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The Polda Basin — a seismic interpretation of a Proterozoic–Mesozoic rift in the Great Australian Bight

H.M.J. Stagg[1], J.B. Willcox[1] & D.J.L. Needham[1]

The Polda Basin is an elongate easterly trending trough underlying the continental shelf in water depths of 50–200 m on the eastern side of the Great Australian Bight. It encompasses an area of about 10 000 km^2, and contains a Proterozoic–Jurassic sedimentary fill. Although it was originally an intracratonic feature, it shows evidence of several phases of tectonism, of which the most recent culminated in the separation of Australia and Antarctica in the mid-Cretaceous.

Seismic interpretation indicates that the trough contains three main depocentres. The eastern Polda Basin lies almost entirely onshore, and contains 1500–2000 m of Proterozoic–Jurassic sedimentary rocks. The central Polda Basin and underlying Itiledoo Basin contain a maximum of 5000 m of Proterozoic–Jurassic continental sedimentary rocks, including massive halite. They are bounded to the south by a set of normal faults, and to the north by a complex faulted monocline. The western Polda Basin is apparently bounded, north and south, by relatively simple sets of east-northeasterly trending normal faults, and is interpreted to contain a mainly Mesozoic sedimentary fill. The central depocentre, in particular, has been affected by northwesterly oriented wrenching.

Overall, the hydrocarbon potential of the Polda Basin is rated as low. None of the three offshore wells drilled encountered significant hydrocarbons; even so, the western depocentre is as yet untested. Potential reservoirs appear to be present, and a number of potential trapping mechanisms can be identified. Such potential traps include halite-induced anticlines, Proterozoic fault-blocks, clastic aprons adjacent to boundary faults, and unconformity traps below the Permo-Carboniferous section. Unfortunately, the existence of suitable source and seal sequences is doubtful, and the basin appears to be too immature for significant hydrocarbons to have been generated. The western Polda Basin is considered to be the most prospective, as inferred by exploration drilling elsewhere in the Great Australian Bight, which shows that Mesozoic sedimentary rocks have some hydrocarbon potential.

Introduction

The Polda Basin is an elongate easterly trending trough that extends for at least 350 km from the Eyre Peninsula in the east to the centre of the Great Australian Bight (GAB) in the west, where it merges with the Ceduna Sub-basin of the GAB Basin (Fig. 1). The basin ranges from 10–40 km in width (with an average of 30 km), has an overall area of about 10 000 km^2, and contains a thick Proterozoic–Jurassic section overlain by superficial Tertiary sedimentary rocks. The sea floor is generally shallow, with water depths ranging from 50 to a maximum of 200 m at the western end of the basin.

The Polda Basin was first recognised as a geological entity in 1966, following an aeromagnetic survey flown for Shell Development (Australia) and Outback Oil (Geophysical Associates, 1966). It is also expressed as a gravity low, both on the Eyre Peninsula (Rowan, 1968; Pettifer & Fraser, 1974) and offshore (Willcox, 1978). Initially, the feature was known as the Elliston Basin, to distinguish it from the previously identified 'Polda Basin', an onshore basin containing Jurassic–Tertiary rocks. Following Flint (in press), we apply the terms 'Polda Basin' to the products of sedimentation that accumulated episodically between the Late Proterozoic and Jurassic, and 'Itiledoo Basin' to the underlying laterally more extensive rocks of Middle Proterozoic age.

From 1966–69, Shell acquired about 2100 km of reflection and refraction seismic data in the general area, before deciding to concentrate their efforts on the deeper-water GAB to the south (see Smith & Kamerling, 1969; Boeuf & Doust, 1975). Bridge Oil was granted an exploration permit over the Polda Basin in 1969, and two further seismic surveys, totalling 2131 km, were recorded in 1970 and 1971 (Fig. 2). Although drilling targets were identified, no drilling took place until 1975, when Outback Oil was granted another exploration permit over the area, and drilled Gemini No. 1. This well reached a total depth (TD) of 894 m in what was, at the time, interpreted as basement; subsequent reinterpretation redefined the 'basement' initially as 'Jurassic volcanics' and later as 'Permian diamictite' (Flint, in press).

In 1978, Outback Oil carried out a detailed aeromagnetic survey, reprocessed some of the 1970–71 seismic data, and reinterpreted all available data. As a result of this reappraisal, Australian Occidental farmed into the lease; subsequently acquired a further 3213 km of moderately good-quality seismic data in 1980–81; and drilled the wells Mercury No. 1 and Columbia No. 1 in 1981–82 (McClure, 1982a, 1982b). Both wells were plugged and abandoned as dry holes at TDs of 3251 and 2168 m, respectively, in sedimentary rocks of Proterozoic age. Since 1982, exploration in the Polda Basin has been dormant, with the exception of seven reflection seismic lines recorded across the western end of the trough during a research cruise by BMR's research vessel *Rig Seismic* in late 1986 (Willcox & others, 1988).

Nelson & others (1986), Flint & Rankin (1991), and Flint (in press) reviewed geophysical exploration and drilling in the Polda Basin, and interpreted a basin history. This paper uses their work and Stagg & others (1990) as a starting point for a more detailed seismic interpretation and assessment of the hydrocarbon potential.

Stratigraphy

The stratigraphy of the offshore part of the Polda Basin is known from three wells — Gemini No. 1, Mercury No. 1, and Columbia No. 1. The stratigraphy of the deep wells, Mercury No. 1 and Columbia No. 1, is shown in Figure 3. Gemini No. 1 and Mercury No. 1 were drilled on anticlinal closures induced by salt mobilisation at depth, whereas Columbia No. 1 tested the pre-Jurassic rocks of a horst-like structure. Gemini No. 1 penetrated a thick Late Jurassic coal-bearing section of poorly consolidated clastic rocks, and a thin underlying section of sandstone to gritstone, subsequently interpreted to be of Permo-Carboniferous age. Mercury No. 1 and Columbia No. 1, although not reaching basement, did penetrate thick sections of Proterozoic sedimentary rocks before being abandoned.

Although correlation between the older parts of the sections in Mercury No. 1 and Columbia No. 1 is tentative owing to intense structuring and the frequently poor-to-fair quality of the seismic data, it appears that both wells bottomed in sedimentary rocks of similar age. From TD to 771 m in Columbia No. 1

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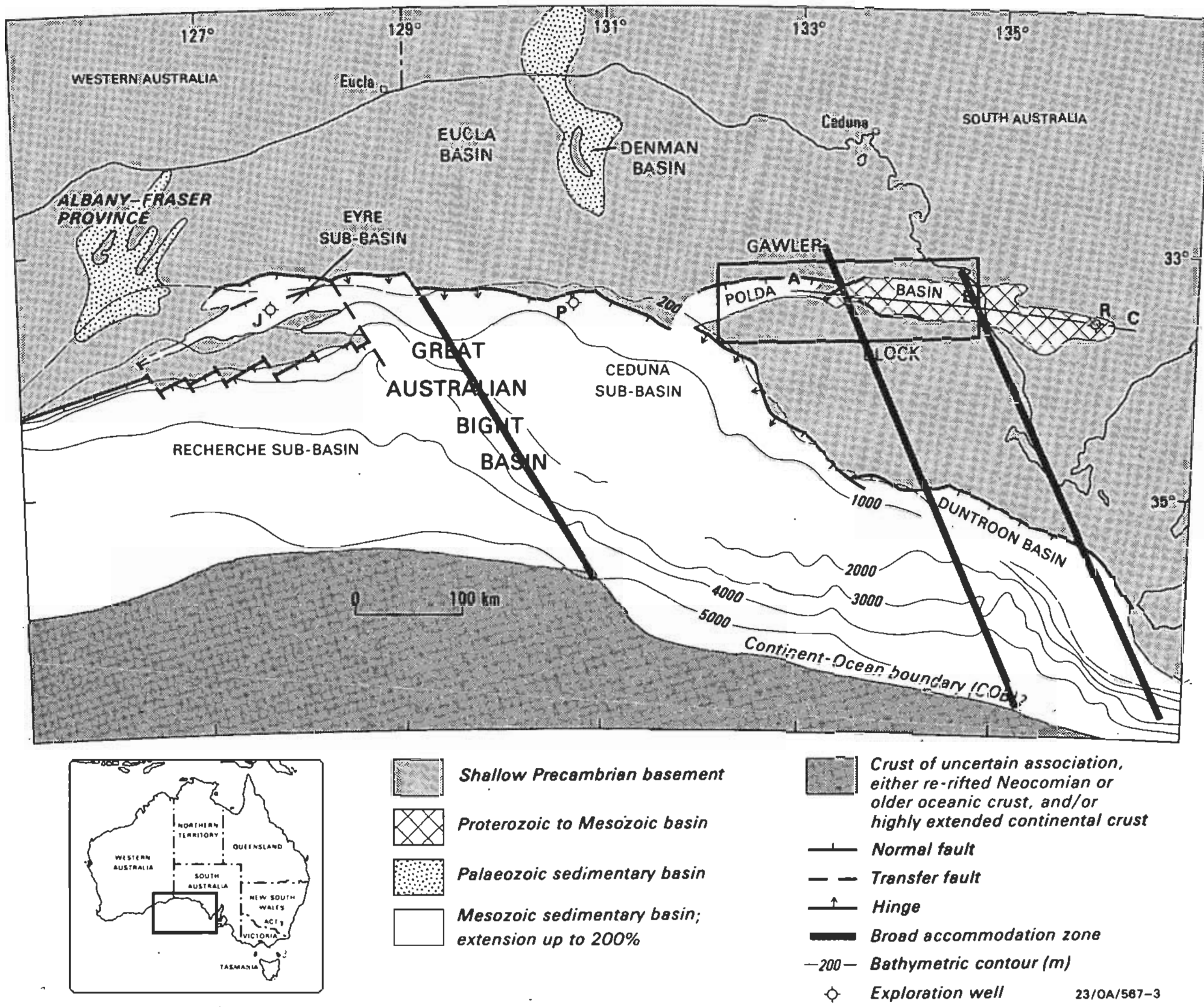

Figure 1. Structural elements of the southern margin of Australia.
The area of the Polda Basin covered by the basement structure map in Figure 7 is outlined by the box. The line A–B–C shown along the axis of the Polda Basin is the general location of the geological cross-section shown in Figure 6. 'J', 'P', and 'R' represent the locations of the Jerboa No. 1, Potoroo No. 1, and CRA 83 KD1A exploration wells respectively.

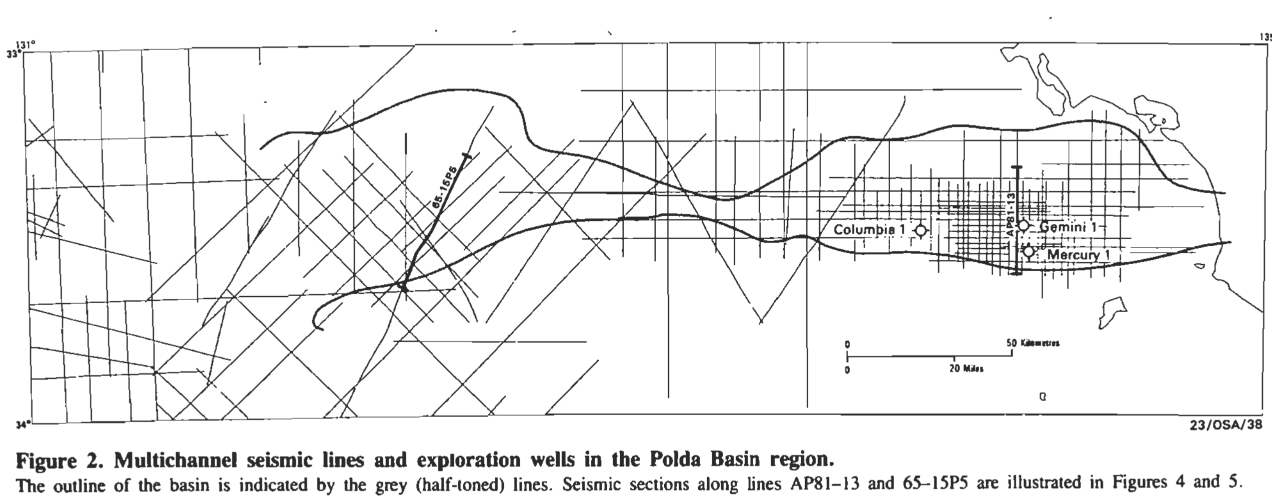

Figure 2. Multichannel seismic lines and exploration wells in the Polda Basin region.
The outline of the basin is indicated by the grey (half-toned) lines. Seismic sections along lines AP81–13 and 65–15P5 are illustrated in Figures 4 and 5.

and to about 900 m in Mercury No. 1, the sections comprised thick deposits of redbeds underlain by massive white sandstone and siliceous siltstone. The major difference between the sections in the two wells is the presence of about 1270 m of massive halite, in the form of salt pillows, in Mercury No. 1; no halite was encountered in Columbia No. 1. Redbeds interbedded with the halite were interpreted to have been 'rafted in' at the time of salt mobilisation (McClure, 1982a). The highly oxidised nature of the redbeds precludes definitive dating. However, comparison of the section with that onshore

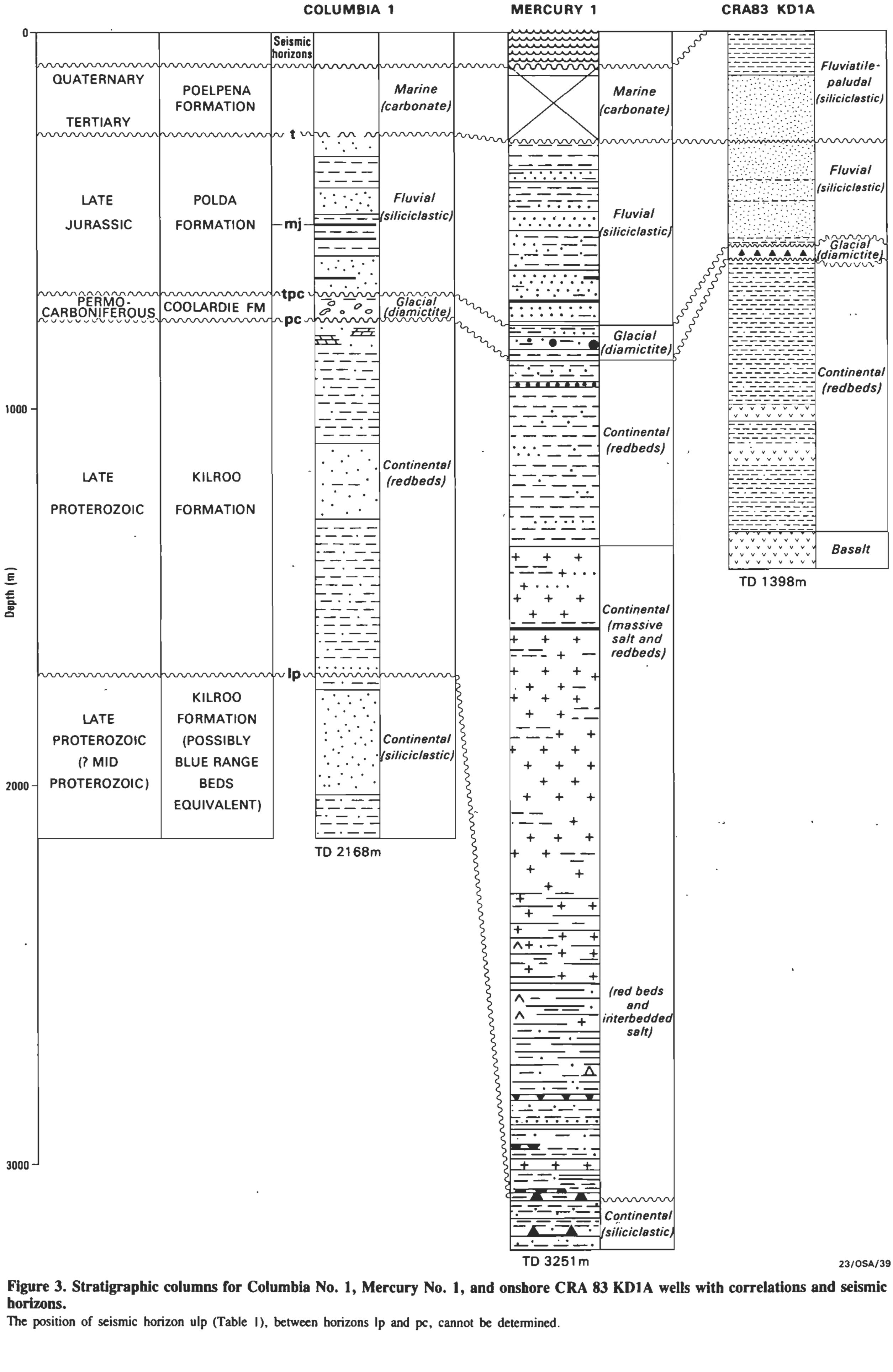

Figure 3. Stratigraphic columns for Columbia No. 1, Mercury No. 1, and onshore CRA 83 KD1A wells with correlations and seismic horizons.

The position of seismic horizon ulp (Table 1), between horizons lp and pc, cannot be determined.

(e.g., in CRA 83 KD1A exploration well; Griffiths, 1990; Figs. 1, 3) suggests that it consists of equivalents of the Kilroo Formation, which is of Late Proterozoic age (Flint & others, 1988).

In both Columbia No. 1 and Mercury No. 1, the top of the redbeds is marked by a prominent unconformity (basin-wide erosional unconformity on seismic sections), which is overlain by thin Permo-Carboniferous glacigene rocks of the Coolardie Formation. This unit consists of siltstone, claystone, and conglomerate. It forms a widespread veneer in the Polda Basin, but is typically difficult to discern from the overlying section in the seismic data.

The Late Jurassic Polda Formation is about 450–500 m thick in both Columbia No. 1 and Mercury No. 1, but is highly variable in thickness throughout most of the Polda Basin, since it infills the topographic lows at the top of the underlying section. The lower part of this unit is largely sand-prone, with some interbedded coal units, while the upper part consists of claystone, siltstone, and fining-upwards sandstone. Depositional environments at Mercury No. 1 are considered to be fluviatile, while the westwards-prograding seismic character of the sediment package east of the well is suggestive of a shallow-lacustrine environment.

The base of the flat-lying Tertiary section (Poelpena Formation) is marked by a prominent angular unconformity with the underlying Late Jurassic section. Although the Tertiary section was not sampled at either well, it is likely to consist of poorly consolidated open-marine carbonates, by comparison with the same interval sampled in wells elsewhere in the GAB — e.g., Jerboa No. 1 (Bein & Taylor, 1981) and Potoroo No. 1 (Shell, 1975).

Seismic horizons

The sequences identified in Mercury No. 1 and Columbia No. 1 can be mapped throughout the Polda Basin with varying degrees of confidence (Stagg & others, 1990). The principal horizons and their geological significance are as follows (refer to Fig. 3 for geological significance, and to Figs. 4 and 5 for examples):

- **horizon t** — base Tertiary: major erosional unconformity separating terrestrially derived, moderate- to high-energy Late Jurassic sedimentary rocks from assumed quiescent shallow-marine sediment-starved carbonate-platform deposits of Tertiary age; this reflector is often masked by the water-bottom multiple;
- **horizon mj** — an unconformity within the Late Jurassic sequence;
- **horizon tpc** — an unconformity separating the mainly glacigene Permo-Carboniferous and fluviolacustrine Jurassic sequences;
- **horizon pc** — top Proterozoic (top Kilroo Formation): the most prominent basin-wide erosional unconformity, separating the intensely oxidised Precambrian redbeds and mobile salt beds within the seismic sequence (lp–pc) from the overlying Permo-Carboniferous glacigene rocks of the Coolardie Formation;
- **horizon ulp** — unconformity, present along the northern part of the basin, which appears to overlie the Late Proterozoic redbed–salt sequence (Fig 4); although the seismic sequence (ulp–pc) has not been penetrated, a Late Proterozoic age is inferred;
- **horizon lp** — an erosional unconformity either within the Late Proterozoic or between the Middle and Late Proterozoic: this horizon is a well defined continuous reflector, except in areas of intense structuring in the central basin deep and in areas of post-horizon lp salt tectonism, which together have given rise to velocity problems in processing and to out-of-the-plane reflections due to high dips; it may be mapped with more confidence than basement over most of the basin;
- **horizon b** — top crystalline basement: this horizon is generally difficult to pick, and consequently the basement map must be considered somewhat speculative.

Seismic-stratigraphic characteristics of the principal seismic reflectors and sequences are shown in Table 1.

Structure and evolution

Nelson & others (1986) have presented a comprehensive account of the tectonic history of the Polda Basin, drawing on the previous work of Thomson (1970), Lambeck (1984), and Veevers (1984). This paper combines their work with a re-evaluation of the seismic data and selected structure and isopach maps that were presented by Stagg & others (1990).

Although Precambrian basement can be readily identified beneath most of the continental shelf in the northeast GAB, it is extremely difficult to map beneath the Polda Basin. A combination of complex basement tectonics, highly structured sedimentary rocks (including salt mobilisation), multiples arising from ringing from the shallow-water bottom and the base Tertiary unconformity, and complex off-side basement reflections does much to disguise basement reflections. As a consequence, the maps and profiles showing basement in the Polda Basin in this paper, while broadly correct, should be viewed with some caution.

Although most published maps portray the gross architecture of the Polda Basin as a moderately simple easterly trending fault-bounded graben, careful mapping shows that this is not so. In both north–south and east–west profiles (Figs. 4 and 6), and map view (Fig. 7), the trough is seen to consist of several discrete depocentres bounded by a complex of faults of different styles, orientations, and ages.

In east–west profile (Fig. 6), the Polda Basin appears to comprise three distinct depocentres, referred to here as the eastern, central, and western depocentres. Our account of the structure and evolution focuses primarily on the central and western depocentres.

The eastern Polda Basin lies almost entirely onshore, where it contains 1500–2000 m of Proterozoic–Jurassic rocks at its eastern and western ends, but only about 500 m above shoaling basement in the centre. In east–west cross-section (Fig. 6), the eastern Polda Basin is a fault-bounded feature, with its western termination just seawards of the present shoreline.

The central Polda Basin contains the major sedimentary body in the basin. Together with the underlying Itiledoo Basin, it comprises a maximum interpreted thickness of 5000 m of Proterozoic–Jurassic rocks west of Mercury No. 1. This part of the basin is the most intensively explored for hydrocarbons. It is separated from the eastern and western parts of the Polda Basin by faulted shallow basement with a trend opposed to that of the main structural grain.

Table 1. Characteristics of the seismic sequences in the Polda Trough

Horizon	*Upper boundary*	*Lower boundary*	*Internal configuration*	*Age*	*Facies*	*Comments*
wb						
	concordant	concordant; ?some downlap	high continuity; moderate amplitude; parallel reflectors	Tertiary	open-marine carbonates	not sampled in wells
t						
	erosional	onlap	low continuity; low–moderate amplitude	Jurassic	fluvial–lacustrine	Polda Formation
mj						
	erosional	onlap	low continuity; moderate amplitude	Jurassic	fluvial–lacustrine	Polda Formation
tpc						
	erosional; rarely concordant	onlap; concordant	low continuity; low–moderate amplitude	Permo-Carboniferous	glacigene	Coolardie Formation; poorly consolidated
pc						
	erosional; concordant	onlap; ?downlap	low continuity; low amplitude; chaotic	?Late Proterozoic	unknown	—
ulp						
	erosional; concordant	?concordant; onlap	low continuity; moderate amplitude; some diapirism with internal chaotic reflections	?Late Proterozoic	redbeds; massive halite	Kilroo Formation
lp						
	?erosional; concordant	obscured by multiples	low continuity; mixed amplitudes	?Middle–Late Proterozoic	redbeds	Kilroo Formation (?Blue Range beds equiv.)
b						
	obscured by multiples		acoustic basement	Archaean	(crystalline rocks)	Gawler Block

The structure of the western Polda Basin is relatively poorly defined, as few modern seismic data are available in this area. The western limit of the Polda Basin is at about longitude 131°50′E, where it merges with the Ceduna Sub-basin of the GAB Basin. However, the prominence of the easterly trend of the Polda Basin across the northern margins of the Ceduna and Eyre Sub-basins suggests that these Mesozoic features also might be underlain by older Polda Basin equivalents (Stagg & others, 1989), or, at least, by a westerly extension of the Proterozoic basement lineament.

In cross-section, the western and central parts of the Polda Basin have markedly different character, and might have developed as separate basins. The western Polda Basin is apparently bounded by a moderately simple fault system to both north and south (Fig. 5), and appears to form a simple graben. The east-northeasterly trend of the major faults in the west (Fig. 7) is roughly parallel to the basin-forming trend in the Eyre Sub-basin, farther west (Bein & Taylor, 1981). This leads us to postulate that the western Polda Basin is essentially a rift-splay formed during the Jurassic–Cretaceous extensional episode before the breakup of Australia and Antarctica, and hence probably contains mainly Mesozoic rocks. On BMR line 65/15 (Fig. 5) we interpret a typical GAB Basin section: thin Tertiary sediments unconformably overlying a Cretaceous section, with ?Jurassic synrift sedimentary rocks infilling the graben; alluvial-fan deposits of Jurassic age might flank the northern margin of the graben.

The central Polda Basin in most studies has been shown as normally and symmetrically faulted. In our interpretation, only the southern margin seems to be controlled by normal faulting (Fig. 4). The structure of the northern margin is complex: it appears to be a monocline modified by normal and strike-slip faulting; in places, wrenching may have caused reversal on faults. In simplified form, the central Polda Basin can be thought of as a half-graben with a hinged northern flank and a fault-bounded southern margin. In plan view, both northern and southern flanks show not only a marked easterly trend, but also prominent northwest–southeast offsets, which might represent accommodation zones (Stagg & others, 1990).

Thomson (1970) and Nelson & others (1986) have suggested that the Polda Basin is a member of the Late Proterozoic intracratonic family of basins that also includes the Ngalia, Amadeus, and Officer Basins. These are characteristically elongate east-west, and, with the intervening areas of uplift, form a series of basins and highs (Thompson, 1970; Nelson & others, 1986). Sedimentation apparently commenced with the deposition of the Middle Proterozoic Blue Range beds of the Itiledoo Basin. This sequence is up to 1.4 s two-way time (twt; ca 2000 m) thick below the eastern half of the central Polda Basin adjacent to the southern bounding fault. Trends within the succession appear to reflect largely the underlying easterly basement trend, particularly in the east of the central basin (Fig. 8).

