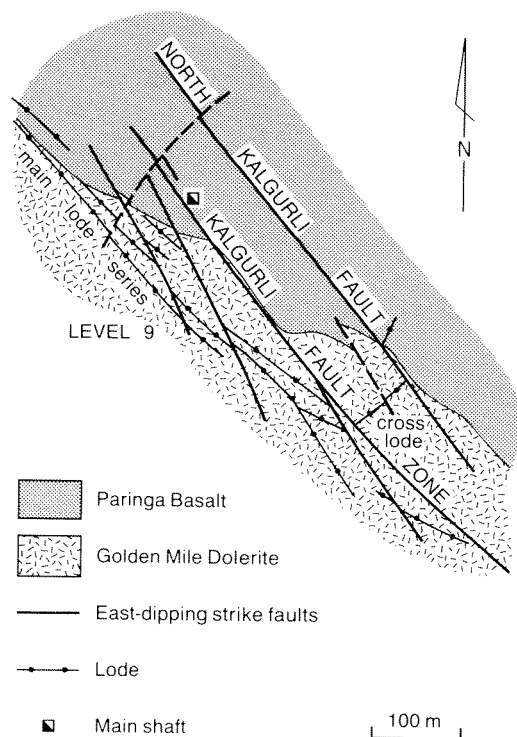


Figure 9. (B) Eastern lode system in Golden Mile Dolerite close to Paringa Basalt contact in the North Kalgoorlie Mine, 9 and 13 Main Shaft levels. From Finucane (1965).

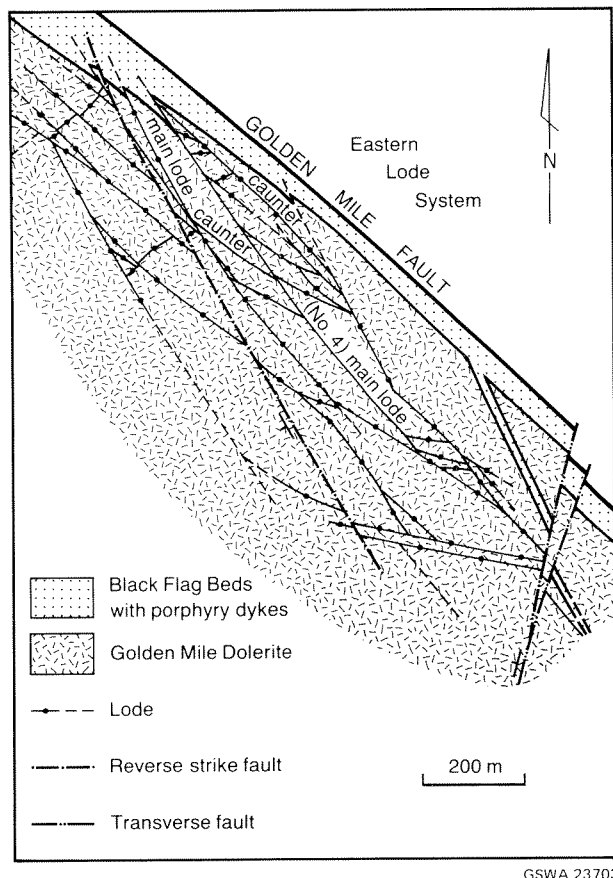


Figure 9. (C) Western lode system approximately 400 m below surface. From Wells (1964).

timing has long been the subject of debate (Gustafson and Miller, 1937; Tomich, 1952; Wells, 1964; Finucane, 1965; Woodall, 1965; Boulter and others, 1987). Table 4 lists the prominent lode and fault structures in a sequence of formations, inferred from literature data and underground observations at North Kalgurli Mines. The following sections describe the structural features that support this history of fault and lode formation, as well as those features that provide evidence for its timing within the regional deformation history.

Main lode system

The steeply dipping Main lode system is divided into two groups: the Western and Eastern lode systems, situated on either side of the GMF (Fig. 2). They show essentially the same features although there are marked variations in relative frequency of the different lodes and faults (Fig. 9; Finucane, 1965).

The planar lodes occur in three dominant orientations (Table 4; Figs 9 A, B, C and 10A), commonly referred to as Main, Caunter and Cross lodes. They have been variously interpreted as fractures, faults, and ductile shears, which were hydrothermally altered and mineralized. Alteration haloes show an outer chloritic zone, and an inner sericite-carbonate zone (Bartram and McCall, 1975; Phillips, 1986). The actual siliceous-pyritic lode centre commonly contains

breccia veins with rotated wall-rock fragments, and is crosscut by subvertical fibrous carbonate-quartz extension veins at a high angle to the lode (Fig. 11C). Displacements across many lodes tend to be minor or negligible.

The Main and Caunter lodes show a pattern whereby one set (mostly Caunter) is bounded by, or terminates against, the other (mostly Main; e.g. Fig. 11). Finucane (1965) also Woodall (1965, p. 76) distinguished two types of Caunter lodes: the 'No. 2 lode' at a small angle counter-clockwise from Main lode, and the 'Caunter lodes' forming a herringbone pattern or a series of tension fractures, of which the enveloping surface is parallel to No. 2 lode (Fig. 10A). This geometry indicates a fracture pattern due to sinistral shear, with Main lode representing the primary shear or fault plane, No. 2 Caunter lode the synthetic or Riedel shear, and the 'real' Caunters forming the complementary extension fractures (Fig. 10B). This interpretation is supported by the following: the sinistral displacement along Main lodes (Finucane, 1965; Woodall, 1965); a local, gentle, sigmoidal, foliation pattern indicating sinistral movement; and minor extension across Caunter lodes. Therefore, the formation of the lode pattern is correlated with D_3 sinistral wrenching along the BLF. The minor displacements along most lodes suggest that the fracture pattern may have developed at any stage during sinistral wrench faulting, but that very little movement took place after their initial formation.

Cross lodes, at right angles to Main lodes and S_3 , dip steeply northwest or southeast (Finucane, 1965; Figs 10A, 11A). Generally, they consist of a number of closely spaced fractures and/or veins with alteration zones extending outwards subparallel to S_3 . Cross fractures and faults are present in the same orientation but without alteration. Conflicting crosscutting relationships suggest that Cross lodes formed contemporaneously with Main and Caunter lodes. They are interpreted here as extension fractures controlled by regional D_3 shortening, and are thus perpendicular to S_3 . Other cross-lode orientations at a high angle to the Main lodes possibly correspond to antithetic, or conjugate Riedel, shear fractures developed during sinistral movement (Fig. 10B).

Flat lodes

Shallow-dipping lodes are found in the Eastern lode system at the contact of the Paringa Basalt with the Golden Mile Dolerite, where they are associated with interflow sediments within the basalts. The ores are generally telluride-rich and contain vanadium-rich muscovite ('green leader'), indicative of high gold grades. Examples are the Oroya hanging-wall and footwall shears which bound the famous Oroya Shoot (a pipe-like, shallow, southeast-plunging orebody.) These structures occur on the southwest-dipping fold limb of the Kalgoorlie Anticline, with the shear zones subparallel to bedding, and the shoot along a parasitic fold (Larcombe, 1912; Tomich, 1959; Fig. 10C). Little is known about the textures of the Oroya ores which have long been mined out. However, Larcombe (1912) suggested extensive open-

space infill textures above a postulated 'middle fault', which lay between the hanging wall and footwall shears. Both bounding shears show predominantly reverse movement, as inferred from sigmoidal foliation patterns (Larcombe, 1912 p. 21, 126; Tomich, 1952, p. 115, 116).

A simple explanation for these structures is shown in Figure 10D. The D₁ Kalgoorlie Anticline has been rotated during D₂ into a position where its axial plane is at right angles to the D₃ shortening direction. On its western limb this resulted in antithetic or reverse shear along mechanically weak, interflow, slate layers. Where a pre-existing parasitic fold was present, the shear zones formed an off-stepping pattern (Rodgers, 1980), whereby an extensional domain was created in their overlap

(i.e. on the short limb of the fold). This domain, or 'extensional jog' (Sibson, 1985), became a major conduit for the mineralizing fluids.

Westwards in the North Kalgurli Mine a 'flat fault' along the basalt-dolerite contact and another, 100 m below this, are persistent anastomosing structures with shallow southeasterly dips (Fig. 11A). Newman (1987) suggested that these faults can be correlated with the Oroya bounding shears. The faults crosscut and offset Main lodes with an upper-block-east movement, which is confirmed by rotation of the foliation (see below). The linear intersection zones are characterized by extensive carbonate alteration and 'implosive' breccia textures, similar to those found in and below the Oroya footwall shear.