Sedimentation continued through the Late Proterozoic with the deposition of redbeds and evaporites. Although this succession was originally deposited throughout the central and eastern areas, subsequent salt mobilisation has radically altered its distribution. The bulk of the succession is concentrated in a

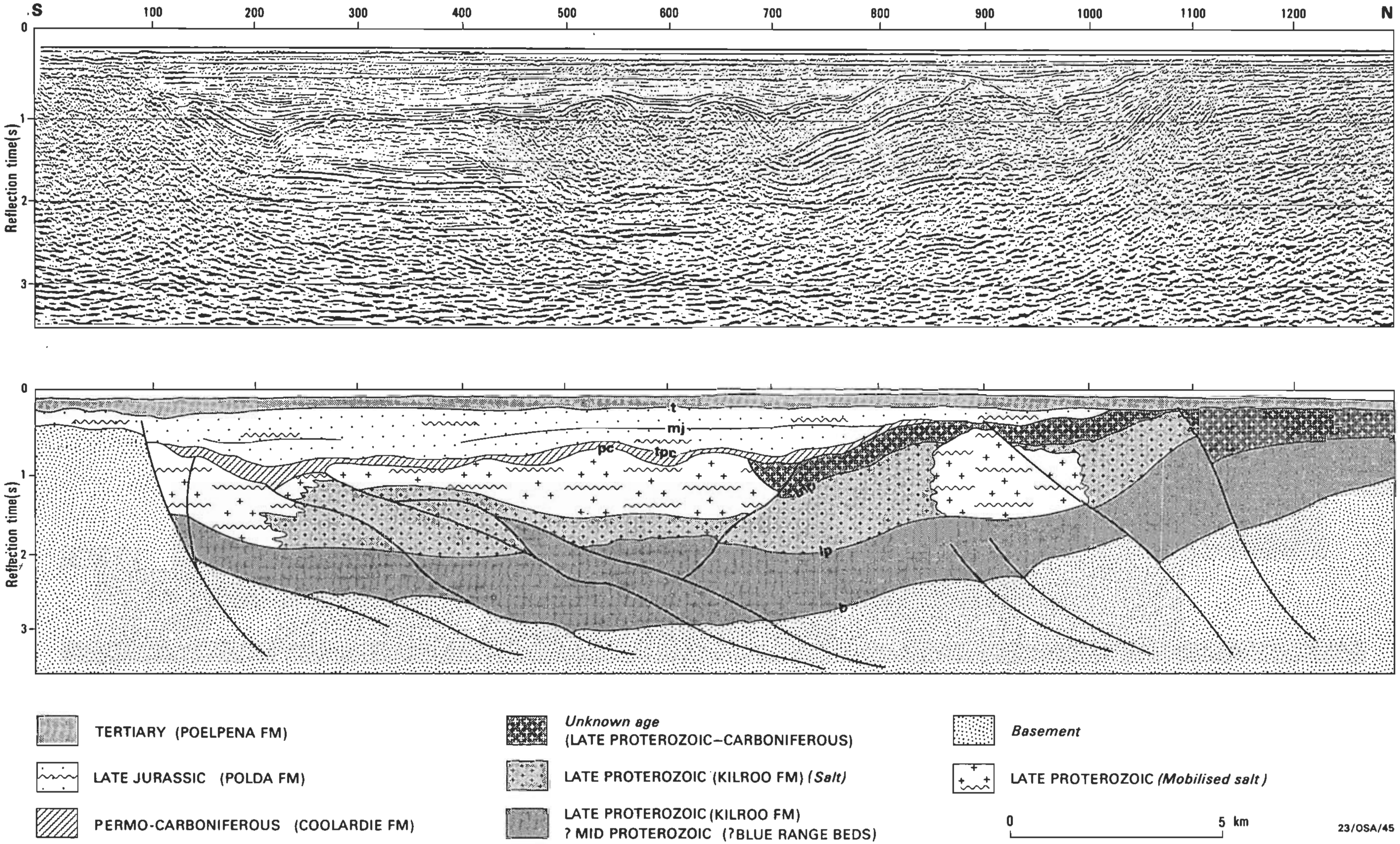

Figure 4. (a) Uninterpreted seismic profile and (b) line drawing of seismic line AP81–13 from the central Polda Basin, showing the southern bounding fault, salt mobilisation, and the complexly faulted monoclinal northern margin.

northwesterly trending belt of rocks up to 1.5 s twt (ca 3000 m) thick across the central Polda Basin (Fig. 9). Where the total thickness of the Kilroo Formation is greater than 0.9 s twt (ca 1400 m), it normally contains massive salt deposits.

The onset of the Petermann Ranges Orogeny in the latest Proterozoic to earliest Cambrian (Austin & Williams, 1978; Veevers, 1984) changed the fundamental stress regime over the continent. It generated northwesterly oriented dextral strike-slip faulting that is expressed as positive flower structures (Nelson & others, 1986, figs. 17 and 18), offsets in the southern bounding fault (Fig. 7), and apparent *en-echelon* offsetting of depressions in magnetic basement (Nelson & others, 1986, fig. 3a). These structures were probably reactivated later in the history of the basin, perhaps as recently as during the Jurassic–Cretaceous rifting.

There is no obvious thickening of the Late Proterozoic succession against the southern boundary fault system, which — by implication — postdates the deposition of this succession. Consequently, the Late Proterozoic rocks originally might have been more widely distributed, and the Polda Basin could be a structural remnant of a much more extensive basin.

Our interpretation of the north–south cross-section (Fig. 4) shows that, in this region, the age of the major phase of tectonism can be constrained only to within the Late Proterozoic–Carboniferous interval. This event apparently caused mobilisation of the halite in association with either strike-slip faulting or north-to-south-directed thrusting. 'Thrust sheets' of Proterozoic sedimentary rocks appear to have detached at or just below the basement. Mobilisation of halite appears to have taken place over quite a long period of time, and possibly in two phases. Most of the relief at the top of the Kilroo Formation (horizon pc; Fig. 10) is salt-induced, and the structural highs are intensely eroded. This suggests that the first and major mobilisation phase terminated before the onset of deposition of the Coolardie Formation. Structuring within the Coolardie Formation and the lower part of the Polda Formation also appears to be due to halite movement, and we conclude that a second phase of mobilisation took place between the Permo-Carboniferous and the Jurassic.

A major basin-wide erosional hiatus occurs between the top of the Proterozoic section and the thin glacigene sedimentary rocks of the Permo-Carboniferous Coolardie Formation (horizon pc; Fig 4). The Coolardie Formation is uniformly thin. It consists of a veneer of coarse glacigene rocks, up to 100 m thick, which have been correlated with those of the St Vincent and Arckaringa Basins by Nelson & others (1986). The Late Jurassic Polda Formation subsequently filled the topographic lows in the underlying strata. It is as much as 1 s twt (ca 1500 m) thick, although the average is nearer 0.5–0.6 s twt (700–800 m). Although this unit is largely of fluviatile origin in the wells, low-relief westwards-prograding foresets suggest shallow-lacustrine deposition in places. These Jurassic rocks probably can be correlated with the oldest synrift rocks of the Ceduna and Eyre Sub-basins, and are interpreted to constitute a major part of the sedimentary fill of the western Polda Basin.

The Jurassic Polda Formation is the oldest sequence to show syndepositional thickening from the basement platform into the Polda Basin, and along the southern bounding fault system. This implies that the fault system was most active during the Jurassic, and that, as a consequence, the present-day configuration of the Polda Basin is the result of selective preservation rather than a reflection of the original (Proterozoic) tectonic setting.

Our seismic interpretation (Fig. 5) strongly suggests that the western Polda Basin also formed in the Jurassic. This is consistent with the structural relationships observed in the Eyre Sub-basin to the west, and probably applies to the GAB Basin as a whole. If so, then the southern bounding fault system, and the northwesterly trending cross-faults (?transfer faults) which compartmentalise the basin, were created during rifting of the southern margin of Australia.

The available seismic data do not enable us to determine if the Permo-Carboniferous glacigene rocks were also synrift deposits, or if they were more-widespread platform deposits that have been since eroded off the shallow basement. If these rocks were synrift deposits, then they would imply that the preservation phase of the Polda Basin began in the Permo-Carboniferous.

No younger Mesozoic rocks have been penetrated in the wells, and the seismic data suggest that the Cretaceous is probably entirely absent from the central Polda Basin. Whether this lack of Cretaceous rocks is due to erosion or non-deposition has not been determined. The Mesozoic rocks are terminated by a major erosional unconformity, as in the outer parts of the Ceduna and Eyre Sub-basins. The overlying Tertiary sequence comprises a thin ($<$0.2 s twt, $<$200 m) veneer of carbonates and sands blanketing both the basin and the adjacent basement.

Hydrocarbon potential

No traces of hydrocarbons were encountered in the three offshore Polda Basin wells, other than an insignificant 40 ppm of methane from a rafted black limestone within the mobilised halite beds in Mercury No. 1. Consequently, few geochemical analyses of samples from the wells were carried out.

All the wells were considered to test valid hydrocarbon plays, although Gemini No. 1 was terminated before reaching the target sequences. Mercury No. 1 was sited on an anticlinal closure above an interpreted halite pillow in the 'salt belt' of the central Polda Basin. Areas of closure ranged from 44 km^2 at the base Jurassic level to 24 km^2 near the top of the salt, with vertical closures of 265 and 365 m, respectively (McClure, 1982a). Columbia No. 1 was designed to test for hydrocarbons within an interpreted horst structure in the western half of the central Polda Basin. At the level of interest (close to the Proterozoic reflector lp; Fig. 8) the area of closure was 18.5 km^2, and the vertical closure was 540 m (McClure, 1982b).

Reservoir and seal potential

In all three wells, the fluviatile Late Jurassic Polda Formation proved to be extremely porous and permeable. However, its reservoir potential is considered to be poor owing to its shallow subsurface depth, its probable lack of intraformational seals, and the uncertainty about whether it contains suitable source rocks (McClure, 1982a). The unit might provide a more viable reservoir in the undrilled western Polda Basin, where the sedimentary section is interpreted to be mainly of Mesozoic age and the porous Late Jurassic rocks might be much deeper. The potential reservoir properties of the Jurassic section reinforce the observation from other wells in the GAB that the Jurassic–Neocomian section constitutes a good hydrocarbon target.

Several intervals within the Proterozoic Kilroo Formation appear to have some reservoir potential in both Columbia No. 1 and Mercury No. 1. In Columbia No. 1, argillaceous and silty sandstones are present in the upper part of the Kilroo Formation, but they appear to have generally low porosities and little apparent permeability. However, log-derived porosities in the

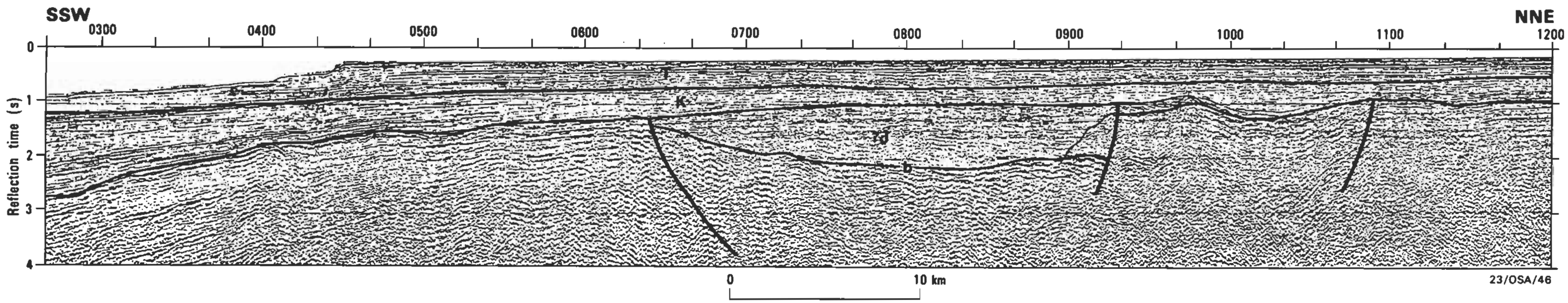

Figure 5. Portion of BMR survey 65 line 15 part 5 (65–15P5) from the western Polda Basin, showing a simple graben filled with rocks interpreted as Jurassic.

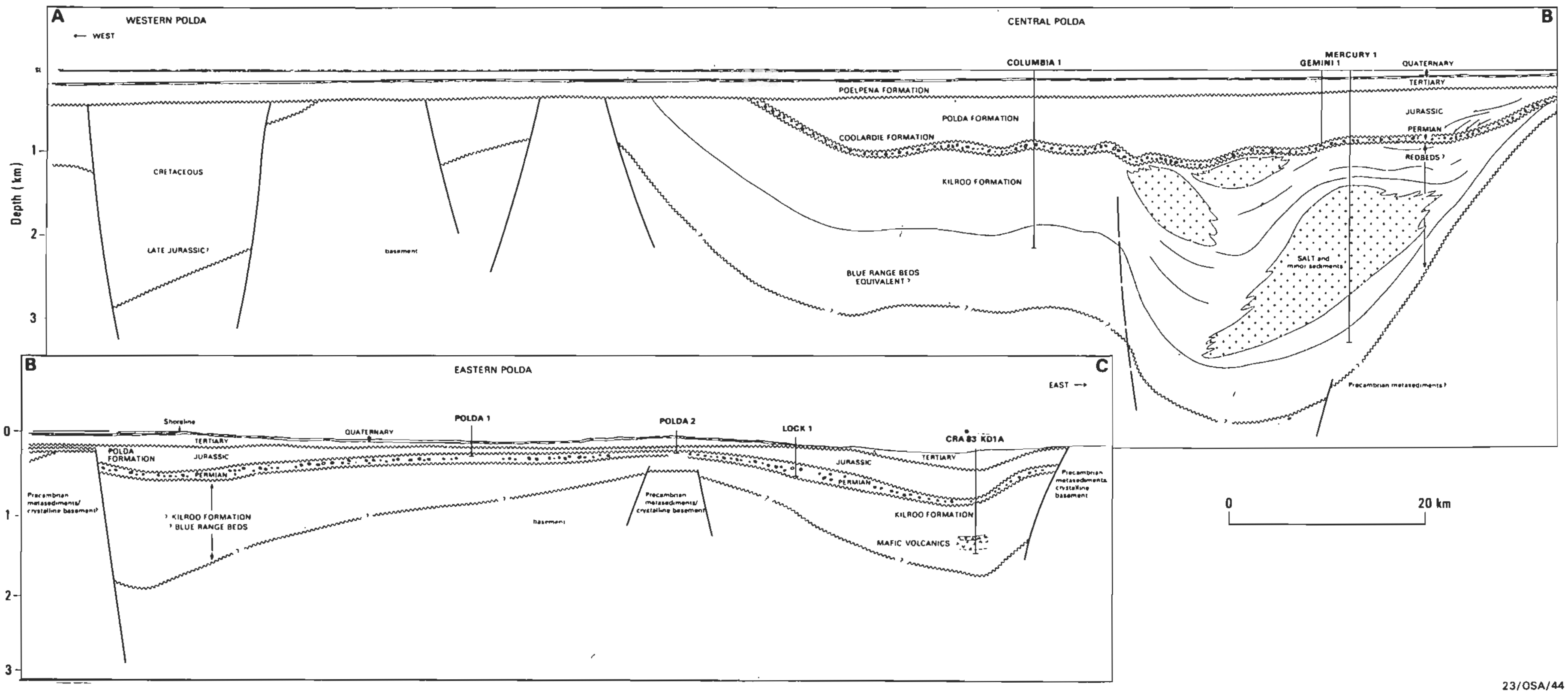

Figure 6. Generalised geological cross-section from west to east along the axis of the Polda Basin, based on composite seismic sections and well data. The two sections abut at 'B'. The general location of the profile is shown in Figure 1.

cleaner sandstones in this unit indicate values up to 19%. Thick quartzose sandstones are present in the basal sequence in the well; despite extensive silicification, they still have porosities in the range 10–15%, and SP logs suggest that they might have limited permeability. In Mercury No. 1, thin sandstone intervals in the top of the Proterozoic section have maximum log-derived porosities of 18%, whereas thick sandstone beds in the basal sequence — with porosities of about 13% — provide the best potential for reservoir development.

Source rocks and maturity

Because of the low apparent source potential of the sedimentary rocks (much of the Proterozoic redbed sequence is heavily oxidised), only limited geochemical analyses have been carried out. No analyses of the Late Jurassic Polda Formation were carried out at the time of drilling, presumably because of the rather unconsolidated nature of the rocks and their likely immaturity. However, the presence of coal within the Late Jurassic section, in all three offshore wells, is suggestive of some source potential elsewhere, particularly where the section has been buried deeply enough. Geochemical analysis of samples in the interval 310–810 m in Mercury No. 1 (McKirdy, 1984) indicate that the Polda Formation has good source potential, with a mean total organic carbon (TOC) content of 2.56%. Rock-Eval pyrolysis shows good genetic potential (S1 + S2), ranging from 2.97 to 22.42 kg t^{-1}.

In Mercury No. 1 (McClure, 1982a), a geochemical analysis was carried out on a sample from the rafted black limestone within the massive halite section. Headspace gas from this sample was particularly wet, suggesting that the sample came from a depth close to the maximum of the oil-generation window. The TOC content of the sample was only 0.06%, indicating that, despite the gas, it constituted a very poor petroleum source rock.

In Columbia No. 1 (McClure, 1982b), five samples covering the interval 770–820 m at the top of the Proterozoic section were geochemically analysed. Headspace gases indicate that the rocks have not reached a maturity level equivalent to the onset of oil generation. TOC analysis shows that the rocks have poor to moderate source potential, while Rock-Eval pyrolysis shows them to be both immature and of poor source potential.

Geothermal gradients in Mercury No. 1 and Columbia No. 1 range from 4.3–4.4°C km^{-1} for the Jurassic and younger section, and 1.7–2.1°C km^{-1} for the pre-Jurassic section. These gradients suggest that the Polda Basin is a moderately 'cold' basin, and that hydrocarbon maturity will be reached only at considerable depth. Geohistory analysis has not been attempted for the Polda Basin wells because the biostratigraphic control is poor.

Overall, the source potential of the central Polda Basin appears to be low owing to the lack of maturity in the Jurassic rocks, and the high degree of oxidisation of the Proterozoic rocks. However, two deep wells can hardly be considered a comprehensive test of the basin, particularly the western Polda Basin, where potential Mesozoic source and reservoir rocks might be present but are totally untested.

Play concepts

The lack of good-quality seismic data below the level of the Permo-Carboniferous (horizon pc) in the Polda Basin is a serious hindrance to the recognition of hydrocarbon plays. With this in mind, we suggest that the following play types could have potential.

- *Halite-induced anticlinal closure in the upper part of the Kilroo Formation and in the Permo-Carboniferous and younger sequences (as in Mercury No. 1; post-horizon pc).* Individual areal and vertical closures appear to be substantial, but the lack of success in Mercury No. 1 is a negative factor.
- *Sub-halite traps caused by relief in the Proterozoic succession below the halite (immediately above and below horizon lp).* Halite mobilisation and relative movement on thrust sheets might have induced the formation of such traps, which are likely to be subtle and identifiable only with very high-quality seismic data and velocity control. Recognition of these traps will require the recording of new data, or the application of new processing techniques to old data.
- *Basement-involved faulting of Proterozoic rocks, producing horst blocks (as identified in Columbia No. 1).* The current data quality does not allow confident interpretation of this trap type, which should be pursued farther.
- *Clastic aprons and braided alluvial deposits adjacent to the steep boundary faults.* Such plays might apply in the western Polda Basin (see Fig. 5). As elsewhere in the GAB, this play requires reservoirs to be sealed against both the fault plane and the overlying rocks.
- *Unconformity traps at the top Proterozoic Kilroo level (horizon pc).* Although there are several opportunities for reservoir development below this unconformity, the overlying Permo-Carboniferous glacigene sedimentary rocks might prove to be inadequate seals.

The above play types are most applicable to the central Polda Basin, but are probably of low potential owing to source and maturity limitations. We consider that the acquisition of high-quality seismic data (possibly using innovative acquisition and processing techniques to enhance primary reflections) is paramount if play types are to be further developed in the central Polda Basin. The current data quality causes difficulties in identifying the basin-forming structures and in following facies development and distribution within individual units. High-quality data are also required in the western Polda Basin (where existing data are, for the most part, of 1966–76 vintage — and very low quality) in order to develop play concepts. This part of the basin is believed to have a higher hydrocarbon potential because of the interpreted presence of a thick sequence of Mesozoic sedimentary rocks.

Acknowledgements

We are grateful to Drs N.F. Exon and R.J. Korsch of BMR, Messrs C.D. Cockshell and A.J. Hill of the South Australian Department of Mines and Energy, and Mr L.A. Tilbury of Woodside Offshore Petroleum Pty Ltd for critically reading this manuscript. The figures were drafted by Ms M. Huber of BMR's Cartographic Services Unit.


23/OSA/40
Gemini 1
Mercury 1
Columbia 1
134°
133°
132°
33°15′
33°30′
33°45′

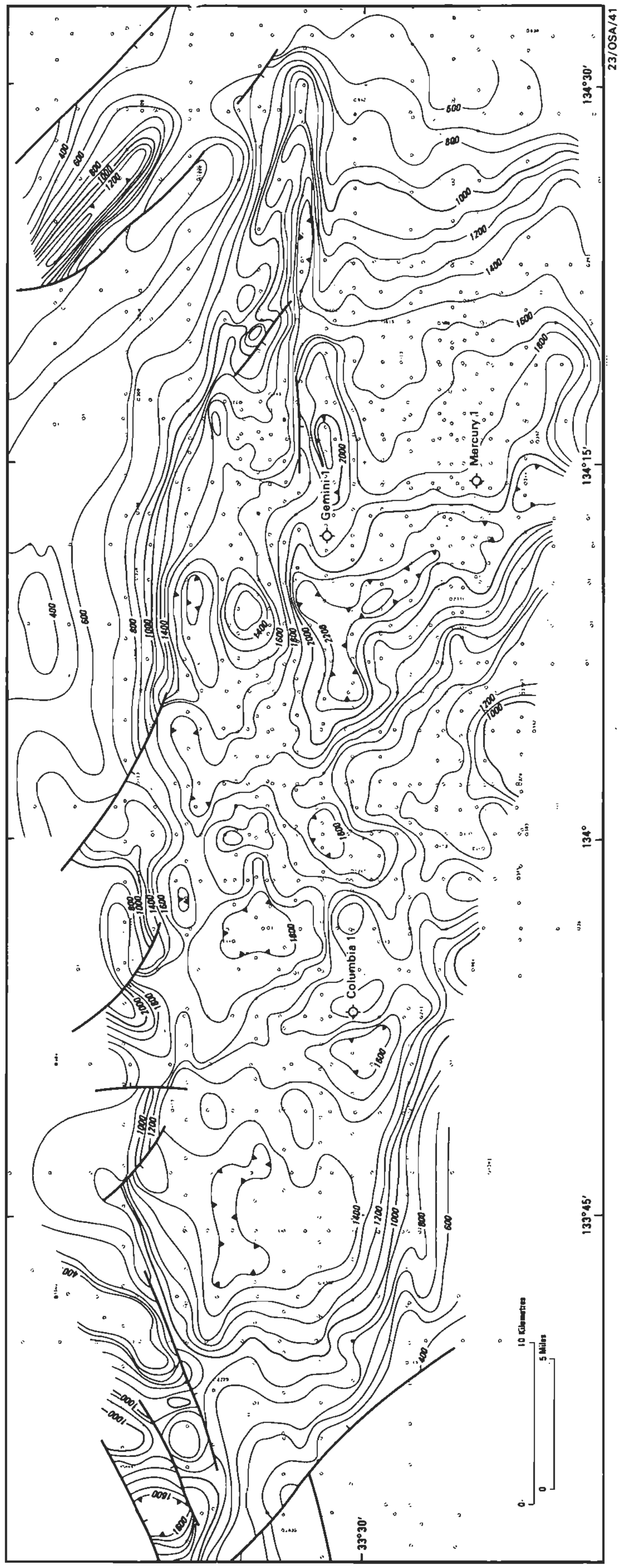
23/OSA/41
Gemini 1
Mercury 1
Columbia 1
134°30′
134°15′
134°
133°45′
33°30′
10 Kilometres
5 Miles

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Figure 7 (upper). Basement structure contours in the offshore Polda Basin.
Contours are in milliseconds twt. The area of shallow basement roughly at centre of this map represents the boundary between the western and central parts of the Polda Basin.

Figure 8 (lower). Structure contours of the ?top Blue Range beds equivalents in the central Polda Basin (Proterozoic; horizon lp).
Contours are in milliseconds twt.

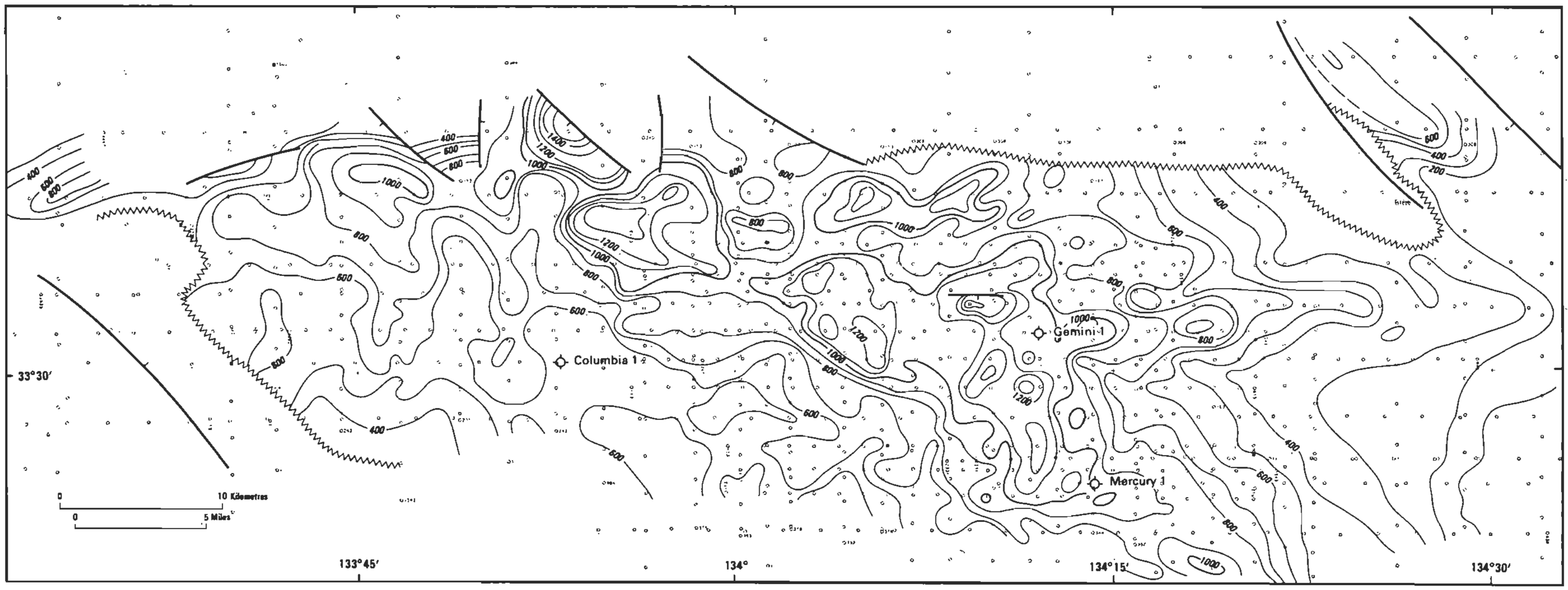

Figure 9. Isopachs of the Kilroo Formation in the central Polda Basin (seismic sequence lp–pc; major halite interval).
Contours are in milliseconds twt.