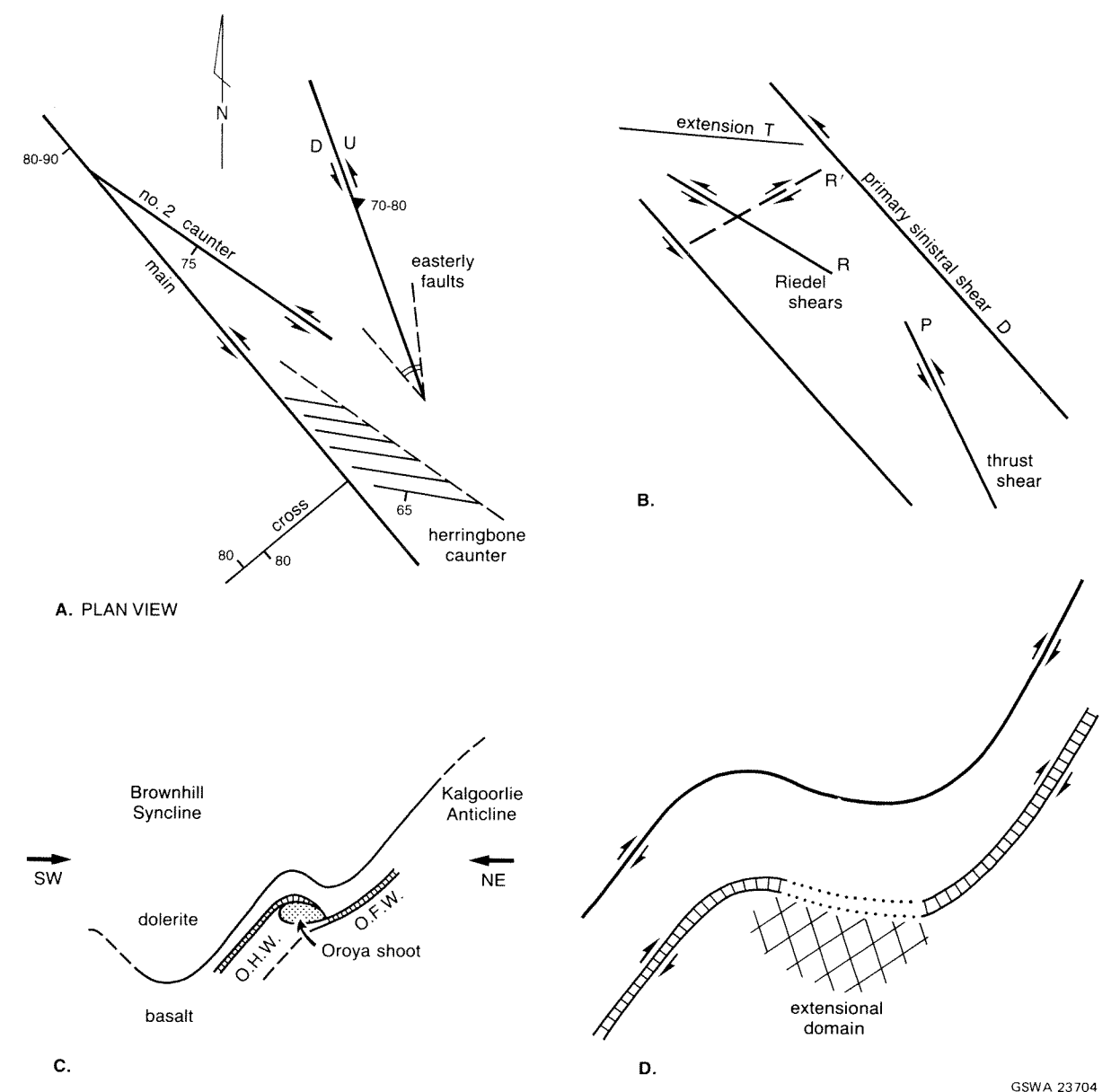


Figure 10. (A) Schematic map pattern of main lode system and east-dipping strike faults. Orientations from Finucane (1965). (B) Sinistral-shear fracture system (Tchalenko, 1970). (C) Schematic cross-section through Golden Mile, showing location of Oroya Shoot and its bounding shears. (D) Possible explanation for Oroya Shoot development (see text).