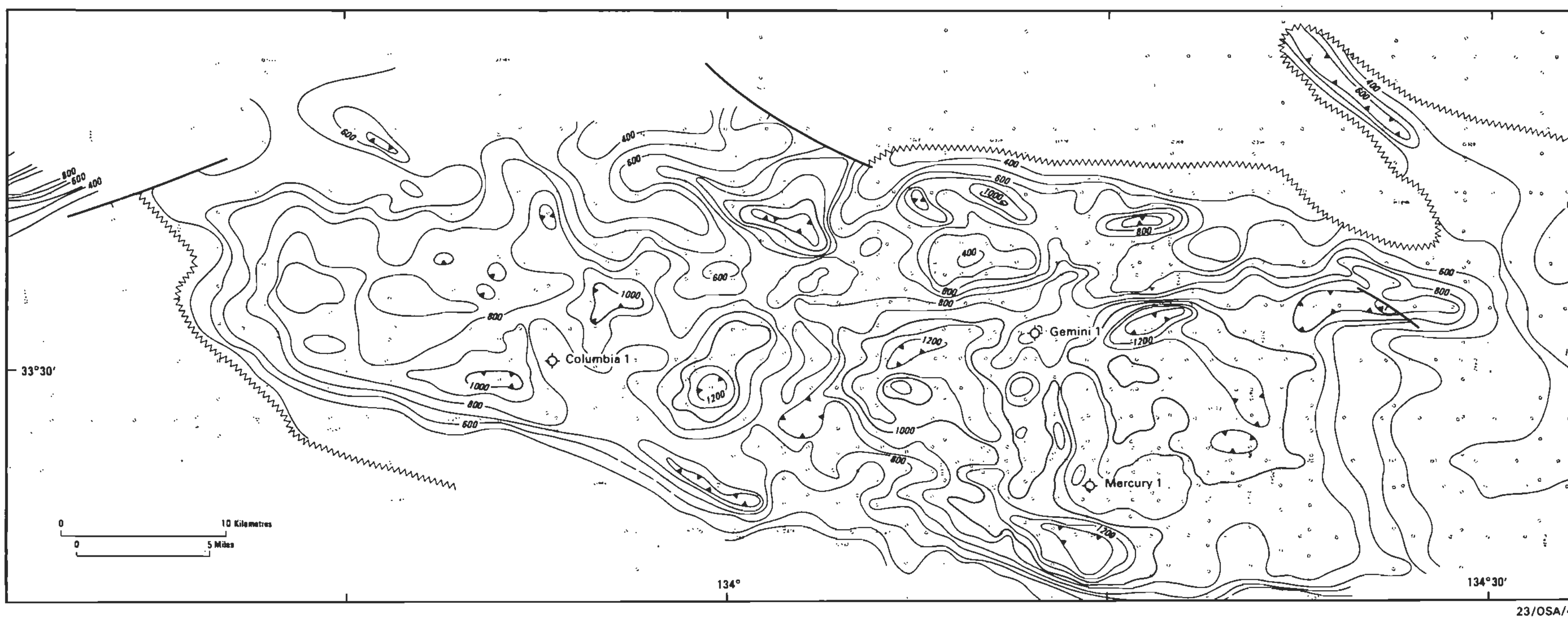

Figure 10. Structure contours of the top Kilroo Formation in the central Polda Basin (top Proterozoic; horizon pc).
Contours are in milliseconds twt.

BMR Journal of Australian Geology & Geophysics, 13, 15–18

Fossil shark teeth dredged from the Great Australian Bight

N.S. Pledge[1]

Two fossil shark teeth found in rocks dredged from the walls of submarine canyons in the Great Australian Bight are described. One of them, found in chalk ooze of Late Oligocene age, is referred to *Isurus* sp. cf. *I. desori*. The other, from a Late Cretaceous glauconitic sandstone, is described as a new species of *Echinorhinus* — the first time a fossil of this family has been identified in Australia. Reference is made to a misidentified tooth from the Albian of Queensland, *viz. Corax australis* Chapman 1909, which may be congeneric with the new *Echinorhinus* species.

Introduction

Surface rocks of the continental slope of southern Australia were sampled in November 1986 (Davies & others, 1989). Some of the samples were obtained by gravity or piston coring. Others were collected by dredging selected targets in the walls of some of the numerous submarine canyons of the Great Australian Bight.

Two of the dredge samples examined by J. Clarke contained shark teeth, which were sent to me for identification. They were also examined for microfossils by S. Shafik, B. Mc Gowran, and N. Alley, to determine their ages (Davies & others, 1989; Shafik, 1990).

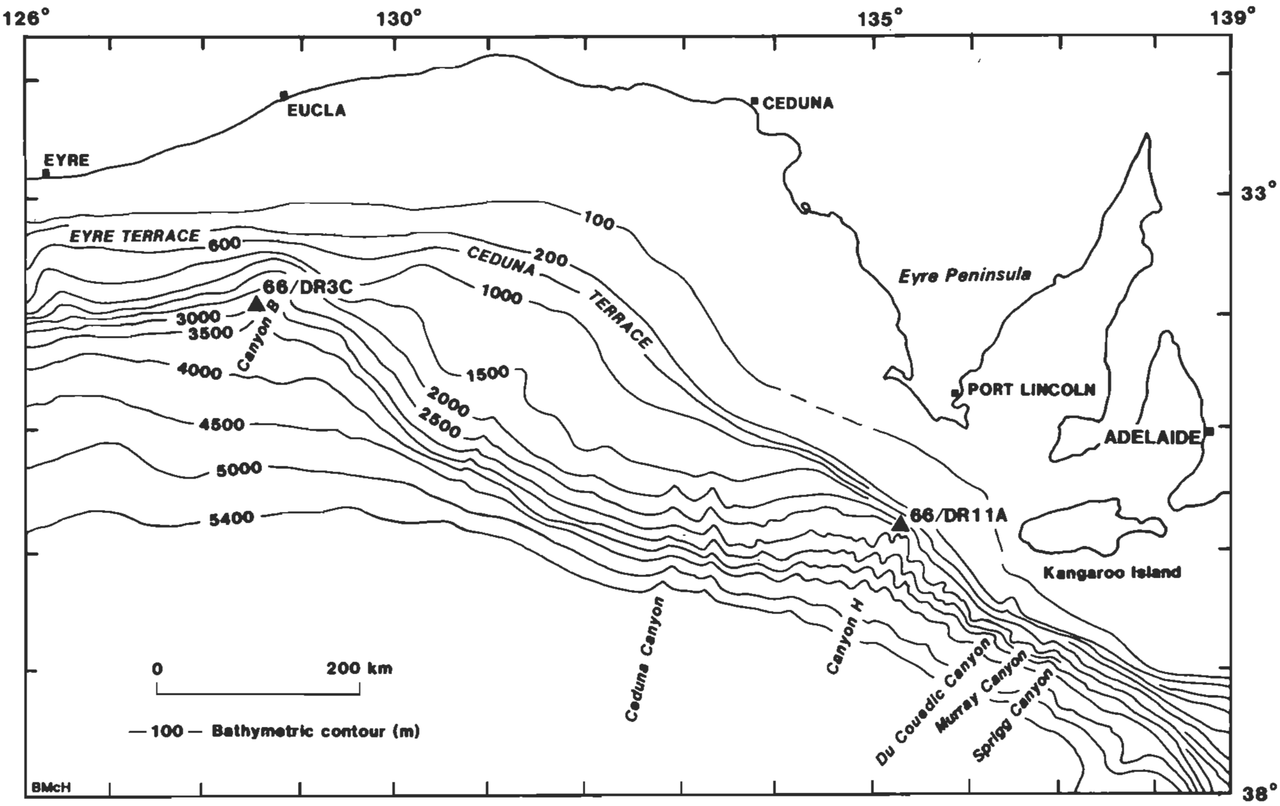

Figure 1. Location map (after Davies & others, 1989).

Dredge sample 66/DR11A — from 'canyon H' (Fig. 1), at the eastern end of the Ceduna Terrace south of Eyre Peninsula — is a white chalk ooze dated as Late Oligocene (B. McGowran *in* Davies & others, 1989). It contained the crown of a large shark tooth. Sample 66/DR3C — from 'canyon B', in the Eyre Terrace south of Eucla — is a glauconitic, calcareous, clay-pellet, gravelly, quartz arenite (Clarke & Davies, *appendix A in* Davies & others, 1989) whose age is estimated as 'probably Late Cretaceous (younger than Turonian)' on palynological evidence and Maastrichtian according to nannofossil studies (Shafik, 1990). It contained a complete shark tooth of a form not previously recorded in Australia. The specimens are housed in the Commonwealth Palaeontological Collection (CPC), BMR, Canberra.

Geology

The following information was kindly provided by J. Clarke (Flinders University, personal communication 1987).

Sample 66/DR11A was dredged from a depth between 2118 and 3622 m. The site was on the continental slope between latitudes 35°49.6′ and 35°50.1′S and longitudes 135°09.6′ and 135°18.8′E, south of Eyre Peninsula (Fig. 1).

The fossil was excavated from a very soft, poorly compacted and cemented, porous, white, foraminiferal spicular wackestone (chalk). The rock contains spicules from calcisponges,

[1] South Australian Museum, North Terrace, Adelaide, South Australia, 5000.

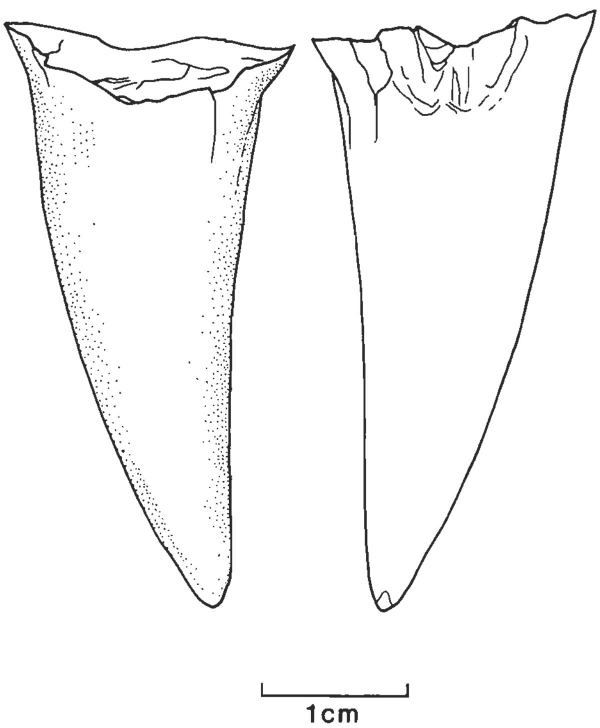

Figure 2. *Isurus* sp. cf. *I. desori*, an upper right anterior tooth, CPC 30662, from sample 66/DR11A, 'canyon H'.

demosponges, and hexactinellids, along with planktic foraminifera and rare radiolaria and pteropods. It shows no evidence of reworking.

The wackestone is considered to have accumulated in a deep pelagic marine environment from the precipitation of biogenic sediments. It has undergone very little diagenesis.

Sample 66/DR3C was dredged from the Eyre Terrace from a depth between 3285 and 3506 m. Its position was fixed between latitudes 33°57.2′ and 33°58.5′S and longitudes 128°33.8′ and 128°36.5′E.

The fossil was on the surface of a dark grey–green glauconitic, calcareous, clay-pellet, gravelly, quartz arenite. Large grains (black clay pellets, quartz gravel, and the shark tooth) comprise 20 per cent of the rock. In thin section, the rock is seen to be composed of angular to subangular quartz grains, glauconitic peloids, and rare fragments of thin-shelled molluscs. The provenance of the quartz grains (both sand and gravel) is metamorphic. The grains have been cemented by poikilotopic ferroan calcite. Pyrite has locally replaced the calcite cement.

The rock was probably deposited in a shallow-marine high-energy environment. Bottom waters were slightly reducing, as indicated by the abundant glauconite. The coarse quartz gravel suggests a nearby fluvial source. The clay pellets must be of local derivation as they would have been mechanically incapable of undergoing extensive transport; they may have been derived from a low-energy reducing environment such as a lagoon, delta, or tidal flat. The inferred environment was nearshore, probably near an estuary or delta. Sedimentation rates were low, and extensive reworking is apparent; the shark tooth also might have been reworked. The rock was cemented during deep burial under reducing pore-water conditions.

The sample contains a poorly preserved palynological and dinoflagellate assemblage.

Systematic palaeontology

Class **Chondrichthyes** Huxley, 1880
Subclass **Elasmobranchii** Bonaparte, 1838
Order **Lamniformes** Berg, 1958
Family **Lamnidae** Muller & Henle, 1838
cf. ***Isurus desori*** (Agassiz, 1843; Sismonda, 1849)
(Fig. 2)

Locality. Dredge site 66/DR11A, 'canyon H', continental slope south of Eyre Peninsula.

Age. Oligocene (Clarke & Davies, *appendix A in* Davies & others, 1989).

Description. This tooth (CPC 30662) is large, with a crown measuring 36 mm vertically from the base of the enamel, and 17 mm wide at the base. The root is missing. The crown is slightly inclined, with the tip just inside the base. It tapers smoothly from a slightly flared base to an acute apex. The mesial margin is smoothly convex, the distal edge slightly concave. The margins are finely trenchant and smooth, and extend right to the base of the crown as it is preserved. The outer (labial) face is more-or-less flat, the inner (lingual) face quite convex, so that cross-sections are roughly semicircular. The enameloid is smooth and shiny. In profile there is a very slight sigmoidal curve.

Discussion. Without the root, it is difficult to make a positive designation for this tooth. It appears to be an upper right anterior tooth of the blue pointer shark genus *Isurus*, and most closely matches the tooth of *I. desori* figured by Leriche (1957, pl. XLIV, fig. 20). It is rather more slender and tapers more smoothly than specimens figured by Kemp (1970) from the Waurn Ponds Limestone (near Geelong, Vic.) of Late Oligocene age (Abele *in* Douglas & Ferguson, 1988).

Isurus desori was first recorded from the Miocene of Piedmont, northern Italy (Sismonda, 1849). According to Cappetta (1987), it is essentially restricted to the Miocene. However, Kemp (1982) recorded it from the Late Oligocene of southeastern Australia, and a subspecies *I. d. flandrica* is reported from the Early Oligocene of Belgium (Leriche, 1910).

Order **Squaliformes** Goodrich, 1909
Family **Echinorhinidae** Gill, 1862
Echinorhinus eyrensis sp. nov.
(Fig. 3)

Holotype. CPC 30663.

Locality. Dredge site 66/DR3C, depth 3285–3506 m in 'canyon B' at the eastern end of the Eyre Terrace, south of Eucla.

Age. Maastrichtian (Shafik, 1990).

Etymology. '*eyrensis*' for the Eyre Terrace in whose deposits the tooth was found.

Diagnosis. An *Echinorhinus* with relatively high and erect main cusp; mesial and distal secondary cusps pointing upwards and divergent; mesial cusp slightly larger than distal one; and a pair of minute basal cusps mesially and distally.

The specimen differs from all described species (Pfeil, 1983), except *E. cookei* and *E. pfauntschi*, in size and orientation of main cusp; from all species, except possibly *E. blakei*, in orientation and size of mesial and distal secondary cusps; and from all species in relative positions of mesial and distal secondary and basal cusps.

Description. As it was being extracted from the hard matrix in which it was embedded, the tooth sustained some damage which blunted the points of the cusps and softened its outline. Nevertheless, the cusps are evident, if not their actual size.

The tooth is small. It comprises a broad, flat, blade-like root – 13.8 mm long mesiodistally and about 4 mm deep — surmounted by a central main inclined cusp whose tip is missing but seems about to decline further. The crown is only slightly shorter than the root. The main cusp occupies about one-third of the tooth length, and would reach a vertical height of perhaps 6 mm above the base of the enameloid.

On the mesial (anterior) side of the tooth, a smaller, broad, mesially directed, secondary cusp has an axis roughly at right-angles to that of the main cusp. Beyond it mesially and closer to the base, a very small cusp is barely discernible because of abrasion. Distal to the main cusp, a secondary cusp has an axis that diverges only slightly from that of the main one, and basally to that is another tiny cusp at the end of the crown. All cusps are linked by a continuous trenchant margin. The enameloid is smooth on both surfaces.

The greatest thickness of the tooth is barely 2 mm, at the boundary between enameloid and root. The root has the form of a chisel-like blade with an irregularly straight edge. The moderately smooth lingual face of the root shows many fine pores or perforations, where the surface has been rather deeply abraded. By contrast, the labial face appears finely roughened but without obvious pores.

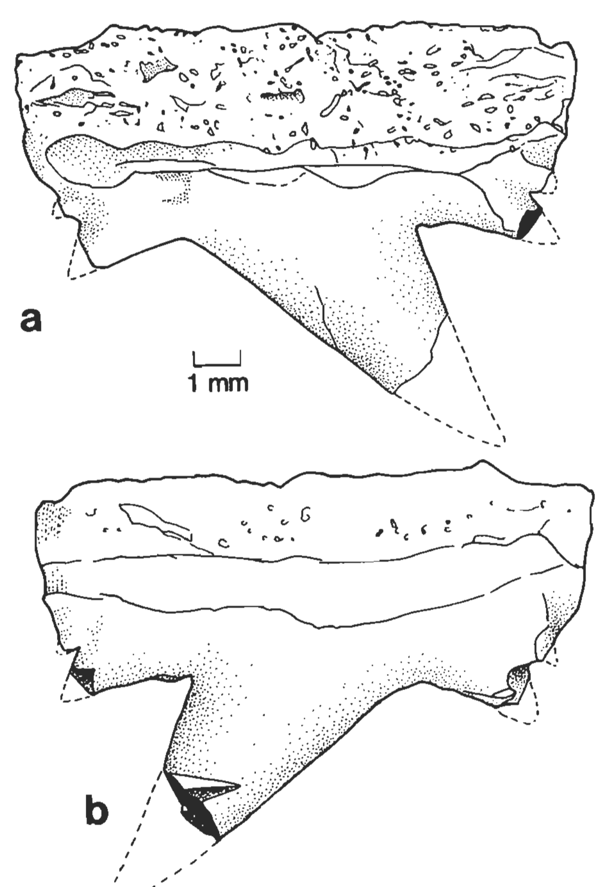

Figure 3. *Echinorhinus eyrensis* sp. nov., a right upper lateral tooth, CPC 30663, from sample 66/DR3C, 'canyon B': a, lingual face; b, labial face.

Discussion. The tooth is considered to be from a bramble shark, *Echinorhinus*. It differs from those of Carcharhiniformes in the form of its root and in its lack of an open pulp cavity and nutritive foramen. It differs from other galeomorphs also in the form of the crown and root. It is similar to hexanchoids in the general form of the root and crown, but differs in having distinct mesially directed cusps on an apparently anterolateral tooth. The nearest approximation among these sharks is with upper lateral teeth (4th or 5th) of *Notorynchus cepedianus* (Peron, 1807), *Heptranchias perlo* (Bonnaterre, 1788; e.g., Kemp, 1982, figs. 5, 8), and *Notidanodon loozi* (Vincent, 1876; Herman, 1975, pl. III fig. 8b), but these forms lack a large mesially directed cusp, and their proportions are different.

The teeth of the squaliform family Echinorhinidae are characterised by being 'very labio-lingually compressed, with very slanted and divergent lateral cusplets' (Cappetta, 1987). The new specimen is compatible with the description of teeth of *Echinorhinus*, but lacks the (i) one to three vertical grooves in the lingual face of the root and (ii) numerous pores below the enameloid on the labial face described by Cappetta (1987). Other members of the family lack the secondary cusps. The absence of the vertical grooves in the new specimen is probably the result of erosion of the tooth, although figures in Pfeil's (1983) monograph suggest that the grooves (*Basalfurche*) are variably developed and may be virtually absent.

Although Pfeil (1983) lists no pre-Tertiary echinorhinids (his oldest is *Pseudoechinorhinus mackinnoni* from the Paleocene of New Zealand), *Echinorhinus* has a history extending back to the Campanian in Angola (Cappetta, 1987). Teeth of the undescribed Cretaceous and Palaeogene species (from Angola, Morocco, and Denmark) are reportedly simpler in structure than Neogene and Recent species (Cappetta, 1987). The possession of basal cusplets by the South Australian fossil, however, likens it more to the modern *E. brucus* (e.g., Garrick, 1960) than to the several Cretaceous and Palaeogene forms — for example, *E. caspius* from the Oligocene of the USSR (Glückman, 1964). It appears to be an anterolateral tooth in which the secondary cusps are somewhat reduced (cf. Cappetta, 1987, fig. 50A).

A tooth referable to the Echinorhinidae — though, until now, misidentified — has been found previously in the Australian Cretaceous. Chapman (1909) erected *Corax australis* for this specimen, preserved in the Toolebuc Formation (Albian) near Hamilton River, east of Boulia, Queensland. His figure shows a tooth almost identical with some of *E. caspius* (Glückman, 1964, pl. IV fig. 8, pl. XXVI fig. 13), *E. schoenfeldi* from the Early Oligocene of Bavaria (Pfeil, 1983), and *E. weltoni* from the Middle Eocene of Oregon (Pfeil, 1983). It also resembles some lateral teeth of the rather variable *Paraechinorhinus riepli* (Pfeil, 1983, figs. 121.1 and 125.2) from the Middle Eocene of Austria. Chapman compared his specimen to *Corax affinis* (now *Pseudocorax*) from the Maastrichtian of Holland. *Pseudocorax*, however, has well developed root lobes (Herman, 1975), and is distinctly serrate on the margins, although the oldest species of that genus has smooth cutting edges (Cappetta, 1987). Herman (1975) placed *C. australis* in *Squalicorax* Whitley, 1939, as the first and most ancient species of that lineage, in which secondary serration was gradually attained. Some members of this family — the Anacoracidae Casier, 1947 — have notable labio-lingual flattening of the root and lack a nutrient groove, features which led Casier (1947) to place the family near the Hexanchidae. Cappetta (1987) felt that this was a case of convergence, and moved them to the Lamniformes.

Neither the 'canyon B' tooth nor the Queensland specimen, although different from one another, really fits the characteristics described for the Anacoracidae, but can be accommodated within *Echinorhinus*. Despite their age difference, they may fall within the same morphospecies — the Queensland tooth being from a more posterior file in which the secondary cusps are reduced to nothing. This, however, is considered unlikely, since in *E. cookei* only files 12 onwards have lost the secondary cusps. The 'canyon B' tooth is therefore regarded as a new species of *Echinorhinus*. To judge from the figures of *E. cookei* in Garrick (1960) and Pfeil (1983), the tooth is probably from the upper jaw, because its mesial secondary cusp is directed away from the root rather than being parallel to it.

The designation of the Queensland tooth is in doubt. Kemp (1991) figures more material, and (personal communication 1991) favours excluding it from *Echinorhinus* and retaining it in *Pseudocorax*.

Discussion

Isurus desori (Ag.) is considered to be a pelagic shark, like its living congener (e.g., Cappetta & others, 1967), so its preservation in rock indicative of this environment is not surprising. More surprising is the occurrence of a shark referable to *Echinorhinus* sp. in a shallow, nearshore environment. *Echinorhinus* is considered to be a deep-water species, inhabiting waters of the continental slope ranging down to a depth of 900 m (Compagno, *in* Stevens, 1987); however, it occurs also in shallows of only 11 m. It is recorded from the Great Australian Bight, but has been rarely taken.

The significance of the 'canyon B' tooth is that it extends, back to the Late Cretaceous, the range of *Echinorhinus* species having teeth of the modern form. This suggests that the evolution of the genus is not as simple as inferred by Cappetta (1987) and Pfeil (1983): whereas other Cretaceous 'species are simpler in structure ...; the mesial cutting edge in particular is generally complete and lacks basal cusplets' (Cappetta, 1987), the new specimen described here has distinct secondary cusps.

The Queensland species, lacking as it does any secondary cusps, is presumably closer to the ancestral form (Cappetta, 1987), and its Albian age makes *Echinorhinus australis* comb. nov. the oldest recognised member of the family.

Acknowledgements

I am grateful to Jonathan Clarke for passing these specimens to me for identification, and for providing the relevant collection data. I am particularly grateful to Mr D.J. Ward, Dr Henri Cappetta, and Dr Jacques Herman for stimulating discussion and suggestions which allowed me to identify the Cretaceous specimen. Noel Kemp and an anonymous referee made constructive comments that benefited the final draft of this paper.

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Late Cretaceous–Palaeogene nannofossil biostratigraphy of Challenger No. 1 well (Challenger Formation type section), offshore Perth Basin, Western Australia

Samir Shafik[1]

Late Cretaceous–Palaeogene calcareous nannofossil assemblages from the mainly carbonate section in Challenger No. 1 well, above the 780-m level, have some similarities with the recently described succession of carbonates in the Perth Canyon, south Perth Basin. The continuity of the marine Palaeogene in these two sections contrasts with the single marine unit (the hemipelagic Kings Park Formation) known in the onshore Perth Basin. In both offshore sections, it is impracticable to subdivide the Palaeogene carbonates into mappable lithostratigraphic units, and identification of known Paleocene and Eocene hemipelagic rock units is evidently not possible although their age equivalents (or partial equivalents) can be detected biostratigraphically.

Marine Oligocene sediments, recently identified (for the first time in the Perth Basin) in the Perth Canyon, are shown to occur in Challenger No. 1. The age of the type section of the Challenger Formation is revised (from Late Eocene) to Middle Eocene–Oligocene. Sediments immediately underlying the type Challenger Formation in Challenger No. 1 are Middle Eocene in age, and consequently are not the Kings Park Formation as previously reported. They probably equate with the basal type section of the hemipelagic Porpoise Bay Formation, suggesting a possibly significant age overlap between the type sections of the Challenger and Porpoise Bay Formations; the latter is probably a more terrigenous facies of part of the former. Lower Eocene beds similar to those discovered recently in the Perth Canyon also occur in Challenger No. 1. The Late Cretaceous assemblages identified in Challenger No. 1 are probably representatives of both the upper Campanian Lancelin beds (lower part) and the upper Santonian–lower Campanian Gingin Chalk.

Three major disconformities (or condensed sections) are detected in Challenger No. 1: at the Eocene/Oligocene boundary (lowermost Oligocene is missing) within the upper part of the Challenger Formation; at the Cretaceous/Tertiary boundary (Maastrichtian and Lower Paleocene are missing), and within the Campanian section. The Late Cretaceous–Palaeogene section in Challenger No. 1 is more complete than coeval sections at nearby Deep Sea Drilling Project sites in the Perth Abyssal Plain and on the Naturaliste Plateau.

Introduction

Challenger No. 1 well (lat. 32°25.3'S, long. 115°00.8'E) was drilled offshore in the Perth Basin (Fig. 1) during early 1975 by West Australian Petroleum Pty Ltd (WAPET). Quilty (1978) described its lithological and foraminiferal faunal successions above the 773-m level. Cockbain & Hocking (1989) nominated the 67-m-thick section in Challenger No. 1, between 530 and 597 m (Quilty's, 1978, 'Late Eocene unnamed formation'), as the type section of the Challenger Formation. Two foraminiferal assemblages were recorded from this section by Quilty (1978), who regarded them as Late Eocene in age. In a recent paper, I discussed these foraminiferal assemblages, and concluded that they suggest a Middle Eocene to (Early) Oligocene age (Shafik, 1991).