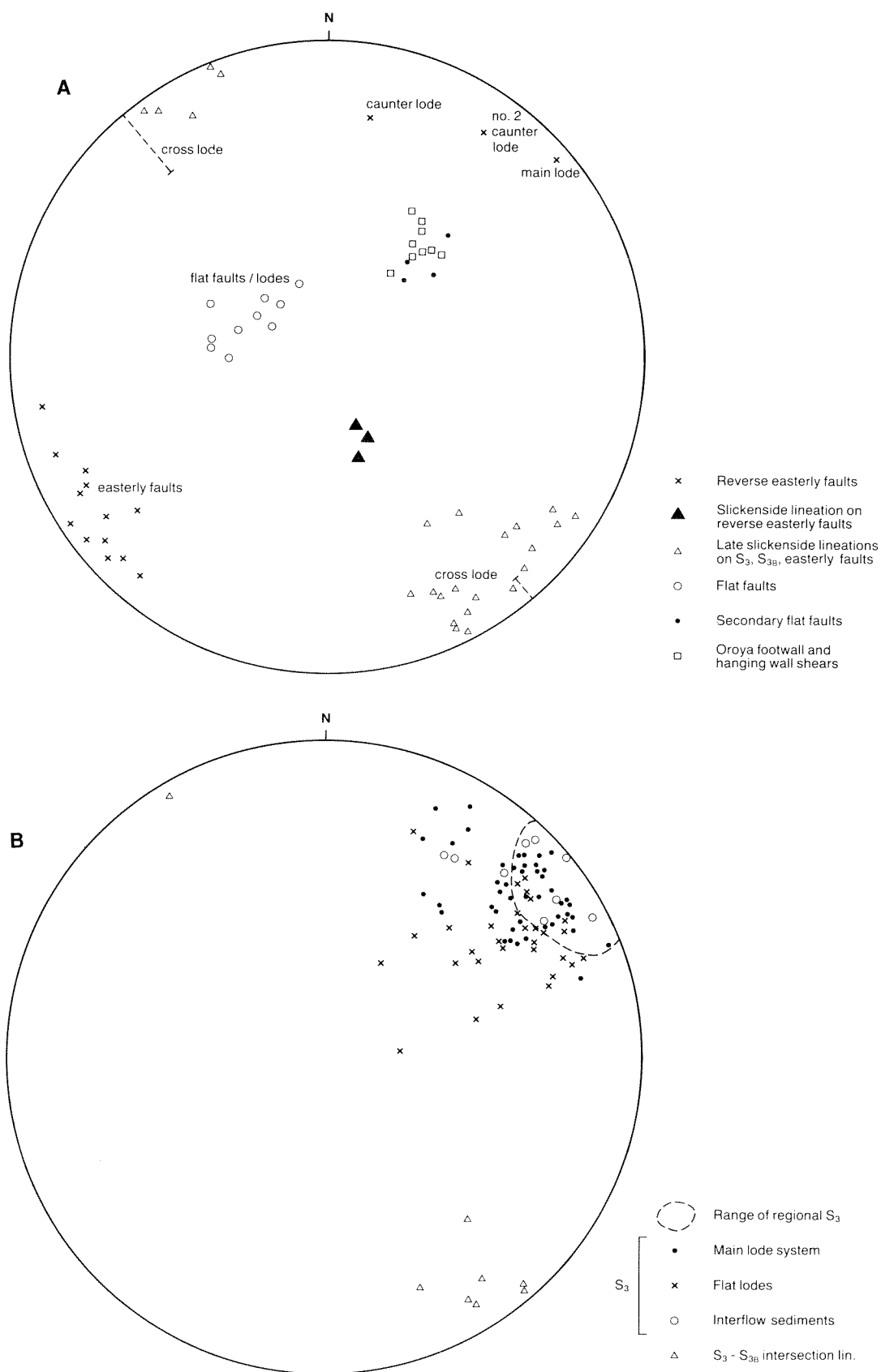
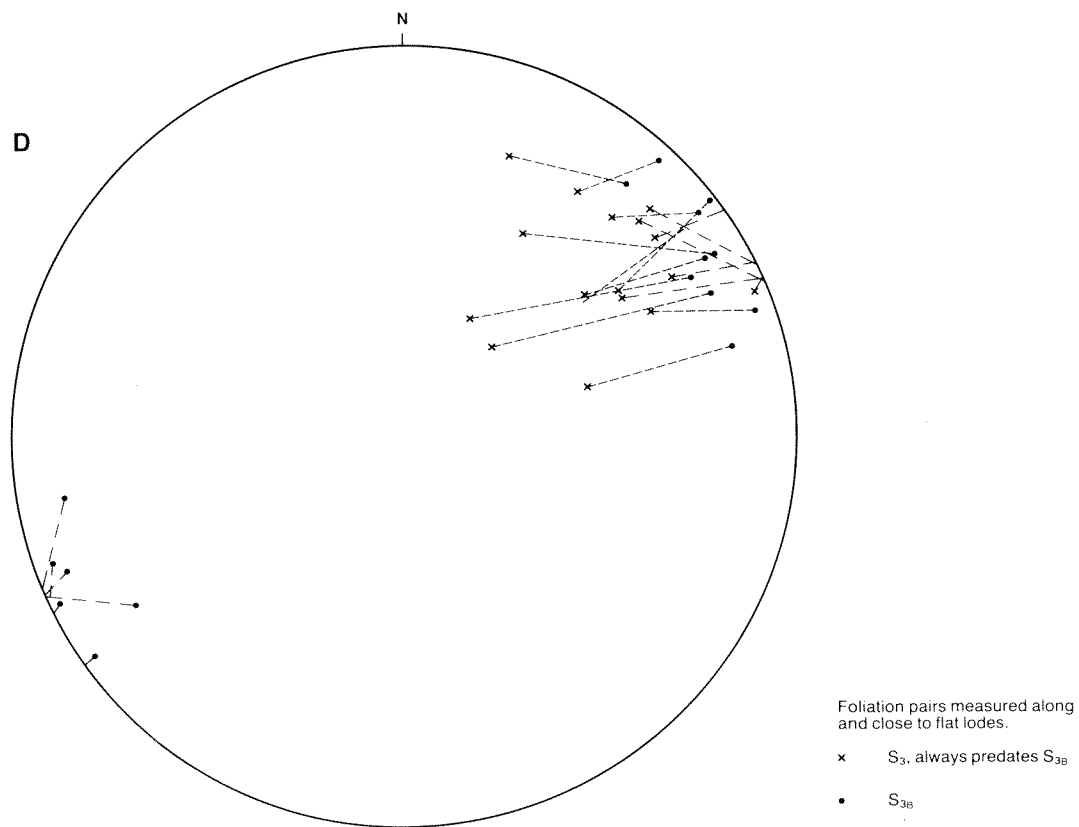
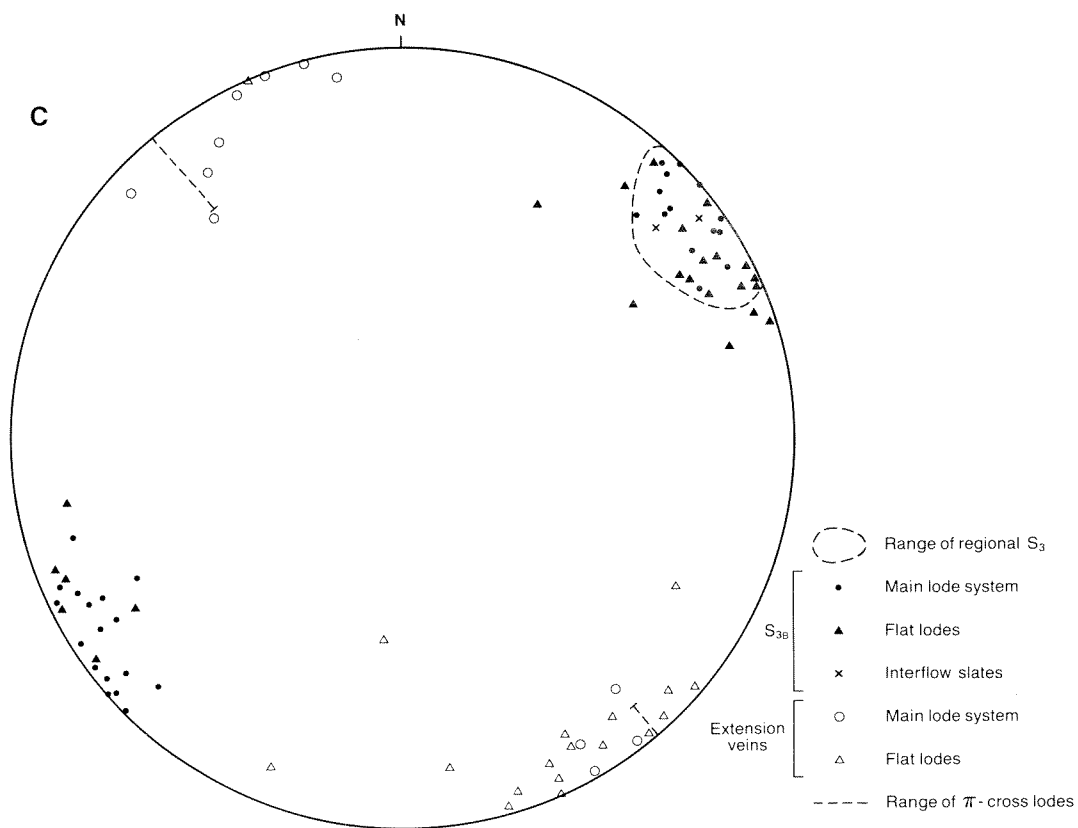


Figure 11. Stereographic projections of structural elements in the Golden Mile. All planar elements are plotted as their poles.
(A) Lode and fault orientations. Including data from Larcombe (1912) and Finucane (1965).



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(B) and (C) S_3 , ' S_{3B} ' and D_3 extension veins in various lodes. Measurements taken in North Kalgurli Mine.
 (D) S_3 and ' S_{3B} ' foliation pairs measured in flat-lode domains.

These alteration assemblages and textures have clearly overprinted alteration in the Main lode, and are associated with higher gold tenors. The flat lodes are offset by, and thus predate, both minor and major east-dipping reverse faults (see below). They are crosscut by characteristic extension veins, which generally have the same orientations as the late fibrous veins in the Main lodes (Fig. 11C), but a different mineral assemblage that includes hematite. A detailed study of these flat lodes is in progress (Jian Hua Sang, personal communication, 1987).

East-dipping reverse-strike faults

The east-dipping strike faults ('easterly faults' of Phillips, 1986), are restricted to the Eastern lode system (that is, to the western limb of the Kalgoorlie Anticline) and are associated with major displacements (Fig. 9). They are more widely spaced than the lodes and consist of a single discrete plane, or multiple planes forming a fault zone, several metres wide. The Kalgurli and North Kalgurli faults show reverse dip-slip movement with a minor sinistral component, as inferred from lode displacements, sigmoidal patterns of the S_3 foliation, and locally well-preserved slickenside lineations (Fig. 11A). Commonly they are associated with carbonate alteration, though they are only mineralized where other lodes abut and are dragged along them. This is illustrated by a near-vertical Cross lode (Ned lode) which shows a sinistral displacement along the easterly North Kalgurli fault in the North Kalgurli mine (Fig. 9B; N. Newman, personal communication, 1986).

These faults are therefore interpreted to post-date the Main lode system. Additional evidence for this timing is the common occurrence of small-scale east-dipping reverse faults (with displacements of 10 cm to 1 m), which crosscut and offset the Main lodes and flat lodes. This conclusion contrasts with that of Finucane (1965) who suggested a pre-mineralization origin, and that of Boulter and Phillips (1985) who considered that the faults were contemporaneous with the Main lode system.

The strike orientation of the faults coincides with those of 'thrust (P) shears' predicted in a sinistral-shear fracture system (Fig. 10A and B). These P shears show synthetic displacement and commonly develop at a later stage during the shearing (Tchalenko, 1970). However, even though the east-dipping faults show a minor sinistral movement component, the dominant displacement is reverse dip-slip. The effect of this movement is to steepen the western limb of the Kalgoorlie Anticline (Fig. 4C; Phillips, 1986), resulting in an overall northeast-southwest shortening. This suggests that displacement along the easterly faults is controlled by the regional D_3 shortening.

West-dipping reverse-strike faults

These moderately dipping faults occur in the Western lode system (Wells, 1964; Finucane, 1965, 1983) where the stratigraphy is near-vertical. Wells (1964) also reported less common, shal-

low, east-dipping, reverse-strike faults. Both faults post-date the Main lode system. They are interpreted here as a conjugate set (developed during regional D_3 shortening) that produced northeast-southwest shortening and vertical extension. They are possibly contemporaneous with the steep, east-dipping, reverse faults in the Eastern lode system.