Substantial new knowledge has been gained recently about the Palaeogene sequence in the Perth Basin. I have recorded several Paleocene, Eocene, and Oligocene marine levels in the Perth Canyon[2] (to the north of Challenger No. 1, Fig. 1) which were unknown previously in the Perth Basin (Shafik, 1991).

Because it has been long believed that the Oligocene corresponds to a period of erosion, with no marine record in the Perth Basin (Quilty, 1977; Quilty & others, in press), my interpretation of marine Oligocene in Challenger No. 1, and my record of a mid-Oligocene nannofossil assemblage from the Perth Canyon (Shafik, 1991), are highly significant. However, it was not possible to determine whether the mid-Oligocene beds in the Perth Canyon, and the suspected Oligocene (uppermost part of Challenger Formation) in Challenger No. 1, are parts of the same unit, without first examining material from Challenger No. 1 (see Shafik, 1991).

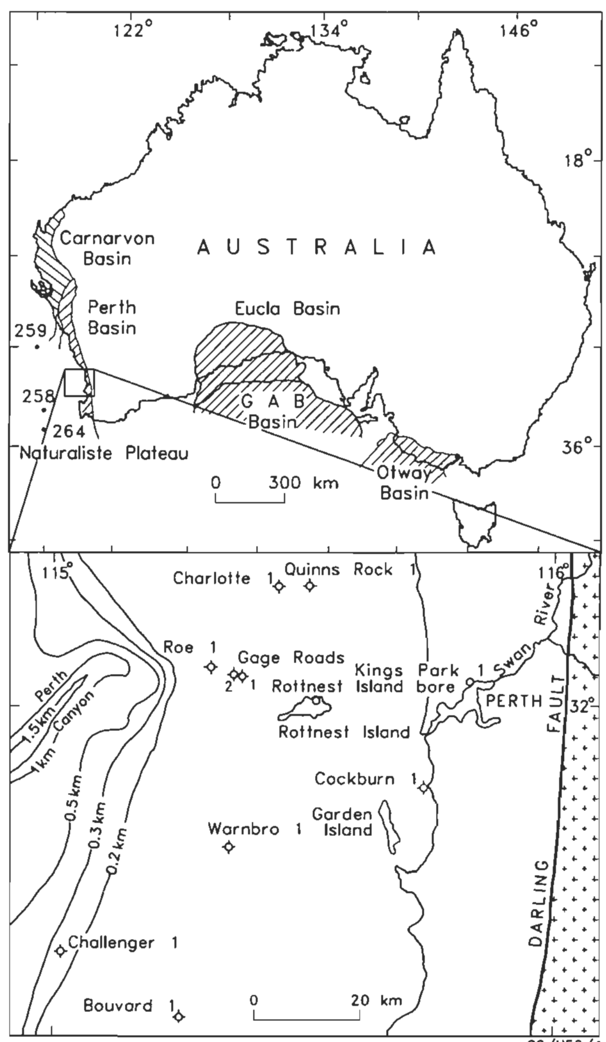

Figure 1. South Perth Basin, Western Australia, showing location of Challenger No. 1 well and other relevant localities.

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[2] Shafik (1991) used the name 'Fremantle Canyon' instead, following Marshall & others (1989) and Quilty & others (in press), but the Hydrographer of the Royal Australian Navy has informed BMR that the name 'Perth Canyon' has precedence.

The aim of this study is to document the calcareous nannofossil assemblages of the section above the 780-m level in Challenger No. 1 in order to: (1) test the assertion of the presence of an Oligocene section in the well; (2) date the type section of the Challenger Formation; and (3) elucidate and attempt to correlate the Upper Cretaceous–lower Tertiary stratigraphy in the well, below the Challenger Formation, with that which was recorded recently in the Perth Canyon and elsewhere in the Perth Basin (see Shafik, 1990a, 1991).

Nannofossil biostratigraphy

Forty-two samples of ditch cuttings, representing a continuous section between 460 and 780 m in Challenger No. 1, were examined for nannofossils. This enabled the establishment of a more detailed biostratigraphy than that previously outlined by Quilty (1978), who used 11 samples of ditch cuttings taken at 15-m intervals. Because I was examining cuttings, biostratigraphic events represented by the highest occurrence of key species are given more credence than those based on lowest occurrence, except for those of short-ranged species. In discussing the foraminiferal biostratigraphy of Challenger No. 1, Quilty (1978) recognised four disconformity-bounded units. Approximations of these units are discussed below, and the results are summarised in Figure 2.

Interval 460–530 m: undifferentiated Neogene and Oligocene carbonates

Quilty (1978) identified two lithological subunits in this interval. The upper subunit (465–498 m) is white chalk with minor pale brown chert and traces of glauconite, and the lower subunit (498–530 m) is white, friable calcarenite with abundant pale pink chert.

Assemblages are poorly preserved: effects of recrystallisation are evident, and the few specimens of *Discoaster* encountered are mostly overgrown with secondary calcite. The younger elements identified among these assemblages include *Calcidiscus leptoporus*, *C. macintyrei*, *Discoaster brouweri*, *D. exilis*, *D. variabilis*, *Helicosphaera kamptneri*, and *Reticulofenestra pseudoumbilicus* (Fig. 3). These elements collectively suggest a Middle Miocene to Early Pliocene age for the upper part of the interval (460–500 m). Quilty (1978) assigned the interval 465–530 m a Late Miocene age.

The assemblage from the base of the interval (sample 520–530 m) is similar to that from the uppermost part of the underlying type section of the Challenger Formation (sample 530–540 m). It includes *Braarudosphaera bigelowii*, *Chiasmolithus altus*, *Coccolithus pelagicus*, *Coronocyclus nitescens*, *Cyclicargolithus abisectus*, *C. floridanus*, *Helicosphaera compacta*, *H. euphratis*, *H. recta*, *Sphenolithus moriformis*, *S. predistentus*, *Reticulofenestra scissura*, and *Zygrhablithus bijugatus crassus*. The age is Oligocene owing to the presence of *S. predistentus*, *R. scissura*, *R. scrippsae*, *H. recta*, and *Z. bijugatus*, and the absence of the Eocene index species *Discoaster barbadiensis* and *D. saipanensis*; the latter two species occur abundantly in most samples from the underlying Challenger Formation up to the 540-m level. The key species *R. scissura*, *H. recta*, and *Z. bijugatus* disappear at 500 m (Figs. 2 and 3). Quilty (1978) regarded the lithological change at 498 m as a contact separating two lithological subunits.

The extinctions of *Reticulofenestra scissura*, *Helicosphaera recta*, and *Zygrhablithus bijugatus* have been used elsewhere to indicate levels at or near the top of the Oligocene (e.g., Edwards, 1971; Bukry, 1973), and the interval between 500 and 540 m is, therefore, Oligocene in age. This age assignment is supported by the occurrence of the species *Cyclicargolithus abisectus*, *Discoaster deflandrei*, and *Helicosphaera euphratis*, which were encountered occasionally in the interval (Fig. 3).

Cyclicargolithus abisectus, *Helicosphaera euphratis*, and *H. recta* co-occur elsewhere in sediments of middle to Late Oligocene age (see, for example, the distribution chart *in* Müller, 1979), and their presence in sample 520–530 suggests a maximum age of middle Oligocene.

The assemblages recovered from between 500 and 540 m in Challenger No. 1 lack the important low-latitude species *Sphenolithus distentus* and *S.* sp. aff. *S. ciperoensis*, which are prominent in a mid-Oligocene assemblage from the Perth Canyon (Shafik, 1991). The presence of these two species in the Perth Canyon section, and their absence from the Challenger No. 1 material, is accounted for by a significant change (or changes) in surface-water temperature during the (middle) Oligocene in the Perth Basin.

Interval 530–597 m: type section of the Challenger Formation

Quilty (1978) identified two lithological subunits in this interval. The upper subunit (530–567 m) consists of white chalk, changing to coarser friable bryozoan–echinoderm calcarenite towards the base, with abundant chert and traces of glauconite. The lower subunit (567–597 m) consists of white friable chalk and bryozoan–echinoderm calcarenite with dark grey chert.

Six samples were examined from the type section of the Challenger Formation. The assemblage from the top sample (530–540 m) is similar to that from the base of the overlying Oligocene unit, but lacks *Chiasmolithus altus* and *Helicosphaera recta* (Fig. 3). It is much less diversified than that from sample 540–550 m, which includes *Braarudosphaera bigelowii*, *Blackites vitreus*, *Chiasmolithus altus*, *C. oamaruensis*, *Clausicoccus cribellum*, *Coccolithus eopelagicus*, *C. formosus*, *Cyclicargolithus floridanus*, *Discoaster barbadiensis*, *D. deflandrei*, *D. saipanensis*, *D. tanii nodifer*, *Helicosphaera compacta*, *H. reticulata*, *H. seminulum*, *Isthmolithus recurvus*, *Lanternithus minutus*, *Pedinocyclus larvalis*, *Pontosphaera plana*, *Reticulofenestra hampdenensis*, *R. scissura*, *R. umbilicus*, *Sphenolithus predistentus*, and *Zygrhablithus bijugatus bijugatus*.

The association of *Chiasmolithus oamaruensis*, *Isthmolithus recurvus*, *Discoaster barbadiensis*, *and D. saipanensis* in the assemblage from sample 540–550 m indicates a Late Eocene age and a correlation with the foraminiferal late P16 Zone (Shafik, 1981). In the same assemblage, indicators of surface-water temperatures collectively suggest a mid-latitude water mass: the cool-water *C. oamaruensis* and *I. recurvus* are common, and are associated with the less frequently occurring warm-water *Helicosphaera reticulata*, *Sphenolithus predistentus*, *D. barbadiensis*, and *D. saipanensis*.

At the 540-m level, *Discoaster barbadiensis*, *D. saipanensis*, *Coccolithus formosus*, *Helicosphaera reticulata*, *Isthmolithus recurvus*, *Lanternithus minutus*, and *Reticulofenestra hampdenensis* disappear, marking the top of the Eocene (Fig. 3). Furthermore, these combined disappearances suggest either a condensed sequence at the base of the Oligocene, or a disconformity (missing lowermost Oligocene sediments) immediately above the 540-m level. The species *Coccolithus formosus*, which crosses the Eocene/Oligocene boundary and disappears within the Early Oligocene (e.g., Martini, 1971), reappears — together with *Reticulofenestra hampdenensis* — in sample 510–520 m (Fig. 3). I interpret these reappearances as a result of minor reworking within the Oligocene section.

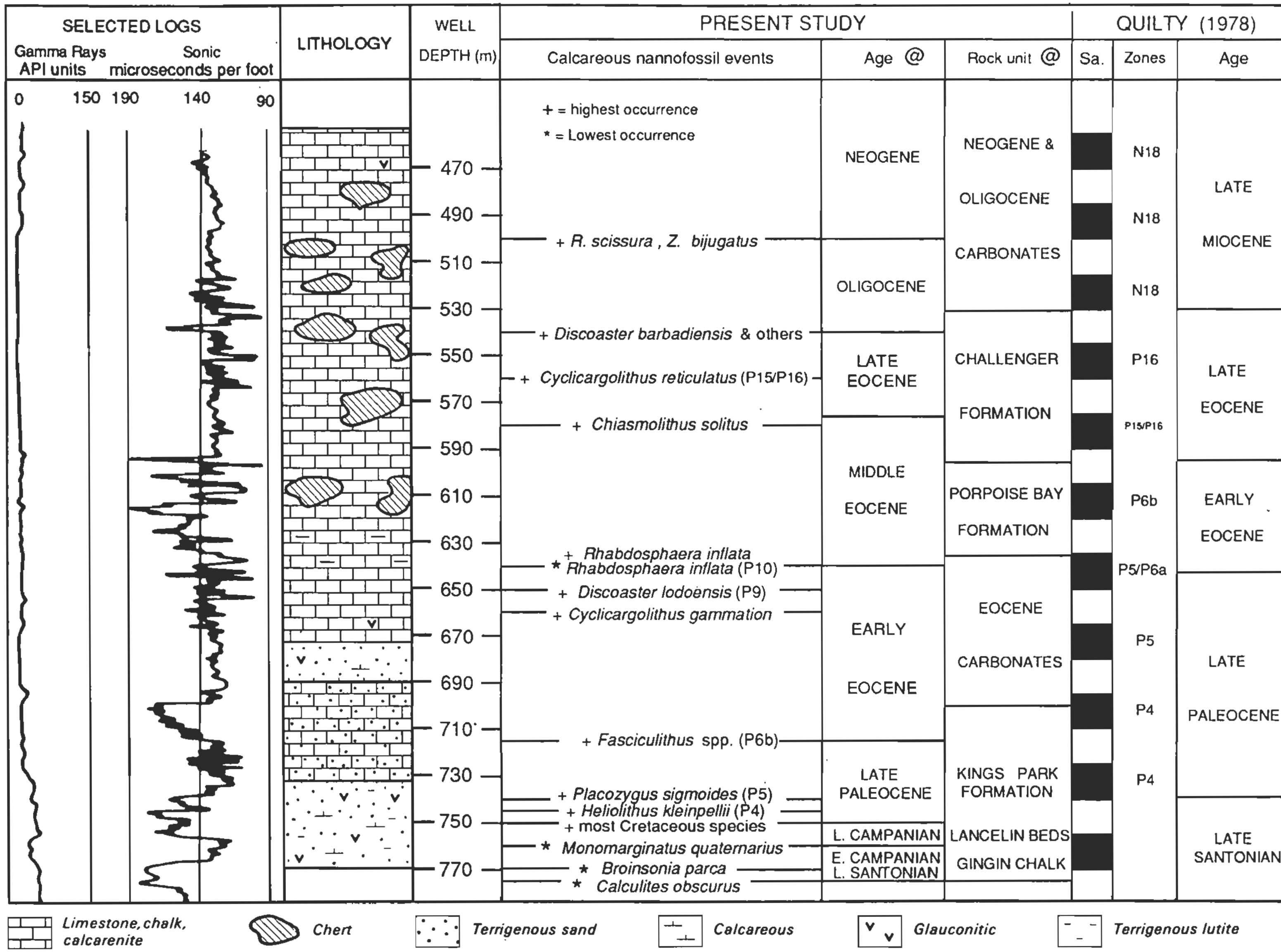

Figure 2. Summary of nannostratigraphy, lithostratigraphy, and previously determined foraminiferal (P and N) zones of Challenger No. 1.
@ most boundaries in these columns are tentatively placed, because the samples on which they are based are cuttings; Sa. sample.

SAMPLE LEVEL (m)	Calcidiscus leptoporus	Calcidiscus macintyrei	Campylosphaera dela	Campylosphaera eodela	Chiasmolithus altus	Chiasmolithus bidens	Chiasmolithus eograndis	Chiasmolithus grandis	Chiasmolithus oamaruensis	Chiasmolithus solitus	Chiphragmalithus calathus	Coccolithus formosus	Coccolithus robustus	Coronocyclus nitescens	Cyclicargolithus abisectus	Cyclicargolithus floridanus	Cyclicargolithus gammation	Cyclicargolithus reticulatus	Discoaster barbadiensis	Discoaster brouweri	Discoaster deflandrei	Discoaster lodoensis	Discoaster multiradiatus	Discoaster saipanensis	Discoaster sublodoensis	Discoaster tanii nodifer	Discoaster variabilis (group)	Discoasteroides kuepperi	Ellipsolithus macellus
460-470	X	X												X						X							X		
470-480	X	X																		X							X		
480-490	X																										X		
490-500	X	X												X	?	X				X									
500-510	X				X									X	X	X					X								
510-520	X	X			?							X		X						X	X								
520-530					X									X	X	X													
530-540	X													X		X													
540-550					X				X			X				X			X		X			?		X			
550-560	X	X							X			X								X									
560-570									X			X						X	X							X			
570-580									X			X						X	X					X					
580-590									X	X		X		X		X		X	X	X				X		X			
590-600					X				X	X		X						X			X			X		X			
600-605					X	?		?	X	X		X			?	X													
605-610					X			X	X	X		X							X		X			X					
610-615						?			X	X		X												X					
615-620						?						X						X											
620-625										X		X				X													
625-630										X		X				X			X										
630-635										X		X																	
635-640								X		X								?	X						X				
640-645										X	X	X				X			X						X			?	
645-650												X						X				?		X					
650-655			X					X		X	X	X						X	X			X		X	X			?	
655-660			X					X		X	X	X							X			X			X			?	
660-670										X		X					X		X			X		X	X				
670-680			X							X		X					X	?	X			X							
680-690						X	X			X		X					X		X			X	X						
690-700			X				X			X		X					X		X			X							
700-710				X			X	X		X							X		X				X						
710-715				X			X			?		X					X					X	X						
715-720				X		X																	X						
720-725				X		X					X	X					X					X	X						
725-730						X	?					X							X				X						X
730-735						X																	X						X
735-740						X	X									X							X						X
740-745						X																							
745-750						X							X										X						X

SAMPLE LEVEL (m)	Fasciculithus involutus	Fasciculithus tympaniformis	Heliolithus kleinpellii	Helicosphaera compacta	Helicosphaera euphratis	Helicosphaera kamptneri	Helicosphaera recta	Helicosphaera reticulata	Isthmolithus recurvus	Lanternithus minutus	Micrantholithus procerus	Nannotetrina cristata	Neochiastozygus perfectus	Neococcolithes dubius	Pemma basquensis	Placozygus sigmoides	Pseudotriquetrorhabdulus inversus	Reticulofenestra hampdenensis	Reticulofenestra pseudoumbilicus	Reticulofenestra scissura	Reticulofenestra umbilicus	Rhabdolithus gladius	Rhabdosphaera inflata	Sphenolithus predistentus	Sphenolithus radians	Toweius eminens	Toweius pertusus	Zygodiscus herlyii	Zygrhablithus bijugatus	NANNOFOSSIL EVENTS (┐ Highest occurr. ┘ Lowest occurr.)	AGE
460-470						X													X												
470-480						X													X												PLIOCENE & MIOCENE
480-490					X	X													X												
490-500					X	X													?	?											
500-510					X	X	X													X									X	R. scissura	
510-520						X	?											X	?	X	?									H. recta &	
520-530				X	X	X	X													X				X					X	Z. bijugatus	OLIGOCENE
530-540					X															X				X					X		
540-550				X				X	X	X								X		X	X			X					X	D. barbadiensis & others	
550-560				X		X				X								X		X	X								X	C. reticulatus	LATE EOCENE
560-570				X						X										X	X								X		
570-580				X					X	X										X	X			X					X	C. solitus	
580-590				X				X	X	X					X			X		X	X								X		
590-600				X				X	X	X				X	X			X		X	X								X		
600-605				X										X	X					X	X			X					X		
605-610									X	X				X	X					X	X	X							X		
610-615															X					X	X								X		MIDDLE EOCENE
615-620															X														X		
620-625										X										X	X								X		
625-630											X			X						X	X	X			X						
630-635																				X											
635-640				X						X	X			X	X								X						X	R. inflata	
640-645										X		X		X				X							X				X		
645-650																				X	X								X		
650-655										X	X			X			X								X				X	D. lodoensis	
655-660										X				X			X								X				X	C. gammation	
660-670																		X											X		
670-680										X																			X		EARLY EOCENE
680-690														X																	
690-700														X						X									X		
700-710														X																	
710-715																											X		X		
715-720	X												X													X	X	X		Fasciculithus spp	
720-725	X	X																									X	X	X		
725-730	X	X											X								X						X	X			LATE PALEOCENE
730-735	X	X																									X	X			
735-740	X																									X		X			
740-745		X											X			X				X							X	X	X	P. sigmoides	
745-750			X										X			X										X	X			H. kleinpellii	

Other important biostratigraphic events identified within the Challenger Formation (Fig. 2) are the highest occurrences of the key species *Cyclicargolithus reticulatus* (in sample 560–570 m, probably coinciding with the lithological change at 567 m) and *Chiasmolithus solitus* (in sample 580–590 m). In continuous sections, the highest occurrence of *C. reticulatus* is Late Eocene (Shafik, 1981), and that of *C. solitus* is Middle Eocene (Martini, 1971).

The assemblage from near the base of the formation (sample 580–590 m) includes *Braarudosphaera bigelowii, Blackites spinulus, B. vitreus, Chiasmolithus oamaruensis, C. solitus, Clausicoccus cribellum, Coccolithus eopelagicus, C. formosus, Coronocyclus nitescens, Cyclicargolithus floridanus, C. reticulatus, Discoaster barbadiensis, D. brouweri, D. saipanensis, D. tanii nodifer, Helicosphaera compacta, H. lophota, H. reticulata, H. seminulum, Holodiscolithus solidus, Isthmolithus recurvus, Lanternithus minutus, Lithostromation perdurum, Markalius inversus, Micrantholithus flos, Orthozygus aureus, Pedinocyclus larvalis, Pemma basquensis, P. rotundum, Pontosphaera multipora, Reticulofenestra hampdenensis, R. scissura, R. umbilicus, Sphenolithus stellatus, Syracosphaera labrosa, Transversopontis pulcheroides*, and *Zygrhablithus bijugatus crassus*.

The presence of *Discoaster saipanensis* and *Chiasmolithus solitus* in the assemblage from near the base of the type Challenger Formation indicates a Middle Eocene age. The younger species in the same assemblage, such as *Discoaster brouweri, Coronocyclus nitescens, Isthmolithus recurvus, Chiasmolithus oamaruensis*, and *Reticulofenestra scissura*, are probably a result of caving or downhole contamination.

Discussion. The nannofossil data presented above indicate that a substantial part of the type section of the Challenger Formation (540 to 575 m) is Late Eocene, confirming — in broad terms — the results of Quilty (1978). The same data also indicate that the uppermost part of the type Challenger Formation (530–540 m) is Oligocene, and its lower part (575–597 m) is Middle Eocene, agreeing well with previous views on the age of the formation (Shafik, 1991).

A disconformity or (more likely) a condensed section is suspected within the lower part of the type Challenger Formation, because it apparently lacks Middle Eocene nannofossil assemblages containing the key species *Cyclicargolithus reticulatus* in association with a large number of reworked Cretaceous species; such an association occurs widely near the level of extinction of *Chiasmolithus solitus* on the Australian western and southern margins (Shafik, 1985), including two locations in the Perth Basin (Shafik, 1978, 1991).

Cockbain & Hocking (1989) thought that the Challenger Formation in Challenger No. 1 rested disconformably on the Upper Paleocene to Lower Eocene Kings Park Formation, but the new nannofossil evidence presented below shows that the formation overlies much younger Middle and Lower Eocene sediments. As discussed below, the Middle Eocene sediments immediately beneath the Challenger Formation (Fig. 2) are probably equivalents of the basal part of the type Porpoise Bay Formation in Rottnest Island bore (Fig. 1), as defined by Cockbain & Hocking (1989).

Lithologically, the base of the type Challenger Formation is not distinguishable from the underlying Middle Eocene carbonates, although this base is clearly marked on the sonic and gamma logs (Fig. 2).

Interval 597–750 m: Middle Eocene–Upper Paleocene carbonates

Quilty (1978) identified three lithological subunits in the interval 597–740 m, but each of them is internally variable — especially the two subunits below 678 m.

The interval 597–750 m is bracketed by the Middle Eocene datum of highest occurrence of *Chiasmolithus solitus* (within the lower part of the overlying Challenger Formation) and the extinction level of most Cretaceous species, at 750 m (immediately below the base of the Paleocene). Biostratigraphic events identified within the interval (Fig. 2) include the up-sequence appearance of the short-ranged *Rhabdosphaera inflata* (at 640 m), and the up-sequence disappearance of species of *Fasciculithus* (at 715 m). The lowest-occurrence datum of *R. inflata* has been used elsewhere to indicate the Middle/Early Eocene boundary (Bukry, 1973), and the highest-occurrence datum of species of *Fasciculithus* has been used to approximate the base of the Eocene in the Perth Canyon succession (Shafik, 1991).

These two events are used to recognise three units within the interval 597–750 m, in the same way as they were used in the Perth Canyon succession (Shafik, 1991). The oldest unit, with the highest occurrence of *Fasciculithus* spp. near its top, correlates with the Kings Park Formation, which is known both onshore and offshore (including in the Perth Canyon). The overlying Eocene section, below the 635-m level, comprises thin Middle Eocene (with *Rhabdosphaera inflata*) and thick Lower Eocene segments. Coeval (Lower and Middle Eocene) beds have been discovered recently in the Perth Canyon (Shafik, 1991).

It is the Middle Eocene section (between 597 and 635 m), immediately underlying the type Challenger Formation, which is difficult to correlate with known stratigraphic successions in the basin, but I suggest that it is a partial equivalent of the type Porpoise Bay Formation. The difficulty reflects in part the lack of significant and reliable biostratigraphic events in the section 597–635 m (Fig. 2); biostratigraphic resolution in Challenger No. 1 is hampered by possible downhole contamination in the ditch cuttings, and most up-sequence appearances are deemed unusable. The difficulty also reflects the uncertainty of the precise age of the base of the type Porpoise Bay Formation (and its upper part); the age of its lower and middle parts is Middle Eocene, from nannofossil and foraminiferal assemblages (Shafik, 1978; Quilty, 1978).

Partial equivalent of the Porpoise Bay Formation (597–635 m). This section is white chalk with chert and traces of glauconite, grading into coarse, compact calcarenite with abundant chert below 615 m. It lacks any significant and reliable nannofossil biostratigraphic event, and its broad age of Middle Eocene (Fig. 2) can be only tentatively narrowed. *Rhabdolithus gladius*, a short-ranged species (confined to the mid-Middle Eocene NP15 Zone according to Martini, 1971), was encountered in two samples (605–610 m and 625–630 m) within this section (Fig. 3), suggesting a maximum age of mid-Middle Eocene and a correlation with the foraminiferal Zone P11 (according to data *in* Martini, 1971). This species has been recorded from near the base of the type section of the Porpoise Bay Formation in Rottnest Island bore (Shafik, 1978). Therefore, a possible correlation exists between the sediments underlying the type Challenger Formation and the basal part of the type Porpoise Bay Formation.

The Middle Eocene nannofossil assemblages from the middle part of the type section of the Porpoise Bay Formation include

Figure 3. Distribution of selected Cainozoic calcareous nannofossil species in cuttings from Challenger No. 1.

the key species *Cyclicargolithus reticulatus*, and correlate with the foraminiferal Zone P12 (Shafik, 1978); coeval assemblages containing *C. reticulatus* have been recorded from the Perth Canyon (Shafik, 1991). *C. reticulatus* is present at one level at least in the section 597–630 (Fig. 3), perhaps as a result of downhole contamination.

The assemblages with *Cyclicargolithus reticulatus* from the middle part of the type Porpoise Bay Formation and the Perth Canyon succession include large numbers of reworked Late Cretaceous calcareous nannofossil species, (Shafik, 1978, 1991). By contrast, the slightly older Middle Eocene assemblages from near the base of the type Porpoise Bay Formation (with the key species *Rhabdolithus gladius* and *Chiasmolithus solitus*) contain very few reworked Late Cretaceous nannofossils (Shafik, 1978). The apparent absence of Late Cretaceous nannofossils from the section 597–630 m in Challenger No. 1, together with the presence of *R. gladius* and *C. solitus*, strengthens further the correlation with the basal part of the type Porpoise Bay Formation.

Discussion. The stratigraphic relationship between the Porpoise Bay and Challenger Formations has never been established: the Porpoise Bay Formation, containing Middle Eocene assemblages, was interpreted to be older than the Challenger Formation, which was thought to be Late Eocene. My nannofossil biostratigraphic study of the Challenger No. 1 section — having shown that the lower part of the Challenger Formation is Middle Eocene — indicates that the two formations are probably partly coeval. The well dated parts of the type Porpoise Bay Formation (containing Middle Eocene assemblages with the key species *Cyclicargolithus reticulatus* and *Chiasmolithus grandis* without *C. solitus*; Shafik, 1978) fall within the suspected condensed section in the lower part of the type Challenger Formation. Indeed, the thick type section of the Porpoise Bay Formation (consisting of 382 m of brown calcareous shale and siltstone; Cockbain & Hocking, 1989) probably represents a more terrigenous facies of part (or less likely most) of the type Challenger Formation.

The key species *Chiasmolithus grandis* consistently ranges through the Eocene of Challenger No. 1 up to sample 635–640 m, and reappears briefly higher (sample 605–610 m). Elsewhere in Australia, this species ranges to the base of the Upper Eocene. It has been recorded, co-occurring with Late Eocene *Chiasmolithus oamaruensis*, in a core sample from the Lacepede Formation in the western Otway Basin (Shafik, 1983), and in association with late Middle Eocene nannofossils in dredges from the Great Australian Bight (Shafik, 1990b). The geographic distribution of *C. grandis* suggests that it disappeared earlier at higher latitudes or in cooler-water regimes. For example, this species persists up to the basal Upper Eocene (co-occurring with *C. oamaruensis*) at DSDP site 214, in the northern Indian Ocean (Shafik, 1983), and at DSDP site 360, south of Cape Town in the southeastern Atlantic Ocean (Bukry, 1978), but disappears much earlier, near the base of the Middle Eocene, in New Zealand (Edwards, 1971) and in the South Campbell Plateau (Edwards & Perch–Nielsen, 1975).

Unnamed Lower–Middle Eocene carbonates (635–700 m). The lithology of the thick section between equivalents of the Porpoise Bay and Kings Park Formations in Challenger No. 1 is variable, although dominantly carbonates. The upper part of the section (635–678 m) consists of compact calcarenite, sporadic limestone below 655 m, and some quartz sand at 660–670 m. The middle part is Quilty's 'subunit 678–694 m', which was described as medium to coarse quartz sandstone with varying amounts of bryozoan calcarenite locally recrystallised to compact limestone. The lower part (below 694 m) consists of chalk, grading into marl and predominating over quartz sand, with sporadic chert.

The key species *Rhabdosphaera inflata*, suggestive of an early Middle Eocene age, was encountered in a single sample (635–640 m) at the top of the section. Associated species in the same sample include *Blackites amplus, Braarudosphaera bigelowii, Chiasmolithus grandis, C. solitus, Coccolithus eopelagicus, C. pelagicus, ?Cyclicargolithus reticulatus, Discoaster barbadiensis, D. sublodoensis, Helicosphaera compacta, H. seminulum, Lanternithus minutus, Micrantholithus procerus, Neococcolithes dubius, Pemma basquensis, P. rotundum, Reticulofenestra samodurovii*, (reworked) *Tranolithus exiguus, Transversopontis fimbriatus, T. pulcher*, and *Zygrhablithus bijugatus crassus*. This assemblage is assignable to the early Middle Eocene *Rhabdosphaera inflata* Subzone of Bukry (1973), or the CP12b Subzone of Okada & Bukry (1980), on account of the existence of *Discoaster sublodoensis* and *Rhabdosphaera inflata*. A correlation with the foraminiferal Zone P10 is possible.

Three assemblages from the underlying section are listed below:

- Sample 640–645 m includes *Braarudosphaera bigelowii, Chiasmolithus solitus, Chiphragmalithus calathus, Clausicoccus cribellum, Coccolithus formosus, Cyclicargolithus floridanus, Daktylethra* sp., *Discoaster barbadiensis, D. sublodoensis, ?Discoasteroides kuepperi, Helicosphaera seminulum, Lanternithus minutus, Micrantholithus* spp., *Nannotetrina cristata, Neococcolithes dubius, Pemma rotundum, Pontosphaera multipora, Reticulofenestra hampdenensis, Sphenolithus radians, Transversopontis pulcher*, and *Zygrhablithus bijugatus bijugatus*.

- Sample 655–660 m contains short *Blackites spinulus, Calcidiscus protoannulus, Campylosphaera dela, Chiasmolithus grandis, C. solitus, Chiphragmalithus calathus, Coccolithus eopelagicus, C. formosus, Discoaster barbadiensis, D. lodoensis, D. saipanensis, D. sublodoensis, D. sublodoensis/D. saipanensis, ?Discoasteroides kuepperi, Helicosphaera lophota, Lanternithus minutus, Micrantholithus* spp., *Neococcolithes dubius, Pemma rotundum, Pontosphaera ocellata, P. pectinata, Pseudotriquetrorhabdulus inversus, Sphenolithus radians, Transversopontis* spp., *Zygrhablithus bijugatus bijugatus*, and *Zygrhablithus bijugatus crassus*.

- Sample 690–700 m includes *Braarudosphaera bigelowii, Campylosphaera dela, Chiasmolithus solitus, Coccolithus formosus, Cyclicargolithus gammation, Discoaster barbadiensis, D. lodoensis, Neococcolithes dubius, N. protenus, Pontosphaera pectinata, Reticulofenestra scissura*, and *Transversopontis* spp.; *R. scissura* is considered to be displaced from higher levels.

The distribution of *Discoaster lodoensis, Cyclicargolithus gammation, Discoaster sublodoensis*, and *Chiasmolithus eograndis* (Fig. 3) in these three assemblages is consistent with an Early Eocene age. Sample 690–700 represents the basal Eocene in Challenger No. 1.

Kings Park Formation equivalent (700–750 m). The up-sequence disappearance of *Fasciculithus* spp. at 715 m is a convenient event which can be used to separate the Kings Park Formation equivalent in Challenger No. 1 from the overlying Lower Eocene beds. However, both the gamma-ray and sonic logs suggest the 700-m level as a more realistic lithological boundary separating these two units, and it is adopted as such in Figure 2. The lithology of the section (700–750 m) is variable: chalk and quartz sand, and glauconitic sandstone near the base. The up-sequence disappearance of most Cretaceous species at 750 m conveniently separates the Upper Paleocene Kings Park Formation equivalent from the Upper Cretaceous Lancelin beds below.

In addition to several Eocene species (*Chiphragmalithus calathus, Coccolithus formosus, Cyclicargolithus gammation, Discoaster lodoensis*, and *Zygrhablithus bijugatus bijugatus*), a number of essentially Paleocene forms, including *Campylosphaera eodela, Campylosphaera* sp., *Chiasmolithus bidens, Discoaster multiradiatus, Fasciculithus involutus, F. tympaniformis, Micrantholithus* spp., *Neochiastozygus* spp., *Toweius pertusus*, and *Zygodiscus herlynii* are identified from 720–725 m in the upper part of the equivalent of the Kings Park Formation in Challenger No. 1; *Braarudosphaera bigelowii* is also noted. The Paleocene species indicate the latest Paleocene *Campylosphaera eodela* Subzone of Bukry (1973), or the CP8b Subzone of Okada & Bukry (1980).

The assemblage from the base of the Kings Park Formation equivalent in Challenger No. 1 (sample 745–750 m) includes several Late Cretaceous species (*Arkhangelskiella specillata, Cribrosphaerella ehrenbergii, Eiffellithus eximius, Gartnerago obliquum, Micula staurophora, Reinhardtites biperforatus, Tranolithus orionatus*, and *Watznaueria barnesae*) in association with *Braarudosphaera bigelowii, Chiasmolithus bidens, Coccolithus robustus, Discoaster multiradiatus, Ellipsolithus macellus, Heliolithus kleinpellii, Markalius apertus, Neochiastozygus perfectus, Placozygus sigmoides, Thoracosphaera operculata, Toweius eminens*, and *T. pertusus*. The co-occurrence of *Heliolithus kleinpellii* and *Placozygus sigmoides* suggests a position near the base of the range of the index species *Discoaster multiradiatus* (Varol, 1989), and an assignment to the Late Paleocene *Chiasmolithus bidens* Subzone of Bukry (1973), or CP8a Subzone of Okada & Bukry (1980).

Discussion. Levels above sample 745–750 m lack the Cretaceous component. Therefore, the base of the Tertiary in Challenger No. 1 could be placed immediately above sample 745–750 m. However, the occurrence of a large number of reworked Cretaceous nannofossils at the base of the Paleocene is not unusual on the Australian western margin (Shafik, unpublished data), and elements of the Tertiary component in sample 745–750 m — unlike those in the Cretaceous section below — are consistent with a Paleocene age. Admixtures of Paleocene, Eocene, and younger species are identified among the Cretaceous assemblages from the interval 750–780 m; these are considered to have resulted from downhole contamination by caving.

Interval 750–780 m: Lancelin beds and Gingin Chalk equivalents

This interval is a greyish green, richly glauconitic calcareous sandstone with rare *Inoceramus* prisms, and is interpreted as an equivalent of the Lancelin beds and Gingin Chalk (see below). The type Lancelin beds have been described as light grey marls, becoming slightly darker and glauconitic near the top, with fragments of *Inoceramus* throughout (Edgell, 1964). The Gingin Chalk (Glauert, 1910) in its type area is a unit of fine-grained chalks and marls sandwiched between two units of greensand (the Molecap and Poison Hill Greensands of Fairbridge, 1953). The Molecap Greensand, Gingin Chalk, and Poison Hill Greensand (arranged in ascending order) form a substantial part of the Coolyena Group of Cockbain & Playford (1973), but have been considered recently as members of the 'Lancelin Formation' by Davidson & Moncrieff (*in* Moncrieff, 1989); the concept of the 'Lancelin Formation' is not followed here, as it serves no useful purpose and mixes two distinctive units — namely the Gingin Chalk and the Lancelin beds.

Three samples were examined from the interval 750–780 m in Challenger No. 1. Their assemblages consist of abundant Late Cretaceous species in association with rare Tertiary (admixture of Paleocene, Eocene, and Oligocene) forms such as *Chiasmolithus edentulus, Coccolithus eopelagicus, Cyclicargolithus abisectus, Discoaster multiradiatus, Reticulofenestra scissura, Toweius eminens, Zygodiscus herlynii*, and *Zygrhablithus bijugatus crassus*. The Tertiary component decreases in number of species and specimens with depth, and is considered to have resulted from downhole contamination.

The Cretaceous component of the assemblage extracted from the highest sample (750–760 m) is similar to those which Shafik (1990a) recorded from the lower part (upper Campanian) of the Lancelin beds in onshore sections. This component includes *Ahmuellerella octoradiata, Arkhangelskiella specillata, Biscutum magnum, Broinsonia parca, Chiastozygus litterarius, Cretarhabdus conicus, Cribrosphaerella ehrenbergii, Eiffellithus eximius, E. turriseiffeli, Kamptnerius magnificus, Microrhabdulus decoratus, Micula concava, M. staurophora, Monomarginatus quaternarius, Prediscosphaera cretacea, Quadrum gothicum, Reinhardtites anthophorus, R. levis, Rhagodiscus reniformis, Tranolithus exiguus, Vekshinella elliptica, Watznaueria barnasae*, and *Zygodiscus bicrescenticus*.

Cretaceous elements of the assemblage from sample 760–770 m are similar to those from sample 750–760, but lack the key species *Biscutum magnum, Monomarginatus quaternarius*, and *Quadrum gothicum*. Instead, *Acuturris scotus, Biscutum coronum*, and *Lucianorhabdus cayeuxii* are present. *Broinsonia parca* is much smaller in this sample than in the one above it. These changes suggest that sample 760–770 m came from the top part (lower Campanian) of the Gingin Chalk equivalent (Shafik, 1990a).

In Challenger No. 1, either a condensed sequence or, more likely, a disconformity is suggested between the Gingin Chalk equivalent (sample 760–770 m) and the Lancelin beds equivalent (sample 750–760 m) by the apparent absence of mid-Campanian sediments. A similar disconformity occurs in onshore sections in the Perth Basin (Shafik, 1990a).

The assemblage from the lowest sample (770–780 m) in the Upper Cretaceous section of Challenger No. 1 includes *Acuturris scotus, Ahmuellerella octoradiata, Arkhangelskiella specillata, Broinsonia* sp. (similar to *B. parca* of Bukry, 1969, pl. 3, fig. 7), *B. dentata, Calculites obscurus, Chiastozygus litterarius, Corolithion exiguum, Cretarhabdus conicus, Cribrosphaerella ehrenbergii, Cylindralithus biarcus, Eiffellithus eximius, E. turriseiffeli, Gartnerago obliquum, Kamptnerius magnificus, Lucianorhabdus cayeuxii, Microrhabdulus decoratus, Micula concava, M. staurophora, Prediscosphaera cretacea, P. spinosa, Reinhardtites anthophorus, R. biperforatus, Tranolithus exiguus, Vekshinella elliptica, Watznaueria barnasae*, and *Zygodiscus bicrescenticus*. This assemblage is similar to those identified from outcrops of the upper Santonian Gingin Chalk in its type area (Shafik, 1990a).

Discussion. Quilty's (1978) assignment of a late Santonian age to the whole 740–770 m section was based on the foraminiferal assemblage in a single sample from its lower part (Fig. 2), and agrees with the nannofossil evidence presented above.

Sediments of Maastrichtian and Early Paleocene age seem to be missing at 750 m, indicating a major disconformity between the Cretaceous and Paleocene in Challenger No. 1. In the Perth

Canyon succession, the disconformity at the Cretaceous/Tertiary boundary is seemingly of much lesser magnitude, because of the occurrence of nannofossil assemblages indicative of late Maastrichtian and Early Paleocene ages (Shafik, 1991).

Discussion

The nannofossil biostratigraphic analysis outlined above indicates discontinuities at three levels within the Upper Cretaceous–Palaeogene section in Challenger No. 1; each of them probably corresponds to a major disconformity. They occur at the Eocene/Oligocene boundary within the upper part of the type Challenger Formation (540 m), at the Cretaceous/Tertiary boundary (750 m), and within the Campanian section between equivalents of the Lancelin beds and Gingin Chalk (760 m).

At the Eocene/Oligocene boundary, several key nannofossil species simultaneously disappear, suggesting a disconformity (missing lowermost Oligocene) and/or a condensed section. At the Cretaceous/Tertiary boundary, Maastrichtian and Lower Paleocene sediments (recorded in the Perth Canyon succession) are missing, suggesting a substantial disconformity. Within the Campanian section (750–770 m) a condensed section or a disconformity (missing mid-Campanian sediments) is suggested, similar to that onshore between the Gingin Chalk and the Lancelin beds (Shafik, 1990a); several key species, absent below 770 m, appear suddenly immediately above this level (at 760 m). These three interpreted major disconformities (or condensed sections) have distinct expressions on the sonic log (Fig. 2).

Middle Eocene assemblages containing the key species *Cyclicargolithus reticulatus*, and including a large number of reworked Cretaceous species, have been recorded from coeval levels in Rottnest Island bore and the Perth Canyon succession in the Perth Basin (Shafik, 1978, 1991), as well as in the Carnarvon Basin and basins on the Australian southern margin (Shafik, 1985). These widespread assemblages seem to be missing from the biostratigraphic sequence of Challenger No. 1, as no reworked Cretaceous species were identified in the Middle Eocene segment near the highest occurrence of *Chiasmolithus solitus*. A minor disconformity, or more likely a condensed section, is suspected in the lower part of the type Challenger Formation near the extinction level of the key species *Chiasmolithus solitus*.

The stratigraphy of the marine Upper Cretaceous–Palaeogene rock units in the south Perth Basin is summarised in Figure 4. Until recently, the Palaeogene sequence was poorly known. The recent discovery of Oligocene and Lower Eocene beds in the Perth Canyon (Shafik, 1991) and Challenger No. 1 (this study) has filled significant gaps in the stratigraphy of the basin. Marine Palaeogene sediments are limited to the Upper Paleocene Kings Park Formation in the onshore Perth Basin; age equivalents of this formation occur in offshore sections (e.g., Challenger No. 1), and in addition there are older Paleocene beds in the Perth Canyon succession (Shafik, 1991). Other Palaeogene rock units known in the Perth Basin are the offshore Porpoise Bay and Challenger Formations (Cockbain & Hocking, 1989).

Away from their type sections, the Kings Park, Porpoise Bay, and Challenger Formations seem to lose their lithostratigraphic identities in the more oceanic setting, for example, of the Perth Canyon. There they seem to overlap and merge into one large carbonate sequence (which includes Lower Paleocene levels as well) difficult to subdivide. Challenger No. 1 substantiates this conclusion to some extent, because the biostratigraphic bracket covering the larger part of the type Porpoise Bay Formation (which includes the extinction datum of *Chiasmolithus solitus*) coincides with the lower part of the type Challenger Formation.

Cockbain & Hocking's (1989) formal naming of the Porpoise Bay and Challenger Formations took into account age determinations obtained during the 1970s (Quilty, 1978), which were based on inadequately sampled material from two separate sections. The stratigraphic relationship between the Porpoise Bay and Challenger Formations was not known, except that the former was older and Middle Eocene; the age of the Challenger Formation was thought then to be Late Eocene. The present study has shown that the lower part of the Challenger Formation is Middle Eocene, and that the two formations are probably partly coeval. Indeed, the type Porpoise Bay Formation is probably a more terrigenous facies of part of the type Challenger Formation.

The Palaeogene marine stratigraphic succession in the Perth Basin is evidently more complete and more calcareous offshore. In the Perth Canyon, the Paleocene, Eocene, and Oligocene occur as a succession of carbonates that are difficult to differentiate lithostratigraphically from one another. In Challenger No. 1, the Paleocene and Eocene section, coeval with parts of the Perth Canyon succession, consists of carbonates with some terrigenous elements. Onshore, the Upper Paleocene–Lower Eocene Kings Park Formation is calcareous shale and siltstone in its type section below Perth.

This study stresses the contrast between the lithostratigraphic and biostratigraphic approaches in subdividing the offshore Palaeogene carbonates in the Perth Basin. In the Perth Canyon, it is probably impractical to subdivide the Palaeogene carbonates into mappable lithostratigraphic units. On the other hand, the several nannofossil events which are used to subdivide the Palaeogene carbonates of the canyon (Shafik, 1991), or of Challenger No. 1, can be identified elsewhere. The concept

AGE	ROCK UNIT	OCCURRENCE
OLIGOCENE	OLIGOCENE CARBONATES	Known only from the offshore, in the Perth Canyon and Challenger No. 1. Correlation between the Oligocene carbonates in the canyon and those in Challenger No. 1 has not been possible. Difficult to differentiate from overlying Miocene carbonates in Challenger No. 1 .
EOCENE late – middle	CHALLENGER FORMATION	Lower part of type section in Challenger No.1 probably equates with most of the type section of the Porpoise Bay Formation in Rottnest Island bore. Difficult to differentiate from other Eocene carbonates in the Perth Canyon.
		Away from their type sections, the two formations lose their lithostratigraphic identities.
EOCENE middle	PORPOISE BAY FORMATION	Hemipelagic unit from the offshore: type section in Rottnest Island bore. Age equivalents of different parts of it are identifiable in the carbonate facies of the Perth Canyon and Challenger No. 1.
EOCENE early	EOCENE CARBONATES	Known only from the offshore, in the Perth Canyon and Challenger No. 1 successions.
PALEOCENE	KINGS PARK FORMATION	Hemipelagic unit: type section underneath Perth. Age equivalents are present in the more calcareous facies offshore.
PALEOCENE	PALEOCENE CARBONATES	Lower Paleocene beds discovered recently in Perth Canyon. They are yet to be identified elsewhere.
LATE CRETACEOUS	BRETON MARL	Onshore in the Breton Bay and Lancelin areas; offshore in the Perth Canyon.
LATE CRETACEOUS	LANCELIN BEDS	Onshore in the Lancelin area including Breton Bay; offshore in the Challenger No. 1 succession.
LATE CRETACEOUS	GINGIN CHALK	Onshore at several localities; offshore in the Challenger No. 1 succession.

Figure 4. Late Cretaceous–Palaeogene stratigraphy of marine sedimentation in the south Perth Basin.

that the Challenger Formation in Challenger No. 1 is calcarenite, chalk, and chert (Cockbain & Hocking, 1989) is probably of limited use in studies of the Palaeogene carbonates of other offshore sections in the basin.

The Palaeogene sections at nearby DSDP sites (see Fig. 1 for location) are either seemingly missing (site 258) or largely reduced (sites 259 and 264), prominently lacking Oligocene sediments. Similarly, the Upper Cretaceous sections at the same sites are either barren or missing (site 259, in the Perth Abyssal Plain) or poorly represented. On the Naturaliste Plateau, the youngest Cretaceous is Santonian at site 258, and early Campanian at site 264. Sediments of late Campanian age, correlatable with the Lancelin beds equivalent in Challenger No. 1, have not been recorded at nearby DSDP sites.

Conclusions

Nannofossil dating of sediments in Challenger No. 1 has identified Oligocene beds overlying the type section of the Challenger Formation. This confirms the occurrence of marine Oligocene in the Perth Basin; the only other known such occurrence is the mid-Oligocene in the Perth Canyon.

The type Challenger Formation in Challenger No. 1 ranges in age from Middle Eocene to Oligocene, and is not just Late Eocene as previously thought. Its uppermost part (530–540 m) is Oligocene, its middle part (540–575 m) is Late Eocene, and its lower part (575–597 m) is Middle Eocene. The type Challenger Formation rests on Middle Eocene sediments — not the Upper Paleocene–Lower Eocene Kings Park Formation as previously reported.

The Middle Eocene sediments that underlie the Challenger Formation in Challenger No. 1 (between 597 and 635 m) are probably equivalent to the basal part of the type section of the Porpoise Bay Formation in the Rottnest Island bore. A significant overlap seemingly exists between the type sections of the Porpoise Bay and Challenger Formations; the type Porpoise Bay Formation is probably a more terrigenous facies of part of the type Challenger Formation.

In Challenger No. 1, a thick section (635–700 m) containing Early and Middle Eocene calcareous nannofossil assemblages extends the geographic limits of coeval beds recently discovered in the Perth Canyon succession.

Representatives of the Kings Park Formation, Lancelin beds, and Gingin Chalk are identified in Challenger No. 1 by their nannofossil assemblages.

Three major disconformities (or condensed sections) are identified from nannofossil evidence in the Challenger No. 1 section. These disconformities are at the Eocene/Oligocene boundary within the upper part of the type Challenger Formation; at the Cretaceous/Tertiary boundary between representatives of the Kings Park Formation and Lancelin beds; and within the Campanian section between representatives of the Lancelin beds and the Gingin Chalk. They have distinct expressions on the sonic log. Another disconformity, or more likely a condensed section, is suspected in the Middle Eocene part of the type Challenger Formation near the extinction level of *Chiasmolithus solitus*.

This and a previous study (Shafik, 1991) have demonstrated that subdividing offshore Palaeogene carbonate sections in the Perth Basin by biostratigraphic means is likely to be more successful than attempting to subdivide them lithostratigraphically (using units defined originally in hemipelagic sections). The Kings Park, Porpoise Bay, and Challenger Formations lose their lithostratigraphic identities away from their type sections; with the occurrence of Eocene beds (older than the type Porpoise Bay Formation) and Paleocene beds (older than the type Kings Park Formation) in the more oceanic sections in the Perth Canyon (see Shafik, 1991), the Palaeogene succession there becomes virtually one big carbonate unit. Subdividing this succession into rock units (which are unlikely to be mappable) seems pointless when microfossil biostratigraphy (e.g., using nannofossils) is likely to provide subdivisions that are identifiable elsewhere.

The Challenger No. 1 and Perth Canyon successions suggest that the Palaeogene in the Perth Basin is more complete and more calcareous offshore. However, at nearby DSDP sites, coeval Palaeogene successions are either seemingly missing (site 258, Perth Abyssal Plain) or largely reduced (sites 259 and 264 on the Naturaliste Plateau).