West-dipping oblique faults

Locally, oblique west-dipping faults crosscut and offset all previous structures with a dextral movement. Finucane (1965) and Fotios (1983) reported similar faults at the southern end of the Golden Mile. These barren faults are correlated (on the basis of orientation, displacement and timing) with the D_4 oblique-fault system, that includes the Golden Pike and Adelaide Faults. One example of an oblique fault in North Kalgurli Mine is associated with two vein sets, that occur in the same orientations as the major quartz veins found along the D_4 Charlotte and Reward faults (see section on Mount Charlotte stockworks).

GOLDEN MILE: FOLIATIONS, LINEATIONS AND VEINS

Two foliations are commonly seen in the lode alteration haloes but not in the siliceous-lode centres. Their microstructures are described and discussed by Ion (1982) and Boulter and Phillips (1985), and here only some important features are mentioned.

The earlier, dominant foliation (S_3 ; Fig. 11B), striking parallel to the Main lode orientation, is weak in the chloritic zones, and is defined by preferred orientations of albite and chlorite aggregates. Locally, it intensifies in the sericitic-lode margins, and is then defined by aligned sericite or chlorite flakes. This foliation is not developed in unaltered domains that still retain the metamorphic actinolite plus albite assemblage.

The second foliation (' S_{3B} '; Fig. 11C) is restricted to sericitic-lode margins where it is defined by aligned sericite flakes forming widely spaced cleavage planes, that crosscut, and are everywhere steeper than, the earlier foliation. In strongly deformed domains along the flat faults and east-dipping strike faults, the two foliations appear to merge into an anastomosing, more pervasive cleavage.

Both foliations apparently formed during D_3 . They are present within the alteration haloes along the Main lode system, that developed as a D_3 sinistral-shear fracture system. Furthermore, they are deformed along the east-dipping reverse faults. Both foliations are interpreted to have formed as a result of D_3 regional shortening rather than due to the sinistral shear because of the following:

- (a) similar foliations are present in interflow slates within the basalts, where S_3 is axial planar to mesoscopic folds;
- (b) their orientations, outside the fault domains, are constant and coincide largely with the regional S_3 (Fig. 11); and

(c) they appear to be an S fabric without a strong linear component.

The S₃ foliation developed late during the alteration along the Main lode system, because it is continuous across the alteration zoning, and locally shows a sigmoidal pattern across Caunter lodes. The second generally weak and localized foliation is clearly rotated (together with Main lodes and S₃) along the flat faults (Fig. 11D), which in turn predate the east-dipping strike faults. This constrains the second foliation development to D₃ (Table 5), and it may indicate a minor perturbation of the main D₃ shortening direction. This is supported by the very steeply east-dipping, rather than west-dipping, attitude in domains where S₃ is not rotated.

Shallow southeast-plunging slickensides (Fig. 11A), defined by very fine sericite rodding, are common on many S₃ planes, but they do not represent a pervasive mineral lineation. Identical lineations are found on the S_{3B} cleavage and on the east-dipping faults, where they overprint the steeply southeast-plunging lineation that formed during reverse movement (Fig. 11A). These shallow slickensides are interpreted to record a stage of minor subhorizontal movement during late D₃ or possibly during D₄.

As mentioned earlier, extension veins occur in both Main and flat lodes. The near-vertical veins in the Main lodes are at right angles to S₃ foliation, and contain virtually horizontal fibrous carbonate-quartz material, perpendicular to the vein wall. The veins in the flat lodes have similar, though more variable, orientations. They include major veins (up to 35 cm wide) with infill textures (*i.e.* quartz crystals) in their centres, and thin, hematite-coated fractures. These veins, along with the Cross lodes (Fig. 11C), indicate several stages of (only minor) subhorizontal extension in a constant northwest-southeast direction during D₃ regional shortening.

GOLDEN MILE LODES: PRESENT AND PREVIOUS INTERPRETATIONS

The Golden Mile lodes are interpreted to have formed during a complex interaction of D₃ sinis-

tral wrench faulting and northeast-southwest shortening (Table 5), whereby shortening outlasted the formation of the sinistral-shear fracture pattern of the Main lode system. The flat faults post-date the Main lodes, and their associated flat lodes are interpreted as a separate mineralization event. Textural and mineral-assemblage criteria also indicate a change in hydrothermal-fluid parameters (Phillips and others, in press).

The history of lode and fault development, proposed here, is a rather simplified interpretation of the complex structural relationships in the Golden Mile. As Wells (1964) has already pointed out, progressive deformation resulted in further movements along earlier formed shears. The east-dipping reverse-strike faults are a possible example of the reactivation. They may have developed as the last stage of the sinistral-shear fracture system (with little or no mineralization), and were then reactivated as reverse faults during regional shortening, because of their favourable orientation on the west-dipping limb of the Kalgoorlie Anticline. It should be reiterated that the D₁ Golden Mile Fault predates the D₃ lode systems, even though it became a locus for alteration.

The interpretation of the Main lode system, presented here, is different to that of Woodall (1965) who suggested the Main lode system to be complementary to the oblique faults (Fig. 12A). In a similar way, Clout and Cleghorn (1987) interpreted the Golden Mile lodes and faults as an intense secondary-shear system between the oblique Adelaide and Golden Pike faults, which developed as splays of a major fault system. In this paper the oblique dextral faults are interpreted to post-date the Main lode system. Boulter and Phillips (1985) considered Caunter lodes and east-dipping faults as conjugate-shear zones, which developed synchronously with the Main lode shears that formed in an approximately axial-planar position during ‘upright folding of the Kalgoorlie Anticline’ (Fig. 12B). However, the Caunter lodes and east-dipping faults have entirely different characteristics (mineralization, movement and distribution). Furthermore, the Main lode system post-dates the ‘upright folding’ event, as argued not only in this paper but also by Gustafson and Miller (1937).

TABLE 5. RELATIVE TIMING OF STRUCTURAL ELEMENTS IN EASTERN MAIN LODE SYSTEM

D ₄	Oblique faults (dextral shear)		? slickenside: shallow southeast to horizontal (dextral shear)
	East-dipping strike faults (sinistral shear) plus reverse dip-slip faults (northeast-southwest shortening)		Slickenside: steep southeasterly (northeast-southwest shortening)
D ₃	Oroya Shoot flat faults/lodes (northeast-southwest shortening)	'S _{3B} '(?)	Late extension veins (quartz-carbonate) and fractures (hematite) (northeast-southwest shortening)
	Cross lodes, Main and Caunter lodes (sinistral shear)	S ₃	Late extension veins (fibrous quartz-carbonate) breccia veins in lode centre (northeast-southwest shortening)

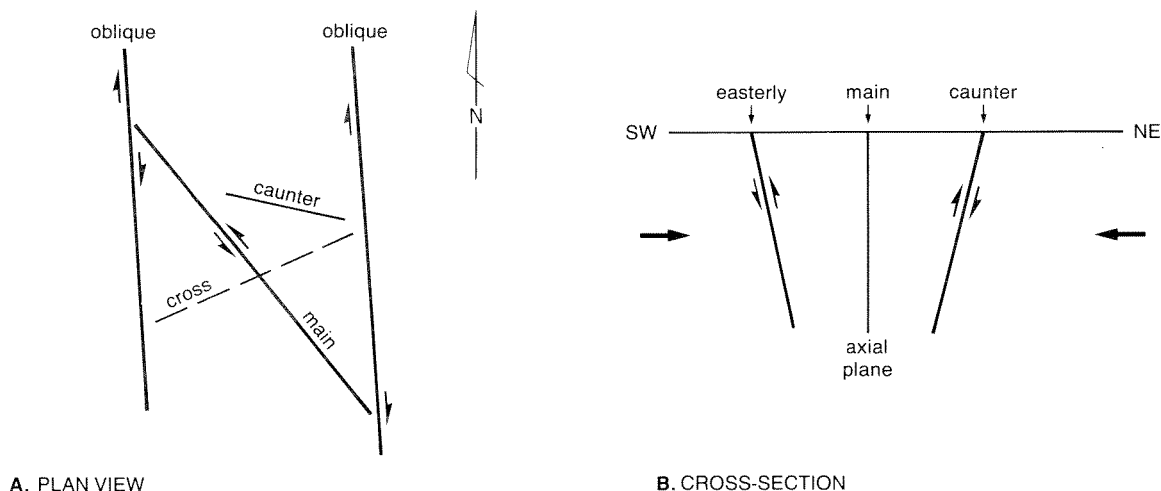


**Figure 12 (A) Schematic plan showing analysis of Main lode system by Woodall (1965).
(B) Schematic cross-section showing analysis of Main lode system by Boulter and Phillips (1985).**

Mueller and Harris (1987) have presented a similar interpretation of the Golden Mile lode systems to the one described in this paper; however, their regional deformation history is significantly different.