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List of calcareous nannofossil species mentioned in this paper

Cainozoic species

Blackites spinulus (Levin) Roth, 1970
Blackites vitreus (Deflandre) Shafik, 1981
Braarudosphaera bigelowii (Gran & Braarud) Deflandre, 1947
Calcidiscus leptoporus (Murray & Blackman) Loeblich & Tappan, 1978
Calcidiscus macintyrei (Bukry & Bramlette) Loeblich & Tappan, 1978
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978
Campylosphaera dela (Bramlette & Sullivan) Hay & Mohler, 1967
Campylosphaera eodela Bukry & Percival, 1971
Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus bidens (Bramlette & Sullivan) Hay & Mohler, 1967
Chiasmolithus edentulus van Hek & Prins, 1987
Chiasmolithus eograndis Perch-Nielsen, 1971
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus oamaruensis (Deflandre) Hay, Mohler, & Wade, 1966
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Chiphragmalithus calathus Bramlette & Sullivan, 1961
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Coccolithus robustus (Bramlette & Sullivan) Shafik, 1991
Coronocyclus nitescens (Kamptner) Bramlette & Wilcoxon, 1967
Cyclicargolithus abisectus (Müller) Wise, 1973
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Cyclicargolithus gammation (Bramlette & Sullivan) Shafik, 1990b
Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971
Discoaster barbadiensis Tan Sin Hok, 1929
Discoaster brouweri Tan Sin Hok, 1927 emend. Bramlette & Riedel, 1954
Discoaster deflandrei Bramlette & Riedel, 1964
Discoaster exilis Martini & Bramlette, 1963
Discoaster lodoensis Bramlette & Riedel, 1954
Discoaster multiradiatus Bramlette & Riedel, 1954
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster sublodoensis Bramlette & Sullivan, 1961
Discoaster tanii nodifer Bramlette & Riedel, 1954
Discoaster tanii tanii Bramlette & Riedel, 1954
Discoaster variabilis Martini & Riedel, 1963
Discoasteroides kuepperi Bramlette & Sullivan, 1961

Ellipsolithus macellus (Bramlette & Sullivan) Sullivan, 1964
Fasciculithus involutus Bramlette & Sullivan, 1961
Fasciculithus tympaniformis Hay & Mohler *in* Hay & others, 1967
Helicosphaera compacta Bramlette & Wilcoxon, 1967
Helicosphaera euphratis Haq, 1966
Helicosphaera kamptneri Hay & Mohler *in* Hay & others, 1967
Helicosphaera lophata Bramlette & Sullivan, 1961
Helicosphaera recta Haq, 1966
Helicosphaera reticulata Bramlette & Wilcoxon, 1967
Helicosphaera seminulum Bramlette & Sullivan, 1961
Heliolithus kleinpellii Sullivan, 1964
Holodiscolithus solidus (Deflandre) Roth, 1970
Isthmolithus recurvus Deflandre *in* Deflandre & Fert, 1954
Lanternithus minutus Stradner, 1962
Lithostromation perdurum Deflandre, 1942
Markalius apertus Perch-Nielsen, 1979
Markalius inversus (Deflandre) Bramlette & Martini, 1964
Micrantholithus altus Bybell & Gartner,1972
Micrantholithus attenuatus Bramlette & Sullivan, 1961
Micrantholithus crenulatus Bramlette & Sullivan, 1961
Micrantholithus entaster Bramlette & Sullivan, 1961
Micrantholithus flos Deflandre *in* Deflandre & Fert, 1954
Micrantholithus procerus Bukry & Percival, 1971
Micrantholithus vesper Deflandre *in* Deflandre & Fert, 1954
Nannotetrina cristata (Martini) Perch-Nielsen, 1971
Neochiastozygus chiastus (Bramlette & Sullivan) Perch-Nielsen, 1971
Neochiastozygus denticulatus (Perch-Nielsen) Perch-Nielsen, 1971
Neochiastozygus junctus (Bramlette & Sullivan) Perch-Nielsen, 1971
Neochiastozygus perfectus Perch-Nielsen, 1971
Neococcolithes dubius (Deflandre) Black, 1967
Neococcolithes protenus (Bramlette & Sullivan) Black, 1967
Orthozygus aureus (Stradner) Bramlette & Wilcoxon, 1967
Pedinocyclus larvalis (Bukry & Bramlette) Loeblich & Tappan, 1973
Pemma basquensis (Martini) Bldi-Beke, 1971
Pemma rotundum Klumpp, 1953
Placozygus sigmoides (Bramlette & Sullivan) Romein, 1979
Pontosphaera multipora (Kamptner) Roth, 1970
Pontosphaera ocellata (Bramlette & Sullivan) Perch-Nielsen, 1984
Pontosphaera pectinata (Bramlette & Sullivan) Sherwood, 1974
Pontosphaera plana (Bramlette & Sullivan) Haq, 1971
Pseudotriquetrorhabdulus inversus (Bukry & Bramlette) Wise *in* Wise & Constans, 1976
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra pseudoumbilicus (Gartner) Gartner, 1969
Reticulofenestra samodurovii (Hay, Mohler, & Wade) Roth, 1970
Reticulofenestra scissura Hay, Mohler, & Wade, 1966
Reticulofenestra scrippsae (Bukry & Percival) Shafik, 1981
Reticulofenestra umbilicus (Levin) Martini & Ritzkowski, 1968
Rhabdolithus gladius Locker, 1967
Rhabdosphaera inflata Bramlette & Sullivan, 1961
Sphenolithus ciperoensis Bramlette & Wilcoxon, 1967
Sphenolithus distentus (Martini) Bramlette & Wilcoxon, 1967
Sphenolithus moriformis (Brnnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus predistentus Bramlette & Wilcoxon, 1967
Sphenolithus radians Deflandre *in* Grass , 1952
Sphenolithus stellatus Gartner, 1971
Syracosphaera labrosa Bukry & Bramlette , 1969
Thoracosphaera operculata Bramlette & Martini, 1964
Toweius eminens (Bramlette & Sullivan) Perch-Nielsen, 1971
Toweius pertusus (Sullivan) Romein, 1979
Transversopontis fimbriatus (Bramlette & Sullivan) Locker, 1968
Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
Transversopontis pulcheroides (Sullivan) Bldi-Beke, 1971
Zygodiscus herlynii Sullivan, 1964
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959
Zygrhablithus bijugatus crassus Locker, 1967

Cretaceous species

Acuturris scotus Wind & Wise *in* Wise & Wind, 1977
Ahmuellerella octoradiata (Górka) Reinhardt, 1967
Arkhangelskiella specillata Vekshina, 1959
Biscutum coronum Wind & Wise *in* Wise & Wind, 1977
Biscutum magnum Wind & Wise *in* Wise & Wind, 1977
Broinsonia dentata Bukry, 1969
Broinsonia parca (Stradner) Bukry, 1969
Broinsonia sp. (similar to *B. parca* of Bukry, 1969, pl.3, fig.7)
Calculites obscurus (Deflandre) Prins & Sissingh *in* Sissingh, 1977
Chiastozygus litterarius (Górka) Manivit, 1971
Corollithion exiguum Stradner, 1961
Cretarhabdus conicus Bramlette & Martini, 1964
Cribrosphaerella ehrenbergii (Arkhangelsky) Deflandre *in* Deflandre & Fert, 1954
Cylindralithus biarcus Bukry, 1969
Eiffellithus eximius (Stover) Perch-Nielsen, 1968
Eiffellithus turriseiffeli (Deflandre) Reinhardt, 1965
Gartnergo obliquum (Stradner) Reinhardt, 1970
Kamptnerius magnificus Deflandre, 1959
Lucianorhabdus cayeuxii Deflandre, 1959
Microrhabdulus decoratus Deflandre, 1959
Micula concava (Stradner) Verbeek, 1976
Micula staurophora (Gardet) Stradner, 1963
Monomarginatus quaternarius Wind & Wise *in* Wise & Wind, 1977
Prediscosphaera cretacea (Arkhangelsky) Gartner, 1968
Prediscosphaera spinosa (Bramlette & Martini) Gartner, 1968
Quadrum gothicum (Deflandre) Prins & Perch-Nielsen *in* Manivit & others, 1977
Reinhardtites anthophorus (Deflandre) Perch-Nielsen, 1968
Reinhardtites biperforatus (Gartner) Shafik, 1979
Reinhardtites levis Prins & Sissingh *in* Sissingh, 1977
Rhagodiscus reniformis Perch-Nielsen, 1973
Tranolithus exiguus Stover, 1966
Tranolithus orionatus (Reinhardt) Reinhardt, 1966
Vekshinella elliptica Gartner, 1968
Watznaueria barnesae (Black) Perch-Nielsen, 1968
Zygodiscus bicrescenticus (Stover) Wind & Wise *in* Wise & Wind, 1977

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New K-Ar constraints on the onset of subsidence in the Canning Basin, Western Australia

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Structural mapping and reconnaissance K–Ar studies have helped to delineate and date the latest deformational stages (D4 and D5) in the King Leopold Orogen, to the north of the Canning Basin. The dates have been determined for schists selected from both contractional shear zones and from rocks metamorphosed to the lower greenschist facies during the final phase of basement deformation. These dates imply that the basement-deforming event started in the latest Precambrian to earliest Cambrian (ca 560 Ma), and that tectonism recurred in the latest Cambrian to earliest Ordovician (ca 500 Ma). The final contractional deformation is slightly older than the oldest-known sedimentary rocks in the basin (latest Tremadoc), and helps to define the time that basin subsidence started.

Introduction

The Fitzroy Trough (Fig. 1) is a deep, complex, composite set of sag basins and half-grabens formed during two or more extensional episodes in the Ordovician, in the Devonian, and possibly in the Permian (Drummond & others, 1991) in the northern part of the Canning Basin. Late deformation in the Jurassic produced open folds with east-northeasterly trending axes, many of which are truncated by steep faults established during earlier Palaeozoic rifting (Forman & Wales, 1981).

Results from BMR88.03 deep seismic profile in the Fitzroy Trough (located east of Blina well, see Fig. 1) suggest that the Phanerozoic sedimentary section might locally attain a thickness of 15–17 km. As the ages of sedimentary rocks in the deeper part of the trough are completely unknown, it has been speculated that Cambrian rocks, which occur in all the neighbouring Phanerozoic basins, might occur in the trough too. The oldest exposed rocks at the northeast margin of the Fitzroy Trough are the Early Ordovician (Arenig) Prices Creek Group and Carranya beds (McTavish & Legg, 1976). Outside the trough, sedimentary rocks as old as latest Tremadoc are known from Samphire Marsh 1 well in the southeast of the Canning Basin (McTavish & Legg, 1976). In order to both clarify the age of the last compressional event that affected the basement to the Fitzroy Trough, and provide maximum ages for the initiation of the Canning Basin, a program of age determination and structural mapping was instigated along the northern margin of the basin and within the adjacent orogen.

Pertinent structural relationships and previous isotopic dating

The structural development of the King Leopold Orogen and adjacent Oscar and Pillara inliers within the Lennard Shelf (Fig. 1) has been re-examined by Tyler & Griffin (1990). Their results, combined with those of our study, are summarised in Table 1. They also observed that within the Precipice Fold Belt the D4 axial-plane cleavage cuts through the unconformity separating the Kimberley Basin succession from overlying Late Proterozoic glacigene rocks, indicating that the D4 cleavage postdates these rocks. The Proterozoic contractional events listed in Table 1 were probably accompanied by transcurrent movements in the Halls Creek Zone (along the eastern edge of the Kimberley Basin), as discussed — for example — by Plumb & others (1985) and White & Muir (1989).

Also formed at a late stage were high-strain zones in the southern part of the King Leopold Orogen (e.g., Stony Creek Shear, Fig. 1), at the southern margin of the Oscar inlier (e.g., Spielers Shear), and (as patchy shearing) along the southern margin of the Pillara inlier (e.g., precursor to Virgin Hills Fault). These zones have similar trends, and contain intensely foliated schists composed of similar lower greenschist facies assemblages (e.g., epidote, chlorite, sericite, biotite). They show ubiquitous quartz veining and post-shearing annealing. Asymmetrical fabrics and southerly dips to these zones, which contain a well developed down-dip stretching lineation, suggest northward-directed thrusting.

In the Oscar inlier the relationship between the final movements in the high-strain zones and the regional cleavage formation is clearer (Fig. 2). Here, only one phase of folding and regional cleavage formation is recognised. This phase postdates the unconformity between the Oscar Range Group (Griffin & others, in press), inferred to be of Middle to Late Proterozoic age, and conglomeratic units which are arguably glacigene (Derrick & Gellatly, 1971) and hence of possibly Late Proterozoic age.

At the southern margin of the Oscar inlier, the south-dipping mylonitic Spielers Shear (Figs. 1, 2), like the other late-stage high-strain zones, shows fabric features that suggest limited northward-directed thrusting, consistent with the fold vergence sense in the overfold zone developed in footwall rocks to the north. However, the thrusting direction indicated by the oblique mylonitic stretching lineation (in the northeastern part of the inlier, Fig. 2) suggests dextral transpression along the Spielers Shear, whereas the shortening direction indicated by the overfold zone implies sinistral transpression on the main fault system during folding (Fig. 2). These relationships indicate two movements separated in time. We suggest that the D4 dextral strike-slip movement on the main fault system in the north of the inlier was followed, somewhat later, by northward-directed thrusting in the Spielers Shear. We refer to this later event as the Spielers event (D5). The dominant shear fabric produced by movement on the Spielers Shear is older than the Late Devonian Pillara Limestone of the Canning Basin succession, which overlaps these sheared rocks.

West of Louisa Downs homestead (Fig. 1), eastward-directed thrusts are assigned to D4, as they formed during overfolding and regional cleavage formation and cut Late Proterozoic glacigene units. Northeasterly and easterly faults such as the Glidden and Pinnacles Faults, which are apparently linked to the same thrust-fault system, also cut the Antrim Plateau Volcanics, which is considered to be of probable Early Cambrian age as it underlies Early? to Middle Cambrian units (e.g., Negri Subgroup) with apparent conformity (Mory & Beere, 1985; cf. Muir, 1980). Thus, some post-Early Cambrian movement, presumed to be D5, has occurred on this fault system. Basement faulting and shearing along a splay of the Pinnacles Fault shows gossanous quartz veining, suggesting a similar style and, possibly, a similar age of movement to the Spielers Shear.

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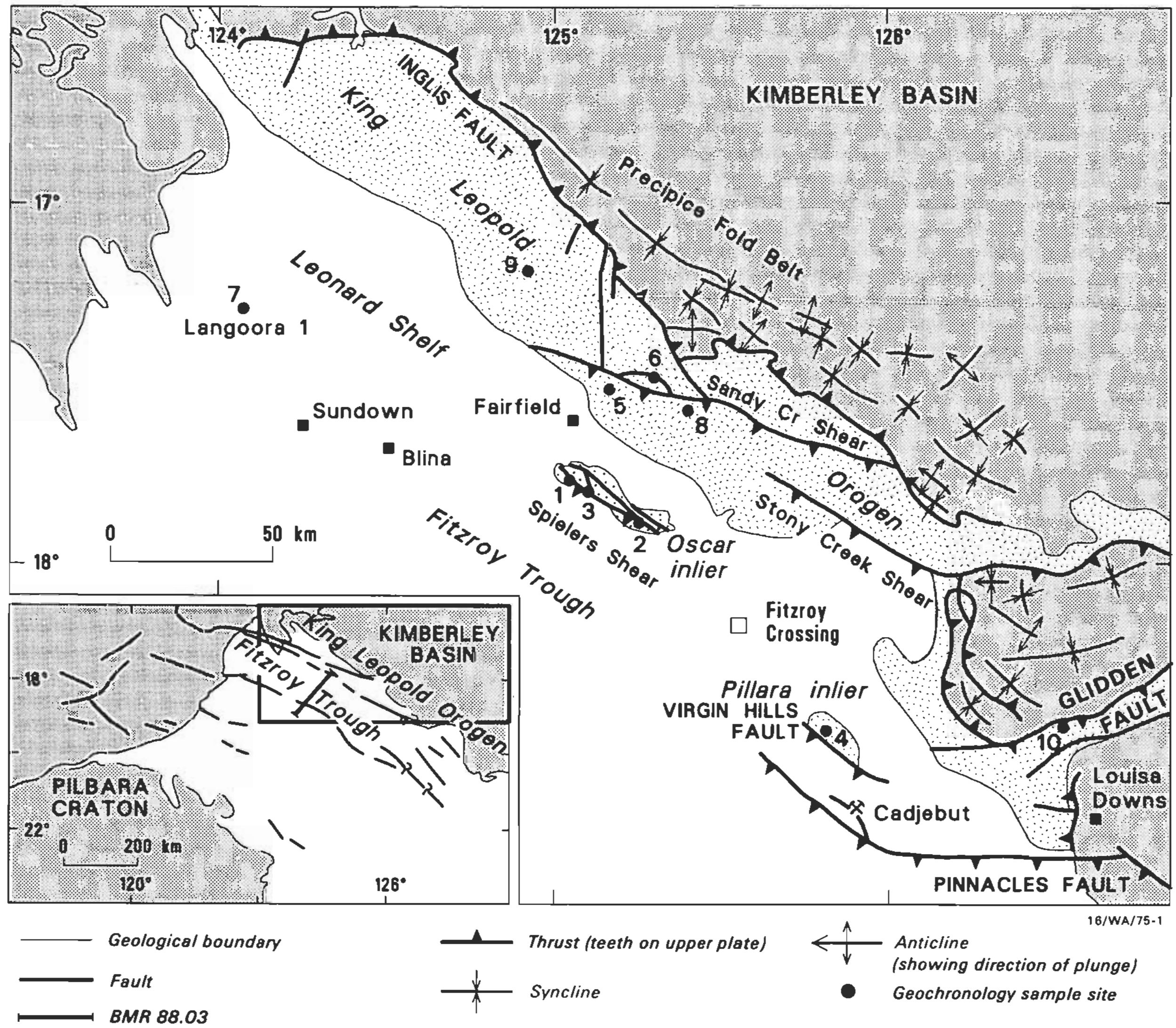

Figure 1. Main structural features at the northern margin of the Canning Basin during the latest Precambrian to latest Cambrian interval.

Before our work started, the consensus view was that the last major deformation to affect the King Leopold Orogen was about 600 Ma (Bennett & Gellatly, 1970). We consider that this date is too old for the King Leopold Orogen (D4), because of the poor precision of the isochrons and their high Sr^{87}/Sr^{86} initial ratios, which imply a lack of isotopic equilibrium in the dated samples. The cleavage formed during D4 is younger than the glacigene successions. The depositional age of an undeformed shale that postdates the youngest tillite interval in an area not affected by D4 is considered to approximate its Rb–Sr age of 639 ± 48 Ma (whole-rock isochron from shale in the Elvira Formation, Plumb, 1981; recalculated after Bofinger, 1967). A shale overprinted by the D4 regional cleavage in the Louisa Downs area has yielded a younger Rb–Sr age of 576 ± 80 Ma (Plumb, 1981); the cleavage and high initial Sr^{87}/Sr^{86} ratios of the shale suggest that this age reflects partial resetting during D4.

Table 1. Summary of tectonic events

*Event, **orogeny***	*Tectonic features*	*Estimated age (Ma)*
D5 Spielers	N- and E-directed shearing; sinistral transpression on faults[1,3]	500–510[1]
D4 Precipice[1,2,3]	Regional phyllonitic cleavage;	530–560[1]
King Leopold	SW-directed folding and limited thrusting[4,5]; local transpressional reactivation of D3 shears	
D3 Yampi[1,2,3]	Folding; N-directed shearing	≥1000[1]
	Pre-Kimberley Basin tilting	?1830[1,2]
D2 **Hooper**[5]	Folding that is pre-granite and post-felsic intrusives[2]	≤1850[6]
D1	Localised zones of high strain[2]	

[1] This paper; [2]Tyler & Griffin (1990); [3]Tyler & others (1991); [4]Griffin & Myers (1988); [5]Griffin & others (in press: i.e., D2 postdates Whitewater Volcanics); [6]Page & Hancock (1988).

Results of this study

We have determined K–Ar ages (Tables 2 and 3) from 10 different basement localities (Fig. 1) in the southern King Leopold Orogen and Lennard Shelf. The sample from site 10 is an undeformed tonalite selected to monitor the time of final plutonism in the basement within the King Leopold Orogen. It yielded an age of 1725 ± 17 Ma, which is considered to approximate the time of cooling following igneous crystallisation. Samples selected from sites 8 and 9 to estimate the age of

Table 2. Sample details

Site, field no. (prefix 8909–)		*Mineral analysed*	*Lithology*	*Mineral assemblage**	*Probable protolith*	*Location*	*Latitude (°S)*	*Longitude (°E)*
1	1077A	Muscovite	Metasediment	ch–ms–qz–fd	?Oscar Range Group	Oscar inlier	17°46.04′	125°04.56′
2	1004	Muscovite	Phyllonitic mylonite	bt–ms–qz–fd–ch	Whitewater Volcanics	Oscar inlier	17°54.79′	125°17.04′
3	1056	Muscovite	Deformed schist	ch–qz–fd–ms	Whitewater Volcanics sliver	Oscar inlier	17°46.85′	125°05.72′
4	1012	Biotite	Foliated adamellite	bt–qz–pl–kf ± ch ± ms	Lamboo Complex	Pillara inlier	18°25.95′	125°48.87′
5	1039B	Muscovite	Schist	gt–bt–fd–qz–ch–ms	Marboo Formation	Kimberley Granite Quarry	17°31.95′	125°09.29′
6	1043B	Biotite	Metasediment	ms–bt–qz–fd	Marboo Formation	NW Fairfield	17°30.25′	125°18.59′
7	1091	Hornblende	Schist	qz–bt–hb	Unknown	Langoora 1 well	17°18.07′	125°06.48′
8	1049	Biotite	Deformed tonalite	hb–bt–qz–kf–pl	McSherrys Granodiorite	N Kurrajong bore	17°36.22′	125°24.02′
9	1026	Biotite	Deformed granite	hb–bt–qz–pl–kf	Lennard Granite	Black Swan Quarry, Gibb River Rd	17°13.69′	124°53.97′
10	1018	Biotite	Tonalite	bt–cp–qz–kf–pl ± ch	Lamboo Complex	Margaret River crossing, N Louisa Downs	18°28.52′	125°36.05′

*bt, biotite; ch, chlorite; cp, clinopyroxene; fd, feldspar; gt, garnet; hb, hornblende; kf, K-feldspar; ms, muscovite; pl, plagioclase; qz, quartz

metamorphism accompanying D3 Yampi deformation yielded ages of 1475 ± 12 Ma (site 8) and 999 ± 9 Ma (site 9). The 999-Ma age reflects intense deformational recrystallisation with the growth of new biotite, and provides a minimum age for the D3 Yampi event. The 1475-Ma age might reflect a composite age, as two size fractions of biotite are present in the sample; however, it places an outside maximum on the age of D3.

Biotite from a muscovite–biotite metasediment (site 6) showing evidence of only one low-grade metamorphism and deformation yielded an age of 700 ± 8 Ma. This rock is located within an offshoot of the Sandy Creek Shear, which cuts the Early Proterozoic Marboo Formation — a sequence of turbiditic rocks (previously designated as part of the Halls Creek Group) in the King Leopold Orogen (Tyler & Griffin, in press). Tyler & Griffin (1990) relate the main shearing recorded in the Sandy Creek Shear to the Middle Proterozoic Yampi event. The 700-Ma age might represent either a period of renewed movement and local isotopic resetting, or partial resetting of a Middle Proterozoic isotopic signature during either the D4 or D5 events.

White & Muir (1989, citing C.B. Smith, personal communication, 1988) record an unpublished K–Ar age of 727 ± 10 Ma for a dolerite dyke which they considered to be displaced and retrogressed by the same shear. This dyke continues to the north of the Sandy Creek Shear, and cuts folds and thrusts of the D4 event. Its K–Ar age is therefore anomalous, and the significance of it cannot be appraised until further information is published.

Table 3. Potassium-argon analyses

Site	*Sample (prefix 8909–)*	*%K*	$^{40}Ar^*$ *(× 10^{-10} mole/g^{-1})*	$^{40}Ar^*/^{40}Ar_{Total}$	*Age + 1 (Ma)*
1	1077A muscovite	7.22 7.19	77.383	0.996	532 ± 3
2	1004 muscovite	7.27 7.31	73.484	0.992	504 ± 4
3	1056 muscovite	9.3 5 9.34	96.432	0.997	514 ± 4
4	1012 biotite	7.21 7.25	81.899	0.993	557 ± 8
5	1039B muscovite	3.43 3.43	34.739	0.994	506 ± 4
6	1043B biotite	6.65 6.68	98.831	0.991	700 ± 8
7	1091 hornblende	0.765 0.765	7.1804	0.982	473 ± 3
8	1049 biotite	7.39 7.41	292.88	0.998	1475 ± 12
9	1026 biotite	7.01 7.05	162.60	0.997	999 ± 9
10	1018 biotite	4.63 4.64	2132.09	0.997	1725 ± 17

*Denotes radiogenic argon.
Constants: $\lambda_e + \lambda_{e'} = 0.581 \times 10^{-11} y^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} y^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1}.

In the southwest of the Oscar inlier, a schist showing the imprint of a regional greenschist foliation yielded a muscovite K–Ar age of 532 ± 3 Ma (site 1; Figs. 1, 2). In the Pillara inlier, biotite from a recrystallised adamellite showing an imposed regional deformational foliation yielded a similar age of

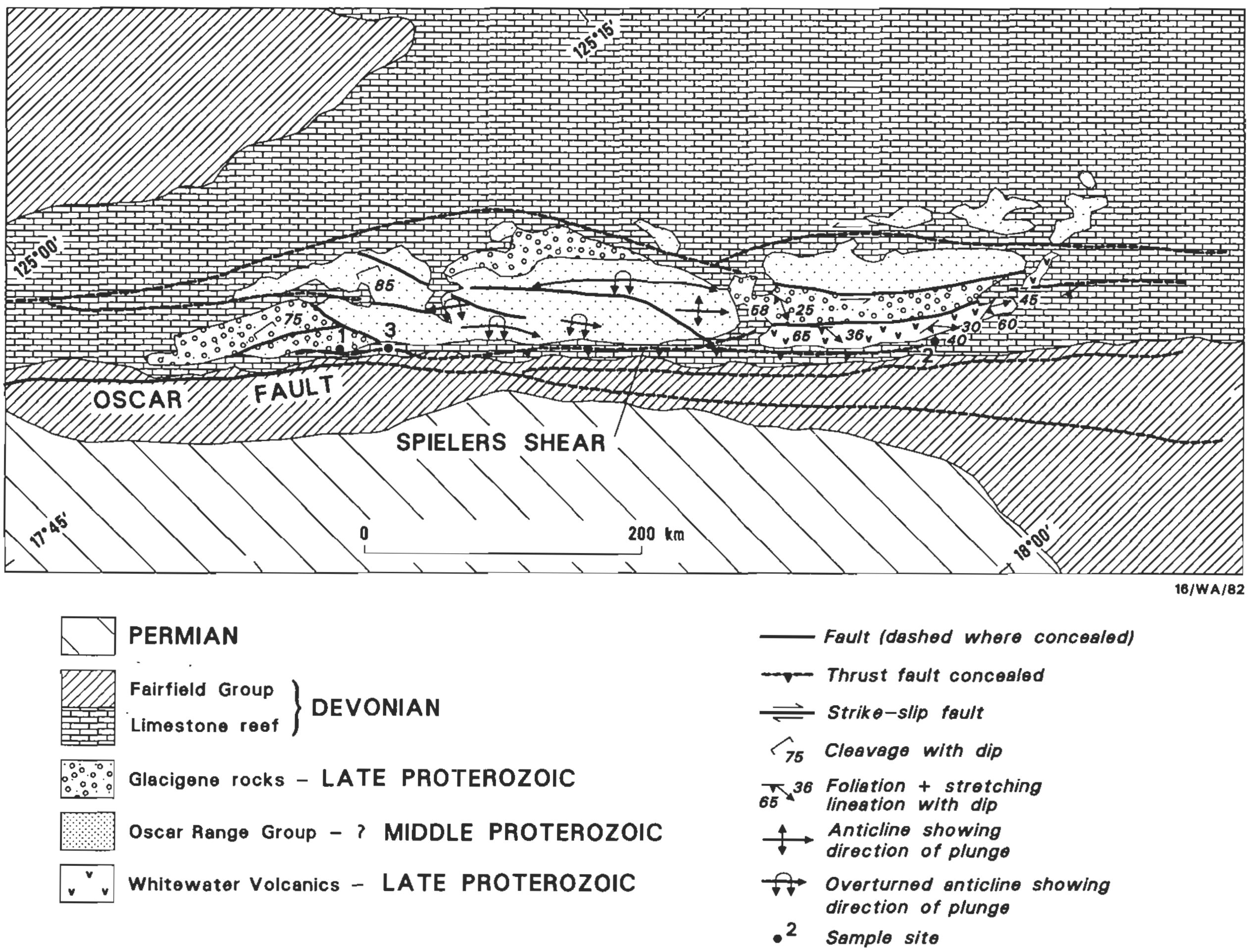

Figure 2. Geological sketch map of the Oscar inlier.

557 ± 8 Ma (site 4). These ages are considered to provide a guide to the time of regional phyllitic cleavage formation during D4.

In the Oscar inlier, the discontinuously exposed Spielers Shear has a weak fabric asymmetry, suggesting limited northward-directed thrusting. Muscovite in phyllonitic mylonite and deformed schist (sites 2 and 3; Figs. 1, 2) from two widely separated exposures of felsic volcanic rock cut by the shear zone yielded latest Cambrian K–Ar ages of 504 ± 4 and 514 ± 4 Ma respectively. These ages are considered to give a guide to the age of the northward-directed thrusting that we refer to D5.

Muscovite (site 5) from a schist in the southern part of the King Leopold Orogen provided a similar age — 506 ± 4 Ma. This schist, from the margin of a mid-Proterozoic dolerite dyke, is considered to be part of a cross-cutting retrograde zone which has a discordant, northerly trend and shows post-crystallisation microfolding. Similarly, deformed actinolite–biotite schist from basement core in Langoora 1 well, near the northwest margin of the Lennard Shelf (site 7), gave a slightly younger age of 473 ± 3 Ma, which is considered to represent somewhat more protracted cooling following low-grade regional metamorphism and subsequent uplift.

Discussion

The foregoing data suggest that there might be two periods of Late Proterozoic to latest Cambrian contractional tectonism in the King Leopold Orogen — ca 530–560 Ma and 500–510 Ma (see Tyler & others, 1991). Even so, further structural and geochronological work is needed to clarify the interpreted events.

Although our results are of a reconnaissance nature, the consistency of the youngest K–Ar mineral ages from widely distributed deformed zones suggests a major period of contractional fault movement in the latest Cambrian to earliest Ordovician. The final contractional deformational event in the basement at the northern margin of the Canning Basin might have extended into the Fitzroy Trough, where it is perhaps recorded by movements along the faults evident in the seismic profile of Drummond & others (1991). This event might also have extended farther south. South of the Canning Basin, the 750–550-Ma ages of deformation in the Paterson Orogen, although poorly constrained (Myers, 1990), could have occurred at much the same time as the deformations that we have documented to the north of the basin. The D4 event south of the basin might be reflected by the cleavage affecting Late Proterozoic glacial rocks in the Paterson Orogen (Williams, 1990). The final phase of deformation in the King Leopold Orogen was apparently contemporaneous with the Delamerian Orogeny in the Adelaide Geosyncline, which is dated at 520–480 Ma (D1, 520–505 Ma; D2, 495–480 Ma; Parker, 1986; Preiss, 1987), and might represent a more widespread event. These speculations on the timing and extent of D5 require much more work before they can be accepted or refuted.

If this latest Cambrian deformation is represented under the basin, then the Canning Basin probably lacks a thick Cambrian succession similar to those in the Wiso, Amadeus, and Officer

Basins to the east (see Shaw & others, 1991), because much of the Canning region would have been elevated by crustal shortening at this time. Nevertheless, the possibility that restricted sedimentation took place between D4 and D5 — as seen, for example, in the Ord Basin (Mory & Beere, 1985) — cannot be excluded. Since the oldest-known trilobite faunas are of latest Tremadoc age (i.e., ca 485 to 490 Ma; Webby & Nicoll, 1989), subsidence and deposition in the Fitzroy Trough appear to have begun in the Early Ordovician, possibly between about 505 and 490 Ma.

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A reconnaissance investigation of the major Palaeozoic aquifers in the Canning Basin, Western Australia, in relation to Zn–Pb mineralisation

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The Canning Basin is a large sedimentary basin with an onshore area of 430 000 km^2. It has a thick, discontinuous succession of Palaeozoic and Mesozoic marine and continental sedimentary rocks covered by Cainozoic surficial sediments. It contains several Zn–Pb sulphide deposits of Mississippi Valley type, mainly in the Lennard Shelf and along the Admiral Bay Fault. To provide a framework for understanding the mechanism of this mineralisation, we made a reconnaissance study of the Palaeozoic aquifers, based on an analysis of data from 30 oil exploration wells.

The major Palaeozoic aquifers in the basin are the Early Permian Poole Sandstone, the Late Carboniferous to Early Permian Grant Group, and the Devonian Tandalgoo Sandstone. These aquifers have a complex structure owing to tectonic and erosional effects, and they are interconnected with the younger and shallower aquifers. The general direction of groundwater flow in the Palaeozoic aquifers is from the southeast toward the west and northwest. Groundwater velocity is in the range of 0.2 to 0.5 m y^{-1}, and temperature ranges from 30 to 83°C. Groundwater salinity is low at the margins of the basin, but increases with depth and along the flow lines. Our study suggests that the present hydrogeological regime is basically different from those active in the Silurian to Permian, the interval during which the Zn–Pb deposits are considered to have formed.

Compaction-driven and gravity-driven fluid-flow models for the formation of the Zn–Pb deposits are considered. A geopressured zone encountered in one location is evidence that the ore-forming fluids could have been generated in deeper parts of the basin, and expelled by compaction into shale-enclosed sandstone lenses. These geopressured lenses could subsequently have been faulted, and the potential ore-forming fluids released. There is insufficient information on the tectonics, palaeotopography, and age of the mineralisation to assess the gravity-driven fluid flow-model.

Introduction

The Canning Basin, in northwest Western Australia, is a large Phanerozoic intracratonic basin with an onshore area of 430 000 km^2. In its northern part, a Devonian reef complex on the Lennard Shelf (Fig. 3) hosts numerous Zn–Pb deposits and a few producing oil wells. Several new discoveries along the Pinnacle Fault in the Lennard Shelf, and significant mineralisation in Ordovician carbonates along the Admiral Bay Fault in the Broome Arch, have strengthened the prospectiveness of the Canning Basin for carbonate-hosted Zn–Pb deposits of Mississippi Valley-type (MVT).

The salinity, geochemistry, and temperature of ore-forming fluids in MVT deposits are remarkably similar to some types of oilfield brine found in present-day sedimentary basins, which has led to the development of a basinal brine hypothesis for the genesis of the deposits. This hypothesis is based on the migration of hot saline waters along aquifers and structurally controlled conduits, followed by precipitation of ore at the margins and the arches of the basins.

In 1987, BMR initiated a project to investigate the hydrogeology, salinity, and hydrochemistry of present-day fluids and palaeofluids in the Canning Basin, in order to understand the mechanisms of Zn–Pb mineralisation. As a first step, a reconnaissance study of the major Palaeozoic aquifers has been carried out. This paper presents the results of the hydrogeological investigations. The hydrogeologic data are limited to 30 oil exploration wells. Because this is a major restriction in such a large basin with more than 200 such wells, this study is only the first step in the investigation of the hydrogeology (both past and present) of the Palaeozoic aquifers.

Geography

The Canning Basin is about 500 km wide (NE–SW) and 800 km long (NW–SE). Its elevation ranges from sea level to over 500 m at its margins. It has two main towns, Derby and Broome (Fig. 1), both situated on the coast. The small population is mainly concentrated in the northern and coastal areas; much of the inland area is a vast desert that is virtually uninhabited. According to the 1986 census, Derby and Broome Shires had 6608 and 6048 inhabitants respectively (Australian Bureau of Statistics, 1988). The basin also has a dispersed population at pastoral stations and on Aboriginal settlements.

Three physiographic features dominate the Canning Basin (Fig. 1):

- **the Fitzroy valley** is a moderately flat plain with recent alluvium;
- **the Canning plain, or desert plateau**, is covered with west-northwesterly trending sand dunes; and
- **the coastal plain** extends along the entire coast, and is covered by coastal dunes and samphire marsh.

Major rivers, such as the Fitzroy, Margaret, and Sturt in the north, and the Oakover and De Grey in the south, are not permanent, and may become completely dry during droughts. The Fitzroy River at Fitzroy Crossing has a catchment area of 45 300 km^2, a mean annual flow of 8.2×10^9 m^3, and high flow from January to April. The De Grey River at Coolenar Pool has a catchment area of 49 600 km^2 and a mean annual flow of 0.92×10^9 m^3 (Public Works Department, 1984). Water quality is good in the Fitzroy River at Fitzroy Crossing (total dissolved solids, 90 mg L^{-1}), but highly variable in the De Grey River, where it improves during high flows (Public Works Department, 1984).

The Canning Basin has a monsoonal climate with pronounced wet and dry seasons in the north and along the coast, becoming less defined inland. The mean annual rainfall ranges from over 600 mm north of Derby to an irregular 200 mm in the desert areas in the southeast (Fig. 1, Table 1). Summer is the rainy season in Derby and Broome, and the dry season spans July to November (Bureau of Meteorology, 1988).

The temperature and evaporation potential in the basin are high; for example, at the Fitzroy Crossing gauging station, pan evaporation ranges from 2600 to 3400 mm per annum, and at the Coolenar Pool gauging station, on the De Grey River, pan evaporation ranges from 3500 to 3800 mm and averages 3700 mm per annum (Public Works Department, 1984).

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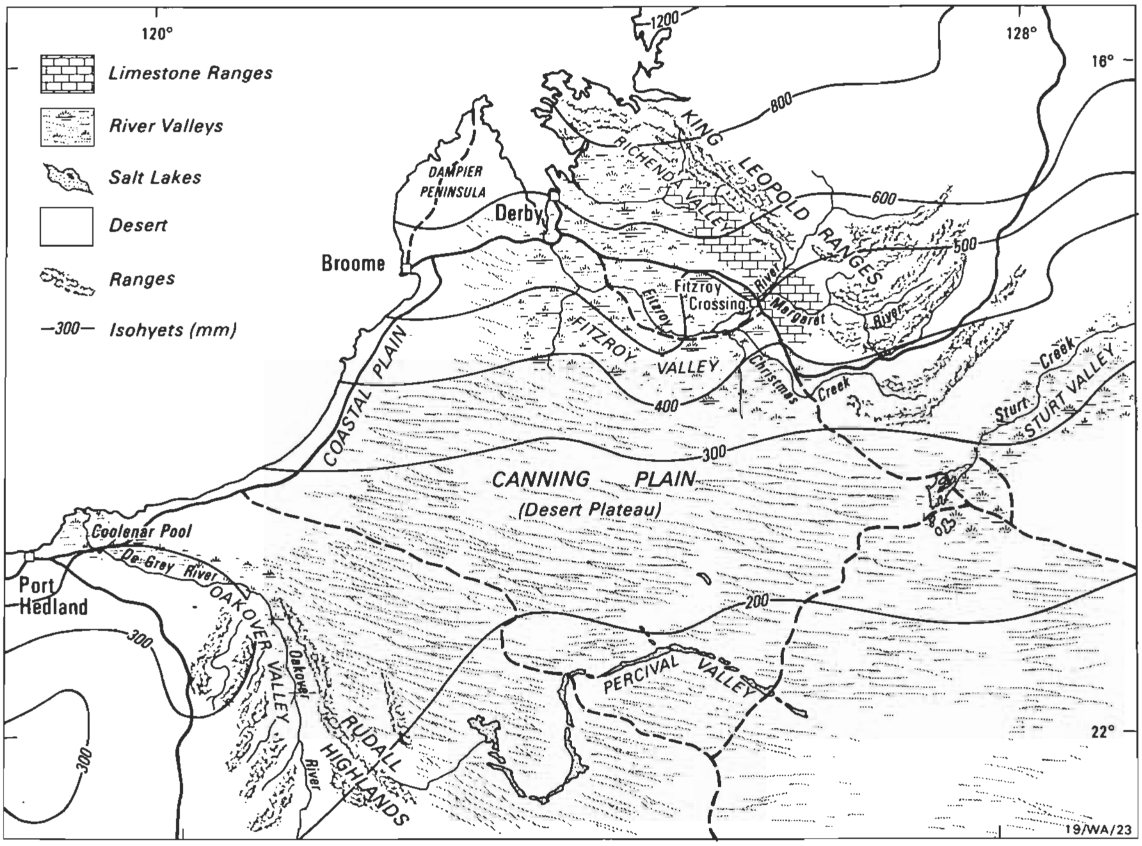

Figure 1. Physiography (from Purcell, 1984) and median annual rainfall (from Parkinson, 1986) in the Canning Basin region.

Outline of geology

The Canning Basin is bounded to the north by the Precambrian Kimberley Craton, and to the south by the Pilbara Craton (Fig. 3). In the north, it is dominated by the Fitzroy Trough, part of a major fault-bounded graben containing over 18 000 m of sedimentary rocks deposited during several cycles of marine transgression and regression between the Early Ordovician and the Late Cretaceous. In the south, the Kidson and Willara Sub-basins contain extensive deposits of marine evaporites.

The geology of the basin and its evolution have been described by a number of authors. The following brief descriptions of the stratigraphic and tectonic development (with emphasis on the Palaeozoic) and the structure of the basin are summarised from Yeates & others (1984), Towner & Gibson (1983), and Brown & others (1984).

Table 1. Mean annual rainfall and temperature for three stations in the Canning Basin

Station	*Elevation* (m)*	*Mean annual rainfall (mm)*	*Mean daily temperature* Min. (°C)	Max. (°C)
Derby	7.0	612	21.7	34.4
Broome	17.0	573	21.2	32.2
Fitzroy Crossing	114.0	537	19.2	35.7

* Datum not specified.
Source: Bureau of Meteorology (1988).

Stratigraphic and tectonic development

The known history of the basin began in the Early Ordovician (see, for example, Shaw & others, 1992, in this issue), with the subsidence below sea level of an erosion surface developed on Precambrian rocks. Early sedimentation generated the shallow-marine sandy, fine clastic, and carbonate deposits of the Prices Creek Group (Fig. 2), and silt, mud, and carbonate deposits of the Nambeet, Willara, Goldwyer, and Nita Formations. By the mid-Ordovician, deposition had slowed, and may have ceased in much of the basin.

After an extensive period of non-deposition and erosion, uneven subsidence initiated the broad downwarp of the Kidson and Willara Sub-basins (Fig. 3), in which fine dolomitic sediments and evaporites of the Caribuddy Group accumulated during the Silurian to Early Devonian.

A postevaporative redbed phase of sedimentation (Tanndulla Group) in an arid environment included the accumulation of the Tandalgoo Sandstone throughout the Kidson Sub-basin during the Early to Middle Devonian. When subsidence recurred, aridity gave way to shallow-marine conditions. Gentle downwarping in the Kidson Sub-basin facilitated the deposition of a thin section of carbonates and minor evaporites (Mellinjerie Limestone) in the Middle–Late Devonian. Thereafter, no further deposition took place in the Kidson Sub-basin until the Late Carboniferous.

Tectonic events caused the subsidence that allowed the Fitzroy Trough and Gregory Sub-basin to become major depocentres in the Devonian. Carbonate sedimentation, accompanied by extensive reef-complex development (e.g., Napier Formation and Pillara Limestone), was dominant on shallow terraces and shelves (Lennard Shelf, Barbwire Terrace, and Jurgurra Terrace), whereas the deeper portions of the trough and sub-basin received a vast influx of mainly fine clastic sediments (Babrongan Formation, Clanmeyer Siltstone, and Luluigui Formation).

Shallow-marine clastic and carbonate sediments (Fairfield Group) covered the carbonate–reef complex in the Fitzroy Trough and parts of the Lennard Shelf. In the Early Carbon-

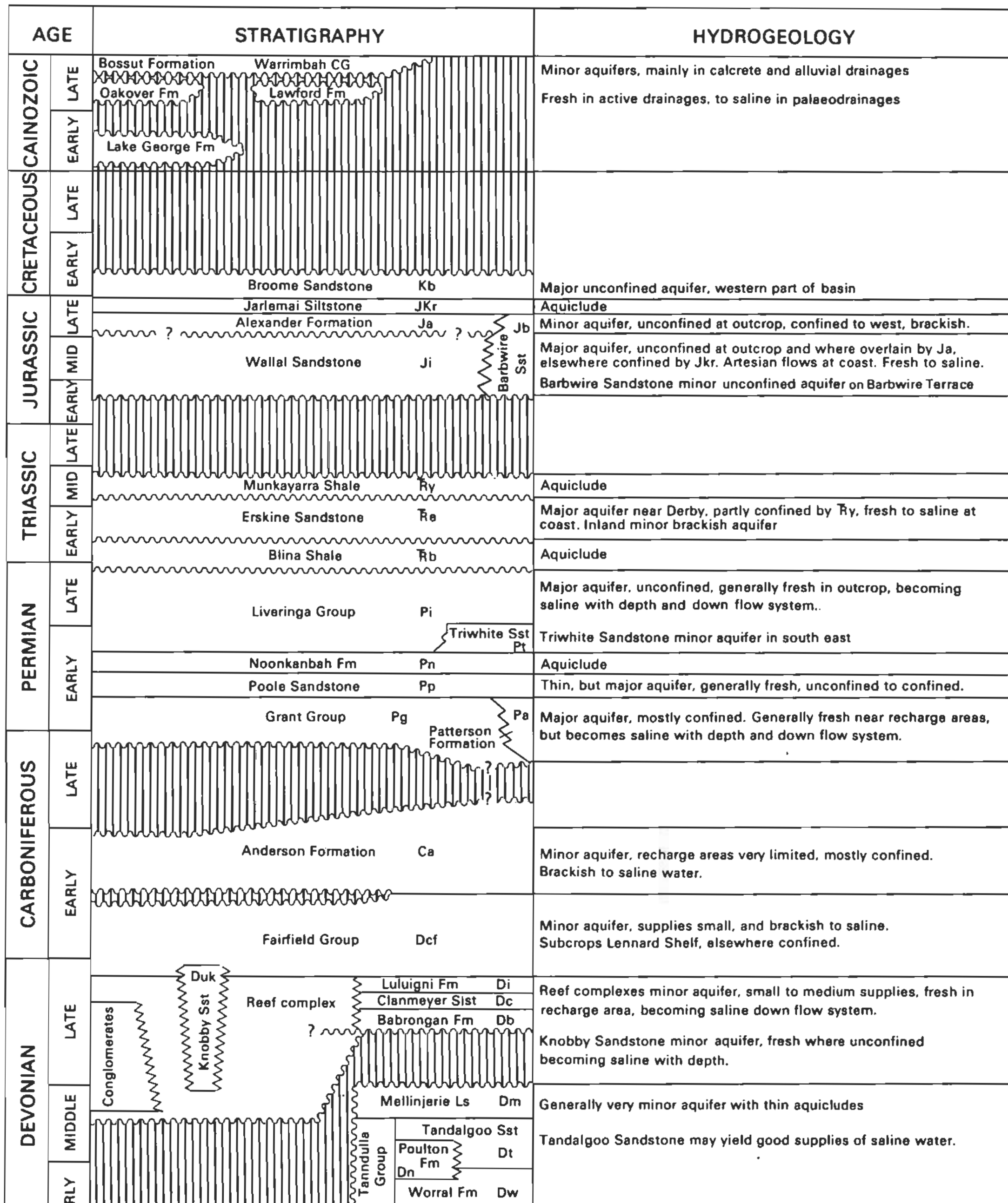

Figure 2. Stratigraphy and hydrogeology of the Canning Basin (from Laws, 1991; based on Mory & Dunn, 1990, with additions).

iferous a major regression commenced. Deposition of marine and continental fine to medium clastic and carbonate sediments of the Anderson Formation became confined to the rapidly sinking Fitzroy Trough.

In the Late Carboniferous to Early Permian, basin-wide subsidence was rejuvenated, and fine to coarse clastic sediments of the Grant Group (consisting of the Betty Formation, Winifred Formation, and Carolyn Formation) accumulated in mainly

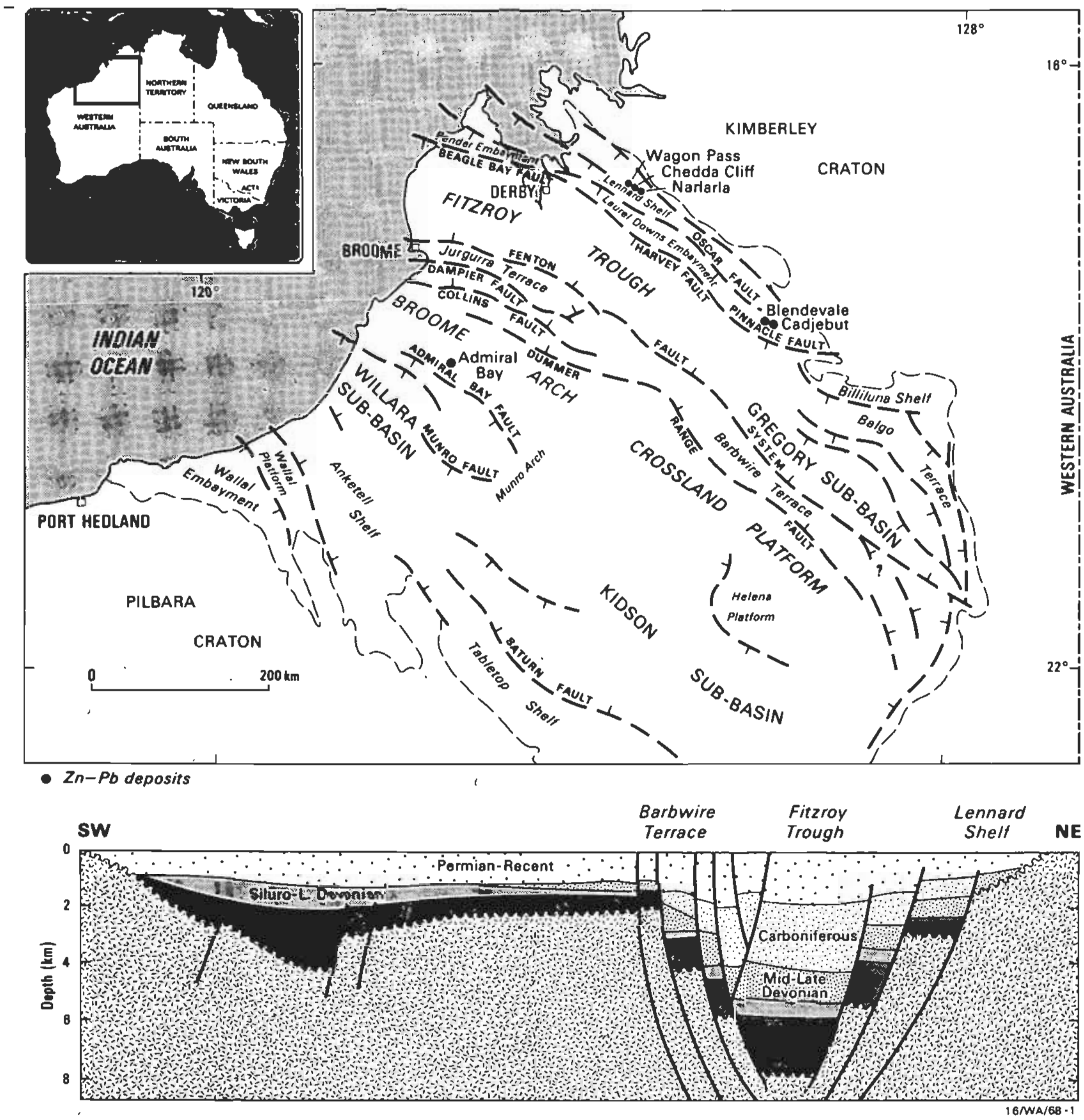

Figure 3. Main structural units of the Canning Basin, and locations of Zn–Pb deposits (after Purcell, 1984).

shallow to deep-marine environments under the influence of a glacial climate. Sporadic tectonism followed deposition of the Carolyn Formation, and the fluvial to shallow-marine Poole Sandstone was deposited on the Grant Group.

The Poole Sandstone is overlain by the shale-and-siltstone-dominated and variably calcareous marine unit of the Early Permian Noonkanbah Formation. At this time, the Broome Arch provided a limited connection between the Kidson Sub-basin and an active depocentre in the Fitzroy Trough. Late in the Early Permian, the Triwhite Sandstone was deposited in the Kidson Sub-basin. At the same time, interbedded sandstone and mudstone of the Liveringa Group were deposited farther north, and became confined to the region north of the Fenton Fault system following emergence of the Broome Arch, which facilitated the erosion of older Permian units on it.

Mesozoic sedimentation continued to be controlled until the Middle Triassic by the tectonic events that had influenced the development of the basin from Early Devonian or possibly Ordovician times. Sedimentation of clastic detritus in fluvial, aeolian, deltaic, and shallow-marine environments dominated the development of the basin during the Jurassic to Early Cretaceous.

After retreat of the Early Cretaceous sea, most of the Canning Basin was probably a large plain. Gross features of this landscape have probably changed little since then. Large-scale drainage was initiated. Topographic depressions containing calcrete, evaporites, and alluvial sediments were developed, and a minor aeolian imprint is now superimposed on them.

Structure

The major structural units of the Canning Basin (Fig.3) are all aligned parallel to the northwesterly elongation of the basin. They include:

- **the Lennard Shelf** — an area of moderately shallow basement in the northeast overlain by up to 3000 m of rocks of mainly Ordovician, Devonian, and Permian ages;
- **the Billiluna Shelf** — a basement feature overlain by 3000 m of mainly Ordovician and Devonian rocks, and separated from the Lennard Shelf by Precambrian basement rocks;
- **the Fitzroy Graben** — a Palaeozoic rift comprising two depocentres (Fitzroy Trough and Gregory Sub-basin) that contain a succession of Ordovician, Devonian, Carboniferous, and Permian rocks, which seismic evidence suggests

is generally 8000 m thick (and a maximum of 18 000 m in the southeast);

- **the Barbwire and Jurgurra Terraces** — two moderately narrow shelf-like basement areas separated from the Fitzroy Trough by the Fenton Fault System; the sequences on the terraces comprise 1500–4500 m of Palaeozoic rocks, veneered by Mesozoic rocks on the Jurgurra Terrace and part of the Barbwire Terrace;
- **the Broome Arch and Crossland Platform** — a broad area of moderately shallow basement overlain by 1000–3000 m of rocks of mainly Palaeozoic age;
- **the Kidson and Willara Sub-basins** — two contiguous basement depressions with maximum estimated depths of 10 000 and 4500 m, respectively, containing Palaeozoic and Mesozoic rocks; and
- **the Anketell–Tabletop Shelf** — an area of shallow basement, covered by a veneer of late Palaeozoic and Mesozoic rocks less than 700 m thick along the southern flank of the Kidson and Willara Sub-basins.

Evaporites

Evaporites are potential source rocks for highly saline ore-forming brines. In the Canning Basin, the Carribuddy Group is the main evaporite-containing unit. Based on seismic and gravity data, and features on Carribuddy salt isopachs, Bentley (1984) discussed the effect of the massive salt sequence in the Carribuddy Group on the structural styles in the southern Canning Basin. In the Willara Sub-basin the thick salt has been moved into large salt swells; on the Broome Arch the structures are mainly salt pillows and salt-solution features.

Craig & others (1984) have presented a Landsat interpretation of the southern Canning Basin. They distinguished several large, previously unknown annular features in thick sedimentary sections. The geophysical signature of these annular features is not consistent with near-surface igneous or metamorphic rocks. Craig & others considered them to be the surface expressions of poorly exposed large-scale diapiric structures. They also suggested that the development of the annular features was controlled, at least in part, by major faults.

Hydrogeology

Previous investigations

Several publications describe the hydrogeology of localised areas of the Canning Basin. Leech (1979) described the geology and groundwater resources of the southwestern corner. Towner & Gibson (1983) and Yeates & others (1984) listed the geologic formations which can be considered as aquifers. Lau & others (1987) provided two simplified hydrogeologic cross-sections of the basin, and named a number of Late Carboniferous and younger units as aquifers: Tertiary calcretes, Cretaceous Broome Sandstone, Jurassic Wallal Sandstone, Triassic Erskine Sandstone, Permian Triwhite Sandstone and Liveringa Group, Early Permian Poole Sandstone, and Late Carboniferous and Early Permian Grant Group.