MOUNT CHARLOTTE STOCKWORKS

The Mount Charlotte stockwork mineralization, within the granophyric unit of the Golden Mile Dolerite, is controlled by two sets of quartz veins between and adjacent to the D₄ Charlotte and Reward faults (Clark 1981; Hopkins, 1983; Boulter and Phillips, 1985). The less dominant set (225/70 NW) is prominent only near pre-existing reverse-strike faults. Clark (1981) and Boulter and Phillips (1985) suggested that the dominant set coincides closely with the predicted extension plane during dextral movement along the faults, and the subsidiary set coincides with the conjugate-shear fracture direction. The Mount Charlotte gold stockworks thus represent a separate D₄ mineralization event, that occurred during D₄ oblique faulting.

Another possible geometrical criterion, for the relative timing of the Golden Mile and Mount Charlotte mineralization, is suggested by the moderately southwest-dipping reverse-strike faults. In the Western lode system of the Golden Mile these faults post-date lode formation, and at Mount Charlotte they predate the oblique faults controlling the vein-stockwork development.

CONCLUSIONS

The structural evolution of the Kalgoorlie greenstones is dominated by horizontal movements including: D₁ recumbent folding and thrusting; D₂ upright folding; and D₃ wrench faulting. The relative timing of emplacement of the regional granitoid domes is not considered here, because no attempt has yet been made to relate the detailed structure at Kalgoorlie with the regional granite problem. Whatever their origins (Archibald and others, 1981; Platt, 1980), any model of granitoid

emplacement should take into account the extensive horizontal tectonics in the Norseman-Wiluna greenstones.

Tectonic repetition of greenstone sequences during D₁ may have taken place on a regional scale, and this mechanism offers a viable explanation for the juxtaposition of similar stratigraphic successions, as an alternative to multicyclic depositional models. However, the relative importance of these models will remain uncertain, until accurate dating techniques can unequivocally establish depositional ages of adjacent structural domains.

The D₃ sinistral Boulder-Lefroy Fault is suggested to be representative of the major faults in the southern part of the Norseman-Wiluna belt. The fundamental controls on the development of the wrench faults, which have overprinted D₂ folds, are not clear but must lie at deeper crustal levels. As suggested by Gee and others (1981), they may reflect long-lived deep faults which acted originally as feeders for the greenstone volcanism, but were apparently buried during deposition and remained inactive until after initial D₂ folding. The concurrence of northeast-southwest shortening and wrench faulting suggests a regional transpressional deformation regime (Sanderson and Marchini, 1984). Further research on a regional scale is required to establish the large-scale movement patterns. Platt and others (1978) and Swarnecki (1987) suggested dextral displacements for major wrench faults in the Agnew and Leonora areas.

The BLF appears to be the locus for a considerable number of gold deposits stretching from Kalgoorlie to Victory-Defiance, south of Kambalda. This suggests that the wrench faults have played a fundamental role in the channelling of auriferous fluids. Deposition of gold in economic concentrations may take place within the fault zones (*e.g.* New Celebration, Jubilee, Golden Hope: Figure 1B), and in secondary structures adjacent to the fault (*e.g.* Kalgoorlie deposits). The three stages of mineralization distinguished in this

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paper (Golden Mile Main lode system, Golden Mile flat lodes, Mount Charlotte stockworks) also indicate that introduction of the fluids occurred over a distinct time interval.

Recognition of a wrench-faulting regime has important consequences for gold exploration. First of all, the fault zone is a primary target. Furthermore, secondary structures such as contractional (reverse, thrust faults) and extensional (normal) faults may be predicted once the movement direction along the main fault is deduced, for example from arrays of quartz veins occurring *en echelon*. As illustrated by the lode geometry on the Golden Mile, host-rock characteristics will influence the development of the fault and shear patterns. Patterns in 'homogeneous' rocks, such as massive dolerite sills, may faithfully mirror the large-scale movement, whereas the layering anisotropy can become the controlling structure in a sequence of basalt flows and sediments.

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PALAEOCURRENT PATTERNS IN THE COLLIE COAL MEASURES — THE IMPLICATIONS FOR SEDIMENTATION AND BASIN MODELS

by A. C. Wilson

ABSTRACT

The Collie Basin is a remnant of a formerly more extensive Permian depositional basin which covered a large area in the southwestern corner of the West Australian Shield. In the Collie area the palaeoslope dipped to the northwest. Repeated cycles of sand, silt and clay were laid down in a braided river system containing a variety of bar forms. These cycles commonly were capped by vegetable matter (now coal) for which a widespread fen and swamp setting is envisaged. The present basin-margin faults did not restrict deposition to the present outcrop but may have separated areas, which at certain times had slightly different subsidence rates.

INTRODUCTION

The Collie Basin is the largest (225 km²) of three adjacent Permian basins in the southwestern Yilgarn Block (Fig. 1). It has a bilobate form with two sub-basins which flank the medial Stockton Ridge and its subsurface extension. The basin contains sedimentary rocks which range in age from Early Permian to Holocene. The Stockton Formation is the oldest unit in the basin and its age is Early Permian. It rests unconformably on the Archaean basement and is overlain conformably by the Collie Coal Measures, which is the dominant sequence within the basin. This formation ranges in age from Sakmarian to Kazanian and is about 1000 m thick. The Nakina Formation, of Cretaceous age (Backhouse and Wilson, 1988), forms an extensive unconformable cover over the older rocks and has a maximum thickness of about 20 m. There are no natural exposures of Permian rocks within the basin.

This paper presents the results of an extensive study of palaeocurrent patterns in the Collie Coal Measures. The findings are used to refine the present depositional model and the existing concepts of basin size and evolution which are outlined below.

Maitland (1900) and Lord (1952, 1976) proposed that Late Palaeozoic sedimentation in the Collie Basin took place in a restricted area more or less coincident with the present outcrop. The alternative view has been put by a number of workers (Jack, 1905; Woolnough, 1916; Lowry 1976; Park, 1982) that for at least part of the period, deposition took place in an area which extended well beyond the present confines of the basin. Subsequent faulting along the present basin-margin faults has preserved evidence of this formerly widespread depositional basin. Lord (1952) concluded that early sedimentation took place in a glaciated valley. Lowry (1976) and Park (1982) thought that coal measures deposition took place

in a fluvial environment with no marine influence. Wilde and Walker (1978) carried out a reconnaissance palaeocurrent study of the Collie Coal Measures and concluded that the Collie Basin is a remnant of a much larger depositional basin.

BASIN STRUCTURE AND STRATIGRAPHY

The Stockton Ridge divides the Collie Basin into two sub-basins each of which has an overall half-graben form (Wilson, 1988). The Cardiff Sub-basin is bounded on the West by a basement lineament and there is little doubt that this is a major fault similar to the Muja Fault, which lies on the western margin of the Premier Sub-basin. That sub-basin is bounded on its eastern side by a northwest-trending fault zone. The Cardiff Sub-basin contains a thickness of about 330 m of Stockton Formation and 1020 m of Collie Coal Measures. For the Premier Sub-basin, the equivalent thicknesses are 60 m and 960 m, respectively. Both sub-basins are deepest close to the western margins and comprise doubly plunging synclines. The Premier Sub-basin contains several interference or cross folds which modify considerably the pattern of coal-seam subcrop.

The stratigraphy of both sub-basins is given in Table 1. There are three coal-bearing members which are broadly equivalent in each sub-basin. The coal-seam correlations are based on work done by the Geological Survey. No definitive correlations have been made between the two sub-basins except for the seams of the Ewington Member.

COLLIE COAL MEASURES

The Collie Coal Measures is a cyclic sequence of (in ascending order) sandstone, siltstone, claystone and coal, with an erosional base to each cycle.

MAJOR PALAEOCURRENT PATTERNS IN THE COLLIE COAL MEASURES

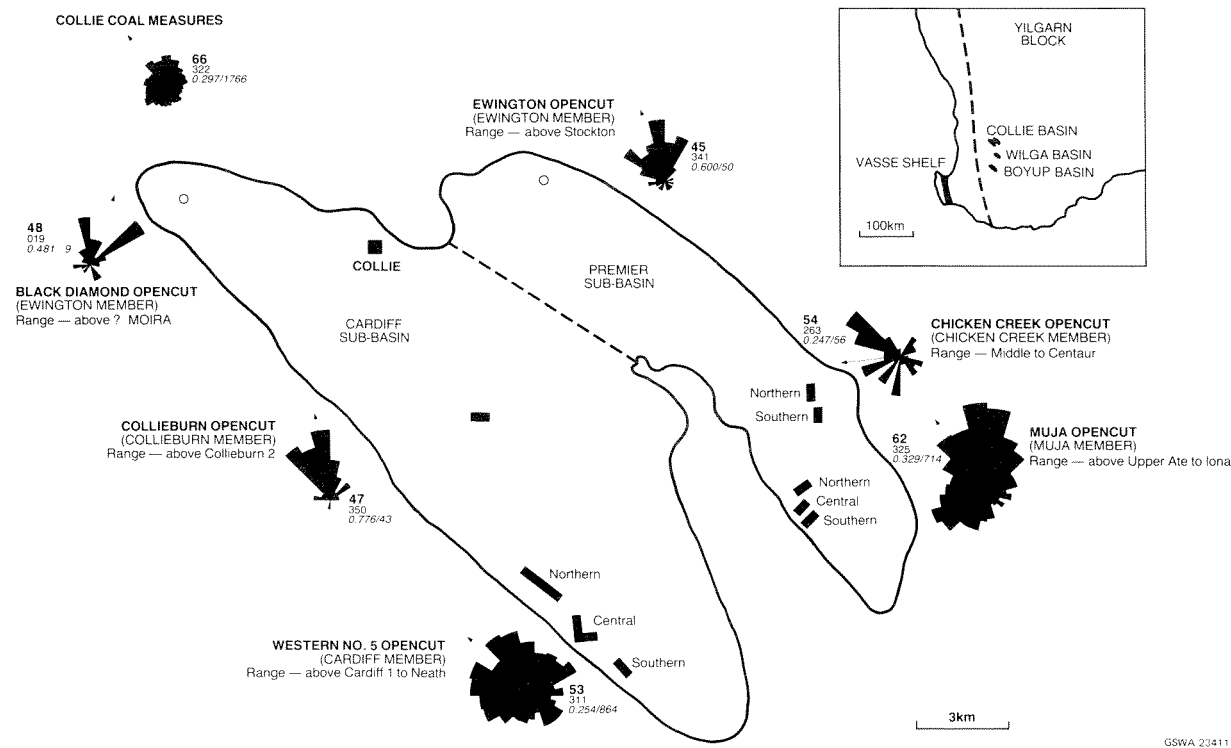


Figure 1. Map of the Collie Basin showing the location of measured sections and palaeocurrent counts. Palaeocurrent roses for each of the members of the Collie Coal Measures are shown. (Reference in Figure 5).

TABLE 1. STRATIGRAPHIC SUCCESSION OF COAL SEAMS, COLLIE COALFIELD

<i>CARDIFF SUB-BASIN</i>		<i>PREMIER SUB-BASIN</i>			
		<i>NORTHERN AND CENTRAL AREAS</i>		<i>SOUTHERN AREA</i>	
<i>Member</i>	<i>Seam</i>	<i>Member</i>	<i>Seam</i>	<i>Member</i>	<i>Seam</i>
CARDIFF	Cardiff 1 Cardiff 2 Cardiff Neath			MUJA	Ate Bellona Ceres Diana Eos Flora Galatea Hebe Iona
COLLIEBURN	Collieburn 1 Alpha Wyvern Collieburn 2 Phoenix Icarus Griffin	PREMIER	Premier 1 Premier 2 Premier 3 Premier 4 Premier 5 Premier 6 Premier 7 Premier 8	CHICKEN CREEK	Apis Uraeus Unicorn Pegasus Hydra Briareus Gryps Chiron Middle Centaur
EWINGTON	Moira Stockton Wallsend	EWINGTON	Moira Stockton Wallsend	EWINGTON	Achilles Ajax Ares

Proposed seam correlations are based on work done by the GSWA.

Table 2 illustrates the essential features of this lithological association.

The cross-bedded sandstones occur in units several metres thick, and have an undulating lower surface and planar upper surface. No large discrete channel-like forms have been observed in the opencut faces. Some coal-seam washouts are known but they are neither numerous nor large. Most of the sandstones have a fine-grained top, but in the lower parts of the units there is no consistent direction of vertical fining. There are no regional grain-size changes in the sandstones of either sub-basin. Clay pseudomorphs after feldspar grains are very common, showing that the sandstones were feldspathic and compositionally immature. Small-scale cross-stratification is well developed in the siltstone, but ripple-drift cross-lamination has not been observed (although it might have been expected to occur). Well-preserved leaf impressions (Rigby, 1966) are present in some of the weakly stratified carbonaceous claystones.

Most coal seams are less than 4 m in thickness; the Hebe Seam, at 13 m, is quite exceptional in its development. The coal is dull to moderately bright and the seams are quite clean, generally containing less than 10% ash (at 25% moisture).

TABLE 2. FEATURES OF A TYPICAL CYCLE IN THE COLLIE COAL MEASURES

<i>Lithology</i>	<i>Structures</i>
	*** TOP ***
Claystone	Gradational contact at base; locally present above coal.
Coal	Small coaly rootlets at base.
Coaly claystone	Thin coaly beds common.
Coaly/carbonaceous, silty claystone; sandy claystone; laminated claystone	Finely laminated some small-scale cross-stratification, leaf impressions in some claystones.
Clayey siltstone; coaly clayey sandstone; clayey sandstone; carbonaceous siltstone; silty claystone	Very obvious striped appearance; well-bedded, abundant small-scale cross-stratification, some sediment injection and small-scale cross-stratification defined by coaly fragments.
Sandstones; pebbly sandstones; claystones	Abundant medium-scale cross-stratification, some over-steepened. Some apparently structureless beds and others with disturbed (diapiric) structures. Claystones from thin beds with small-scale cross-stratification. Lag conglomerate beds. Coal clasts near base of sandstone. Curved or planar erosional base.
	*** BASE ***

Irregular, coaly rootlet 'dykes', which pass gradationally upwards into coal, are preserved below every seam exposed in all the opencuts available for inspection. They vary, on average, from 1 – 10 mm in length. These features are diagnostic of autochthonous coals and their underlying seat earths (compare with Lord, 1975). A widespread fen and swamp setting for coal formation is envisaged, similar to that described by Martini and Glooschenko (1985).

The vertical and lateral variations in lithology, bedding structures and palaeocurrent patterns (see below) within the Collie Coal Measures are of fluvial character. This conclusion is consistent with previous views (Lowry, 1976; Park, 1982). The overall upward-fining cycle (sandstone, siltstone, claystone and coal) is well developed throughout the formation. These cycles are interpreted as a response to fluvial depositional processes, where the locus of sedimentation migrated across the depositional surface. It is not necessary to invoke local faulting (Park, 1982) to account directly for their presence.

PALAEOCURRENT DATA

Planar and trough cross-bedding within the Collie Coal Measures occur on medium and small scales. The former records the dominant current directions within the river system and is generated by megaripples, delta lobes and other bedforms in the bars and channels of the river. Small-scale cross-strata form within ripples, whose orientation is strongly controlled by the larger order structures. The small-scale cross-strata do not provide a good indication of major flow patterns and have not been studied intensively in this investigation.

Between 1982 and 1985, a total of 1766 medium-scale planar and trough cross-strata were measured from 43 localities within the existing and disused opencuts available for study. Where bedding dips exceeded 5°, all measurements were untilted about the present strike by an amount equal to the dip. The original data are held on file at the Geological Survey of Western Australia.

PALAEOSLOPE

The palaeocurrent mean for the Collie Coal Measures (Fig. 1) trends to the northwest and this represents the palaeoslope dip direction. There is no evidence that the Collie Basin acted as a depocentre surrounded by inwardly dipping palaeoslopes.

The palaeocurrent means for the members show an anticlockwise trend through time (Fig. 1 and Table 1). Because of the restricted stratigraphic interval over which palaeocurrents have been measured in the lower members, it is inappropriate to assign much significance to this trend.

STREAM SINUOSITY

Low-sinuosity and high-sinuosity streams have different bar forms, each with its own suite of bedforms and related internal structures e.g. cross-

FLUVIAL BAR FORMS AND PALAEOCURRENT PATTERNS

BAR FORM	VECTOR STRENGTH (SINGLE BAR)	ANOMALOUS UPSTREAM CURRENTS RECORDED	ROSE DIAGRAMS (DIAGRAMMATIC)		DISTINGUISHING FEATURES (WHEN GRAVEL AND SAND ARE PRESENT)
			SINGLE BAR	STACKED BARS	
MEDIAL	HIGH TO MODERATE	NO			UNIMODAL SAND/GRAVEL (STACKED BARS)
LATERAL 1	LOW TO MODERATE	YES			GRAVEL MOVES AT A HIGH ANGLE OR IN AN OPPOSED DIRECTION TO SAND (SINGLE BAR)
LATERAL 2	MODERATE TO HIGH	NO			BIMODAL SAND/GRAVEL (STACKED BARS)
LATERAL 3	MODERATE	NO			SOME SAND MOVES AT HIGH ANGLE TO GRAVEL (SINGLE BAR)
POINT	LOW TO MODERATE	POSSIBLE			BIMODAL SAND UNIMODAL GRAVEL (STACKED BARS)

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Figure 2. Fluvial bar forms and related palaeocurrent patterns, summarized after Bluck (see text).

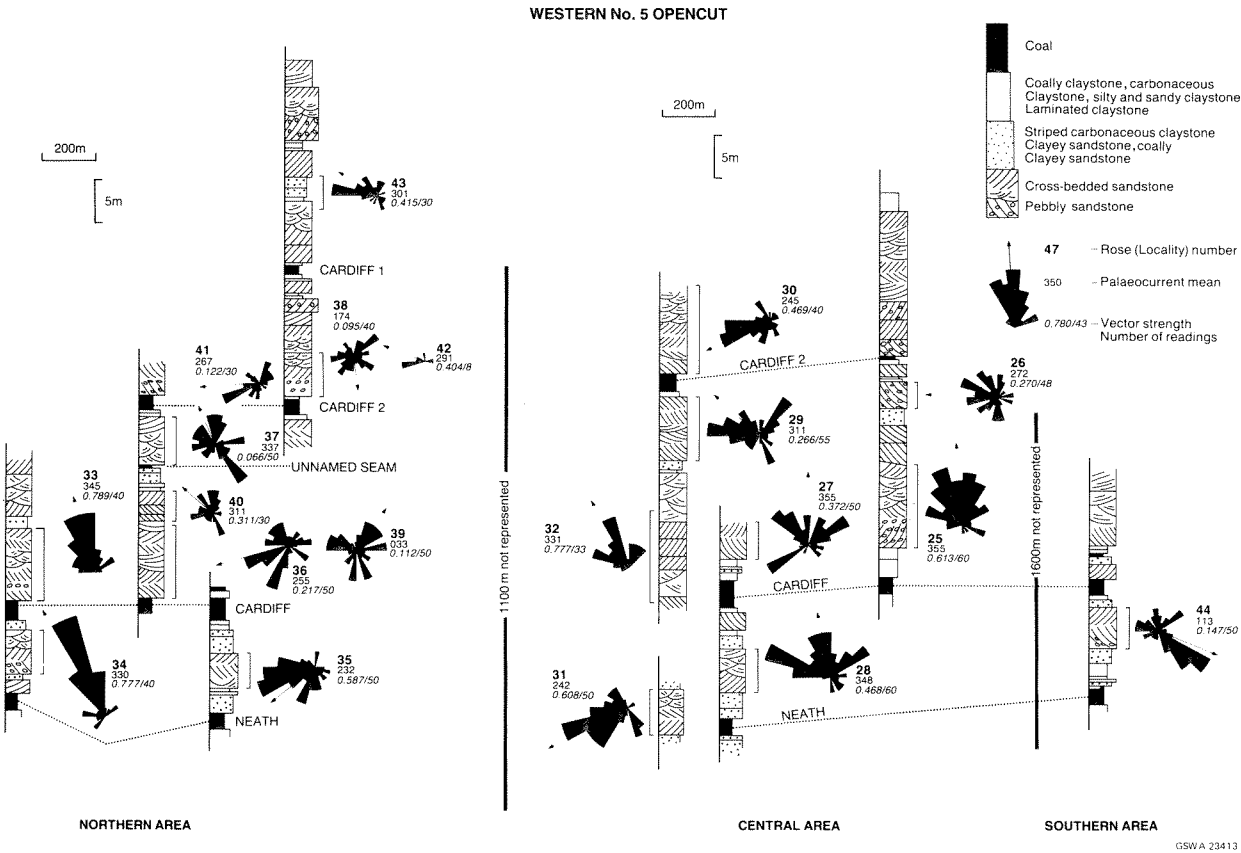


Figure 3. Stratigraphic sections and palaeocurrent results from the Western No. 5 Opencut. (Reference in Figure 5).

bedding. Bluck (1971, 1974, and 1976) in a series of perceptive and detailed studies of sediment transport, within fluvial regimes, has shown that different bar forms create characteristic palaeocurrent patterns which have predictable orientations with respect to mean channel direction. (Fig. 2) There are two principal features which control these patterns:

- (a) the changing current direction at different river stages; and
- (b) the different response of coarser and finer sediment to these changing currents.

With an understanding of these relationships, it is possible to analyze ancient alluvium, postulate the types of bars present, and evaluate the degree of stream sinuosity.

Bluck's (1976) scheme for bar classification includes both point and medial bars as well as lateral 1, 2 and 3 bars. Point bars tend to develop on the inside of meander loops and generally have a crescentic outline; they are attached to the inner bank of the channel. Medial bars have a rhomboidal outline, lie in midstream and have flanking active channels. Lateral 1 bars tend to occur in reaches of high sinuosity and have some similarities to point bars. Although attached to the inner bank they tend to lie athwart the channel rather than on the flank. Lateral 2 bars have a lozenge shape and are not bank attached. Grain size decreases diagonally downstream across the bar. Lateral 3 bars resemble rhomboid medial bars except that their inner channel is smaller than the outer and may be subjected to only intermittent flow.

Discrimination of the bar forms is best in those sequences having a moderate proportion of gravel and good three-dimensional exposures at an appropriate scale. Although both features are lacking at Collie, an analysis of cross-stratification does provide an indication of the bar types which were present during deposition of the Collie Coal Measures.

It is necessary to examine the palaeocurrent patterns over a vertical interval which is consistent with the scale of bars present. For the Collie Coal Measures, the full expression of the fluvial accretionary cycle is developed over thicknesses of 8-10 m (Figs 3 to 5). Allowing for the finer grained overbank sediments and coal, the channel and bar sandstone sequences accumulated over thicknesses of 3-8 m. Sandstone sequences substantially thicker than this have been derived by the superposition or stacking of bars. Sandstone sequences less than about 3 m may not represent complete bar development.

Medial bars have unimodal cross-bed means which point directly down the palaeoslope, with virtually no up-slope readings. Although other bar types can have a similar distribution, those from localities 17, 20, 33, 34, 45 and 47 do have this orientation together with an associated high vector strength.

Lateral 1 and point bars are present in high-sinuosity streams and can produce similar palaeocurrent patterns. These types are readily separable only when a high proportion of gravel is present. Therefore, for the Collie Coal Measures they are discussed together. Single bars are com-

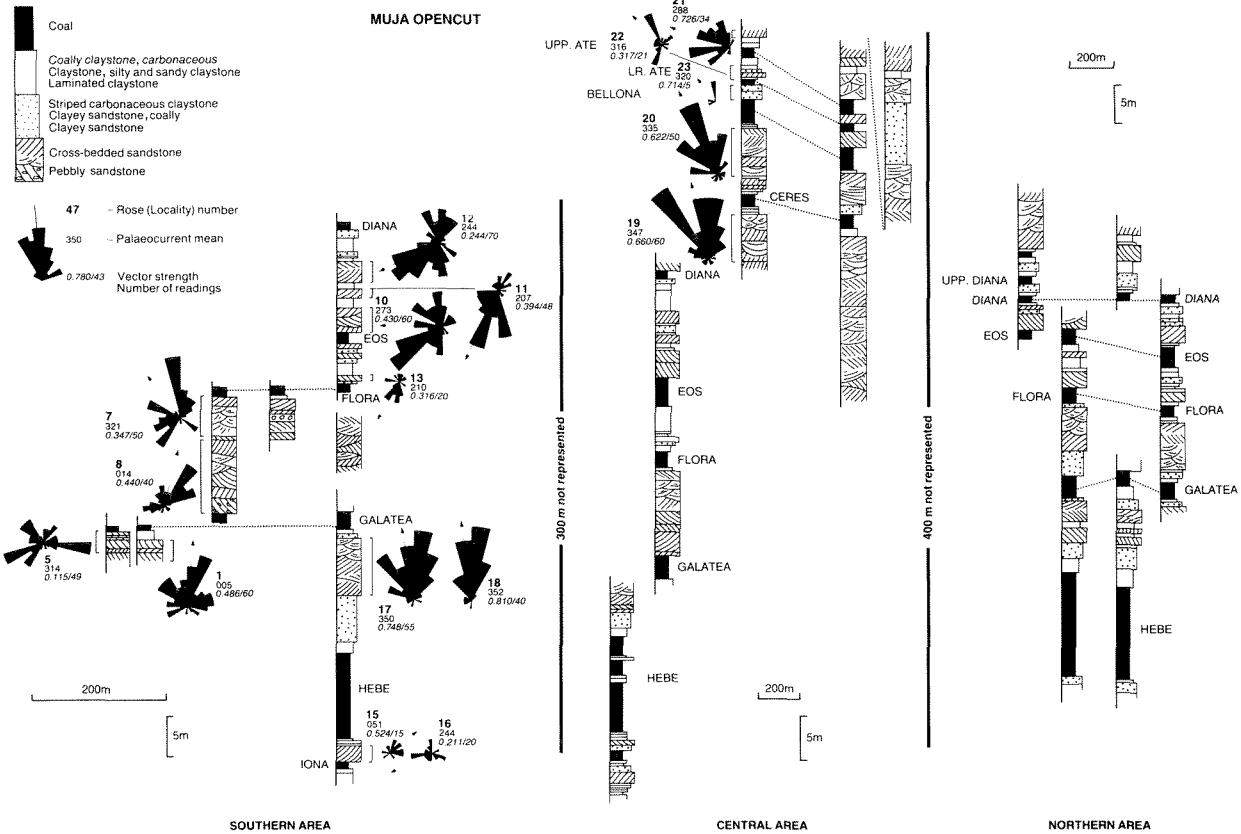
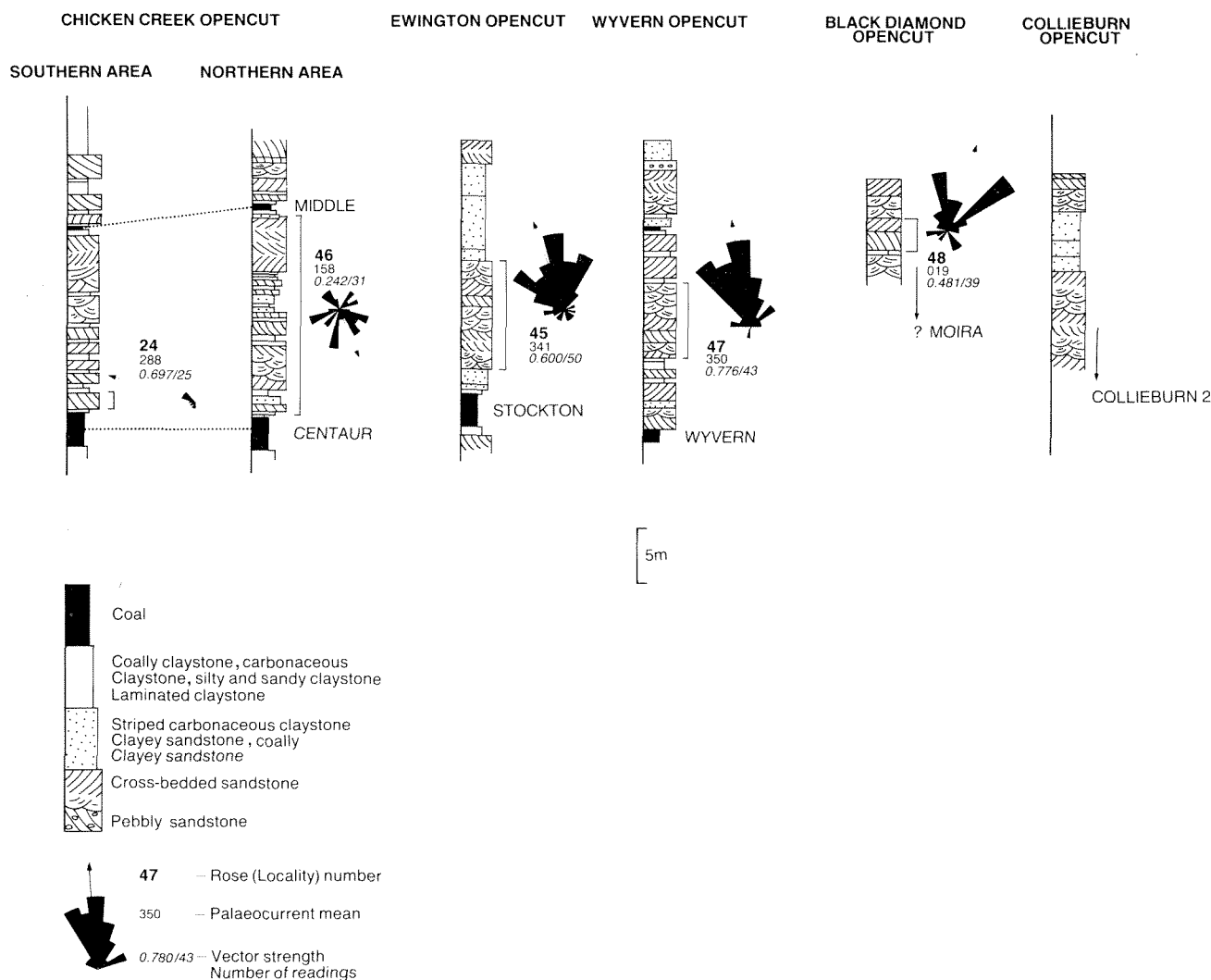


Figure 4. Stratigraphic sections and palaeocurrent results from the Muja Opencut. (Reference in Figure 5).



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Figure 5. Stratigraphic sections and palaeocurrent results from several opencuts within the Collie Basin.

monly characterized by two modes which are at a high angle to each other and to the palaeoslope dip direction. A series of stacked bars will give a mean which points down the palaeoslope. Possible examples of lateral 1 and point bars may be present at localities 5, 10, 12, 22, 29, 38 and 44. Under some conditions lateral 1 bars can give palaeocurrent means which are directed up the palaeoslope. The anomalous means at localities 11, 13, 38, 44 and 16 may have been produced by such bars.

Lateral 2 bars are characterized by palaeocurrent modes which are directed approximately at right angles to the palaeoslope direction. A series of bars will give a mean which bisects two mutually opposed modes. There appear to be relatively few examples of lateral 2 bars but examples may be present at localities 14, 31 and 43.

Lateral 3 bars have palaeocurrent modes which point obliquely down the palaeoslope. A series of bars would produce an overall mean which is directed down the palaeoslope. Examples may occur at localities 7, 8, 26, 27, 28, 41 and 48.

It can be seen from the above examples that several bar types were present in the fluvial system which deposited the Collie Coal Measures. Both low-sinuosity and high-sinuosity bar forms are present, but they do not seem to be developed to the mutual exclusion of the others at any time. This suggests deposition in a complex river system and eliminates the structurally simple, meandering stream as a possible depositional setting.

The lack of discrete channel forms and the presence of an undulating erosional base to the major sandstones suggest that the streams were braided; *i.e.* they had several interconnected channels. Such systems, as at Collie, are compositionally immature and not well sorted, reflecting the high bed-load volume. In turn, this is commonly a function of relatively high rates of physical weathering and erosion.

CONCLUSIONS

Basin implications

The spatial distribution of palaeocurrent means occurring close to the edge of the Collie Basin,

including the Stockton Ridge, shows conclusively (Figs 1, 3, 4 and 5) that sediment transport was independent of the present basin margins. This finding supports Wilde and Walker's (1978) conclusions which were based on a small data set. Thus Archaean basement did not form any positive relief in the immediate vicinity of Collie (cf. Park, 1982). The distribution of lithologies, sandstone grain size, coal ash, coal isopach, and interseam isopach values (unpublished company data) are also independent of the present basin margins. All of these features show minor local variations from average values, which give every indication of being related to an extensive depositional basin. The presence of very similar sequences (Kristensen and Wilson, 1986) at Wilga, Boyup Brook and on the Vasse Shelf (14, 30 and 110 kilometres distant, respectively, Fig. 1) imply an interconnected basin of regional extent within the West Australian Shield.

Tectonic implications

It has been shown that the present faulted margins of the Collie Basin did not confine deposition of the Collie Coal Measures. There is some evidence, however, that these faults may have been active during sedimentation (Lowry, 1976; Park, 1982) which could account for the following features:

- (a) the higher proportion of sandstone and (possibly) greater original thickness of sediment in the Cardiff Sub-basin;
- (b) the lack of an obvious coal-seam correlation between sub-basins; and
- (c) the greater number and proportion of coal seams in the upper two stratigraphic members of the Premier Sub-basin.

The uniform sediment size in the Collie Coal Measures implies that an overall constant net subsidence rate was maintained during deposition. Thus any differences in subsidence rates between the two sub-basins were slight and subtle.

It is difficult to establish the precise role of tectonism in the genesis and evolution of the original depositional basin because only remnants of it are available for study. None of the remnants seems to have lain immediately adjacent to an active tectonic zone. This in itself may indicate that gradual epeirogenic downwarp, or sea-level rise, was the ultimate factor controlling Permian aggradation on the shield.

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