Laws (1987) described the hydrogeology of the Broome area, and Laws & Smith (1989) investigated the regional hydrogeology around Derby, focusing on the characteristics of the Wallal and Erskine Sandstones. Laws (1991) identified the major and minor confined and unconfined aquifers of the basin from the Early Ordovician to the Cainozoic (Fig. 2). Where possible, he provided information on the extent, geologic nature, recharge–discharge areas, yields, and salinities of these aquifers. He placed more emphasis on the major aquifers from the Late Carboniferous to Early Permian Grant Group up to the Cretaceous Broome Sandstone, for which he provided an estimate of the groundwater in storage.

Present investigation

The objective of our study was to investigate the hydrogeology of the sedimentary sequences from the Permian Poole Sandstone down to the basement. To identify the stratigraphic units which can be considered as aquifers, the geologic information has been supplemented by measured values of the porosity and permeability on cores and side-wall samples.

According to this analysis (Table 2) a few extensive stratigraphic units are porous and permeable. These units are the Poole Sandstone, Grant Group, and Tandalgoo Sandstone, which have mean permeabilities of 90, 120, and 510 millidarcies respectively. The calcareous sandstone of the Laurel Formation, the Yellow Drum Sandstone, the carbonate reef complex, and the Poulton Formation are of limited extent, and the number of oil exploration wells intersecting these units is limited, so their hydrogeologic behaviour has not been investigated in this study.

Stratigraphic units containing mainly limestone and dolomite — such as the Napier Formation, Pillara Limestone, Babrongan Formation, Mellinjerie Limestone, Nita Formation, Gap Creek Formation, and Willara Formation — are considered to be impervious in this context.

As no direct (*in-situ*) measurements of hydraulic conductivity were available, the mean values of the measured permeabilities have been converted to their equivalent hydraulic conductivity (Table 3) using a conversion factor of 0.8347 m per day for a permeability of 1000 md (Todd, 1980).

Extent of Palaeozoic aquifers

The Palaeozoic aquifer system in the basin has a complex structure owing to major tectonic and erosional events. The major Palaeozoic aquifers are the Poole Sandstone, Grant Group, and Tandalgoo Sandstone. The major confining units include the Mellinjerie Limestone, Winifred Formation, Noonkanbah Formation, Blina Shale, and Jarlemai Siltstone.

According to hydrogeologic cross-sections (Figs. 4–7), the aquifers are interconnected. The Poole Sandstone overlies the Grant Group, and generally there is no impervious stratigraphic unit between them. Therefore, wherever the Grant Group is fully saturated, the two aquifers may be hydraulically connected. In places, the Grant Group overlies the Tandalgoo Sandstone — for example, on the east side of Contention Heights No. 1, and between Sahara No. 1 and Munro No. 1 (Fig. 5).

Mesozoic sandstone locally covers the Poole Sandstone and Grant Group — for example, on the east side of Contention Heights No. 1 (Fig. 5). The interconnection of the aquifers, and their displacement by the major longitudinal faults, have severely affected the recharge and discharge of the Palaeozoic aquifers.

Poole Sandstone

The Poole Sandstone is of shallow-water (fluvial to marine, and possibly lagoonal) origin, and consists of mainly fine sandstone with some medium to coarse sandstone towards the base (Towner & Gibson, 1983). Originally it was present over most parts of the basin. However, erosion has reduced its distribution, so that it is now mainly absent from a vast area

Table 2. Porosity and permeability of cores and side wall samples from Precambrian to Early Permian units, Canning Basin

Age	*Stratigraphic unit*	*Lithology*	*Porosity*				*Permeability*			
			No. of samples	*Min. %*	*Max. %*	*Mean %*	*No. of samples*	*Min. (md)*	*Max. (md)*	*Mean (md)*
Early Permian	Poole Sandstone	Mainly fine sandstone; some medium to coarse near base	60	1.8	39.4	14.0	58	0.1	1700[a]	90.0
Late Carboniferous to Early Permian	Grant Group (Betty Formation and Carolyn Formation)	Fine to coarse sandstone	130	0	29.0	11.0	130	0	11100[b]	120.0
Early to Late Carboniferous	Anderson Formation	Sandstone, siltstone, shale, mudstone	26	0	5.2	1.3	26	0	0	0
		Sandstone	67	1.8	17.9	9.3	62	0	92.0	2.9
Late Devonian to Early Carboniferous	Fairfield Group									
	Laurel Formation	Sandstone, siltstone, mudstone	15	0	14.5	5.3	15	0	0	0
		Calcareous sandstone	4	14.5	21.0	17.8	4	15.0	146[c]	73.5
		Limestone	6	5.0	10.0	6.6	6	0	0	0
	Yellow Drum Sandstone	Sandstone	6	11.3	20.0	14.6	6	19.0	263[d]	164.3
		Dolomite	6	13.5	18.7	15.4	6	0	13.0	7.3
	Gumhole Formation	Dolomite, dolomitic limestone	4	3.8	8.3	5.4	4	0	0	0
Middle and Late Devonian	Van Emmerick Conglom.	Conglomerate, marlstone, sandstone	8	1.3	16.0	7.9	8	< 0.1	1.8	0.4
	'Carbonate reef complex'	Dolomite, limestone	67	0	13.7	4.7	67	0	867[e]	29.6
		Sandstone	4	10.7	16.7	12.9	4	8.5	116.4[f]	61.2
	Napier Formation	Calcarenite	28	1.2	15.1	6.8	28	0	71.0	3.4
	Pillara Limestone	Limestone, minor dolomite	15	3.0	8.1	4.2	15	< 0.1	<0.1	< 0.1
	Luluigui Formation	Sandstone, shale	3	1.9	2.9	2.4	3	0	0	0
	Clanmeyer Siltstone	Siltstone, shale, dolomite	14	0	4.5	1.5	10	0	0	0
	Babrongan Formation	Dolomite	6	0	1.9	1.0	6	0	0	0
		Siltstone	1	0.7	0.7	0.7	1	0	0	0
	Mellinjerie Limestone	Limestone, dolomite, siltstone	10	1.1	8.5	3.0	10	0	0	0
Early to Middle Devonian	Poulton Formation	Siltstone, shale, sandstone	23	0	24.5	15.0	23	< 0.1	28.0	7.0
	Tandalgoo Sandstone	Sandstone, minor siltstone, shale	40	0.7	31.2	17.0	33	0	3300[g]	510.0
Silurian to Early Devonian	Carribuddy Group:									
	Sahara Formation	Siltstone, sandstone	9	0.7	6.2	3.1	14	0	0	0
	Mallowa Salt	Salty shale, salty siltstone	3	0	10.2	3.8	3	0	0	0
	Nibil Formation	Siltstone, sandstone, halite	11	0	10.0	7.3	11	0	0	0
	Minjoo Salt and Mount Troy Formation	Siltstone, sandstone, shale	3	3.5	6.5	5.2	3	0	0	0
	Bongabinni Formation	Siltstone	2	0.6	2.7	1.6	2	0	0	0
Ordovician	Nita Formation	Limestone, dolomite, shale	13	0	11.5	3.0	13	0	0	0
	Gap Creek Formation (Prices Creek Group)	Dolomite	13	0.9	6.8	2.2	13	<0.1	<0.1	<0.1
	Goldwyer Formation	Shale, limestone	11	0.3	5.7	2.0	11	0	0	0
	Willara Formation	Limestone, shale	3	0.4	2.1	1.2	3	0	0	0
	Nambeet Formation	Shale, interbedded limestone	2	0.6	1.5	1.1	2	<0.1	<0.1	<0.1
Precambrian		Metamorphic and igneous rocks	4	0.6	1.3	0.9	4	<0.1	<0.1	<0.1

[a] Measured in Sahara No. 1 at 307.8 m.
[b] Measured in St George Range No. 1 at 1099.7 m.
[c] Measured in May River No. 1 at 1260.6 m.
[d] Measured in May River No. 1 at 1437.7 m.
[e] Measured in Hawkstone Peak No. 1 at 659.8 m.
[f] Measured in Hawkstone Peak No. 1 at 1132.2 m.
[g] Measured in Sahara No. 1 at 1553.3 m.

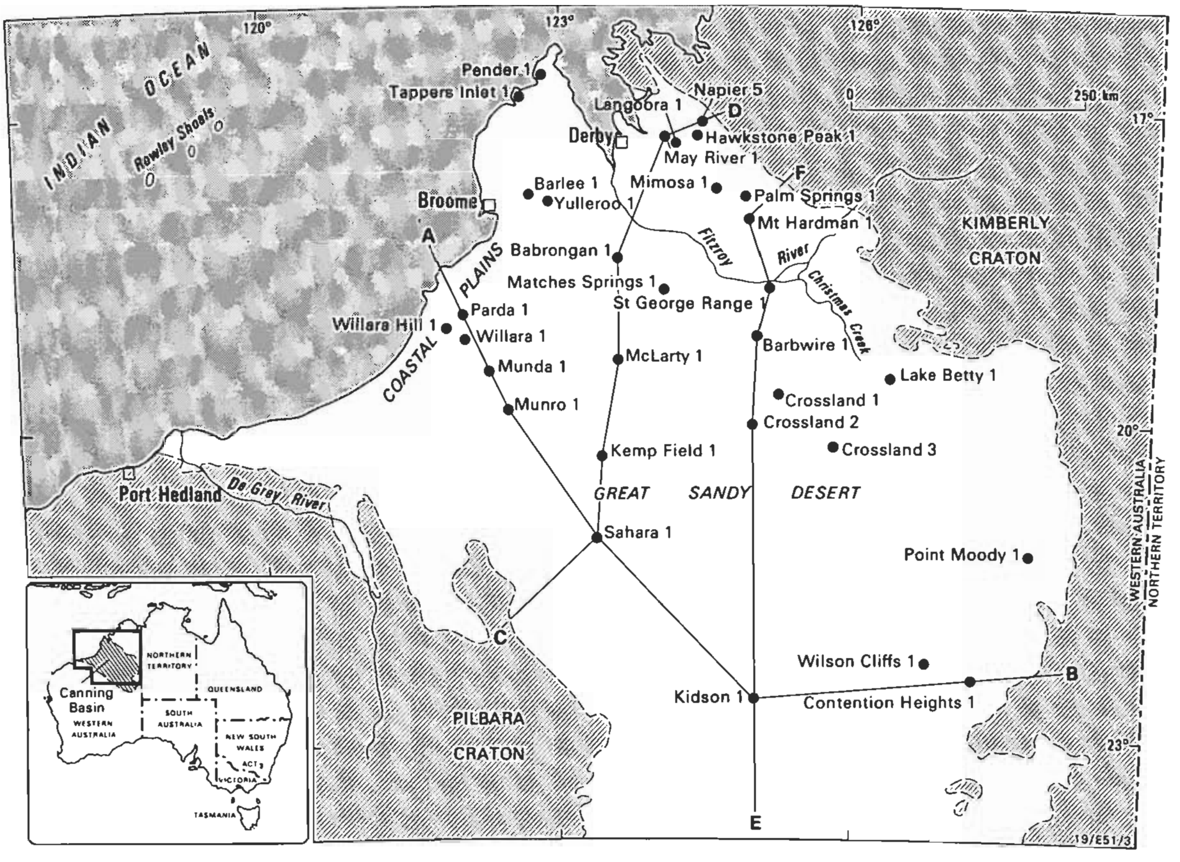

Figure 4. Locations of selected oil exploration wells in the Canning Basin, and hydrogeologic cross-sections shown in Figures 5 to 7.

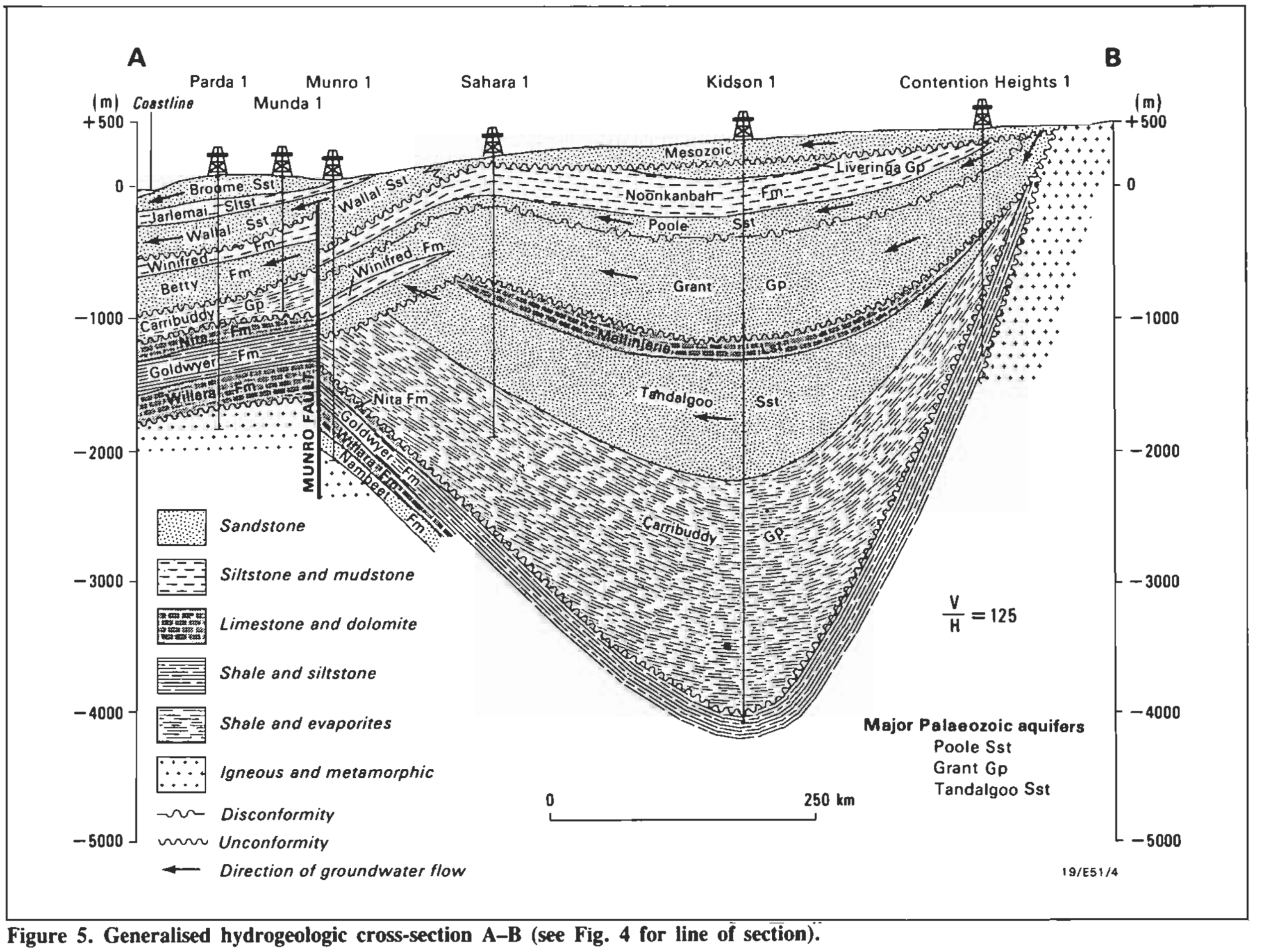

Figure 5. Generalised hydrogeologic cross-section A–B (see Fig. 4 for line of section).

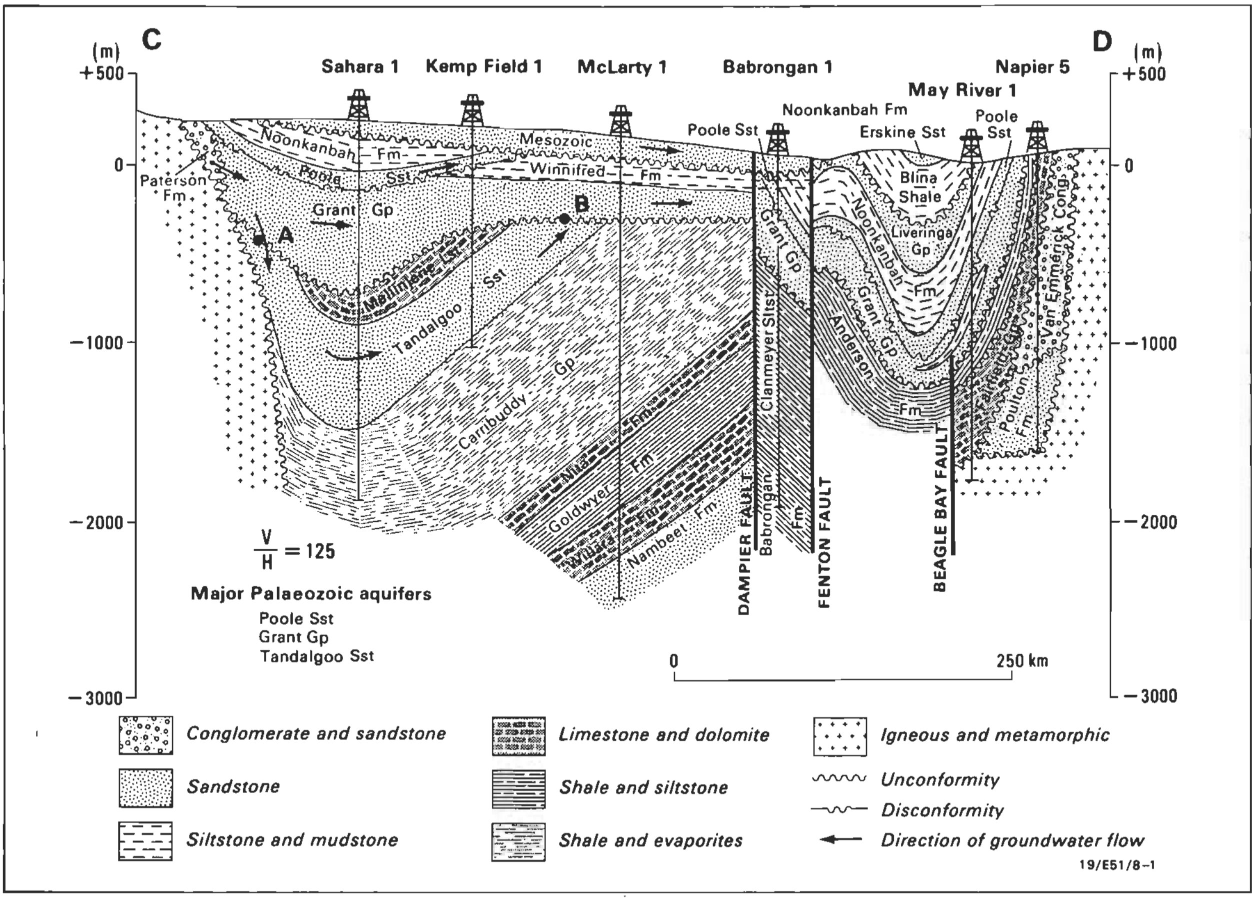

Figure 6. Generalised hydrogeologic cross-section C–D (see Fig. 4 for line of section).

Table 3. Mean values of the porosity, permeability, and hydraulic conductivity of the major Palaeozoic aquifers

Stratigraphic unit	*Porosity (%)*	*Permeability (md)*	*Hydraulic conductivity (m day^{-1})*
Poole Sandstone	14	90	0.075
Grant Group	11	120	0.100
Tandalgoo Sandstone	17	510	0.426

encompassing Munda No. 1, Crossland No. 1, Barbwire No. 1, Matches Springs No. 1, and Barlee No. 1; from a number of other areas such as Pender No. 1; and, according to Laws (1991), from two moderately large areas in the Fitzroy Trough (Fig. 8).

The Poole Sandstone crops out toward the northeastern and southwestern parts of the basin, and on the Barbwire Terrace and Crossland Platform. It also crops out in a few anticlines in the Fitzroy Trough. These structurally controlled outcrops, and particularly those located in the northern part of the basin, where the mean annual rainfall is high, are important for aquifer recharge and groundwater quality.

The Poole Sandstone is about 312 m thick in Point Moody No. 1, and 223 m in Contention Heights No. 1. Its thickness decreases toward the Broome Arch and neighbouring areas, where it is non-existent. On the Lennard Shelf, its maximum thickness is about 82 m in May River No. 1, and in the Balgo Terrace (Fig. 3) it is 86 m thick in Lake Betty No. 1.

The depth of cover above the Poole Sandstone is 927 m in Tappers Inlet No. 1 (Pender Embayment), 580 m in Mimosa No. 1 (Laurel Downs Embayment), and 678 m in Lake Betty No. 1 (Balgo Terrace). Farther south, it is 601 m in both Kidson No. 1 (Kidson Sub-basin) and Munro No. 1 (Willara Sub-basin), but the Poole Sandstone is nearer the surface toward Contention Heights No. 1 (Kidson Sub-basin), where it is at a depth of 175 m (Fig. 9).

Grant Group

The Grant Group is extensive over most of the basin. According to Towner & Gibson (1983), it consists of three units — from top to bottom:

- **Carolyn Formation** — fine to coarse sandstone;
- **Winifred Formation** — siltstone and very fine sandstone; and
- **Betty Formation** — fine to coarse sandstone with minor conglomerate and siltstone.

These units correspond broadly to two glacial periods separated by a largely interglacial phase (Yeates & others, 1984). The Winifred Formation is not present everywhere in the Grant Group (e.g., in Sahara No. 1, Kidson No. 1, and Contention Heights No. 1; Fig. 5). Elsewhere, where the upper part of the Grant Group has been removed by erosion, as in Parda No. 1 and Munda No. 1 (Fig. 5), the Winifred Formation separates the Betty Formation from Mesozoic units such as the Wallal Sandstone. The Carolyn and Betty Formations are aquifers, while the Winifred Formation is an aquiclude.

The Grant Group crops out mainly on the Billiluna Shelf, Barbwire Terrace, and Crossland Platform, and in the Fitzroy Trough. These outcrops are important for aquifer recharge and groundwater quality.

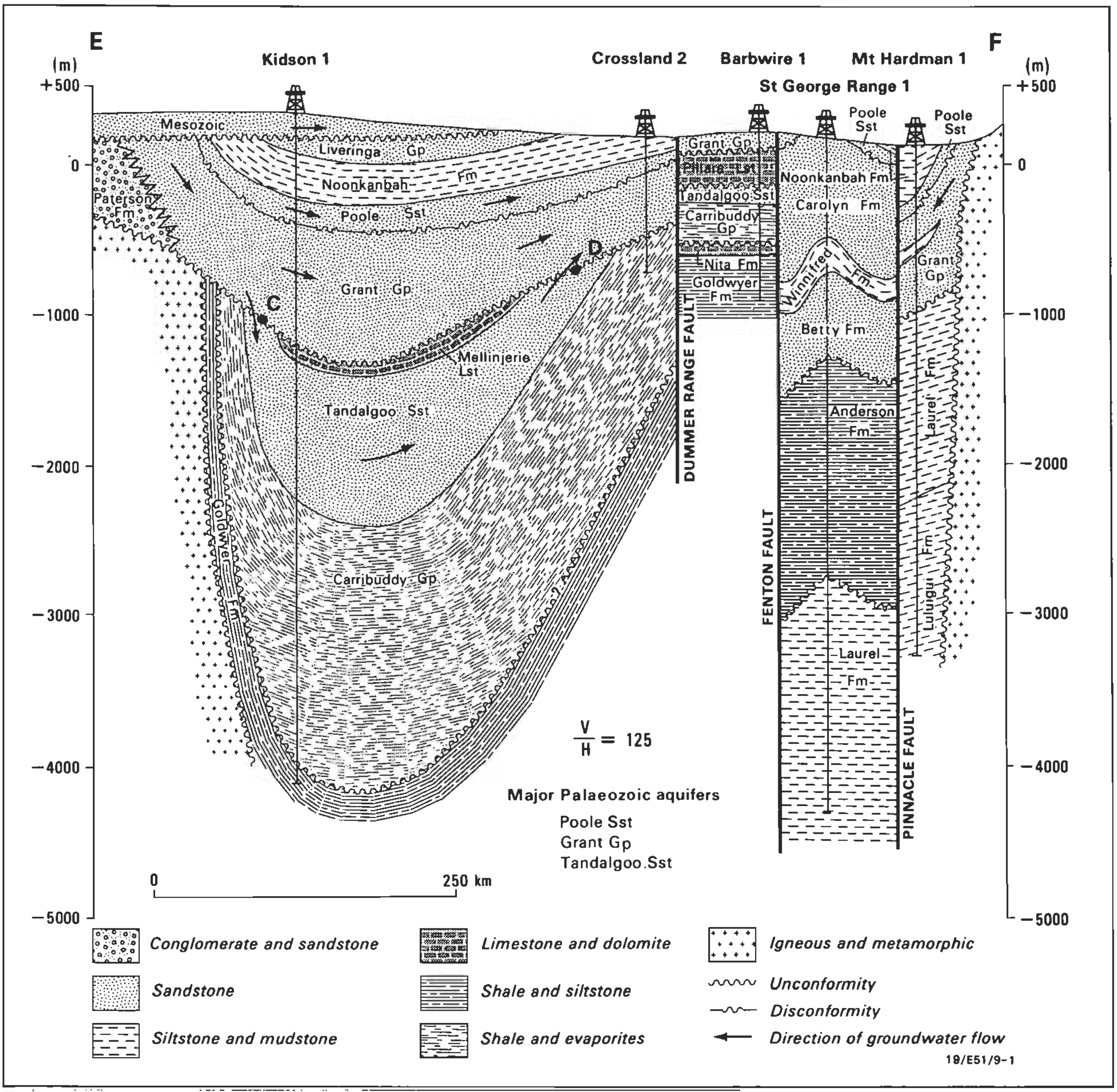

Figure 7. Generalised hydrogeologic cross-section E–F (see Fig. 4 for line of section).

The Grant Group is about 1512 m thick in St George Range No. 1 (Fig. 10), in the Fitzroy Trough, where erosion and tectonic effects have contributed to its absence from Barlee No. 1. It is 657 m in Mount Hardman No. 1, on the Lennard Shelf, and 835 m (maximum thickness in the Kidson Sub-basin) in Kidson No. 1.

The top of the Grant Group is at a depth of 972 m in Tappers Inlet No. 1 (Fig. 11), in the Pender Embayment, and 675 m in Mimosa No. 1, in the Laurel Downs Embayment. It is 764 m deep in Lake Betty No. 1, on the Balgo Terrace, and 442 m in Yulleroo No. 1, in the Fitzroy Trough. In the southern Canning Basin the maximum depth of the top of the Grant Group is about 736 m in Kidson No. 1.

Although the Grant Group is likely to be a multilayered aquifer, the paucity of data, and the lack of an impervious stratigraphic unit between the Poole Sandstone and the Grant Group, preclude us from treating these two units as anything but a single aquifer.

Tandalgoo Sandstone

The Tandalgoo Sandstone is of continental origin, and consists of red–brown medium sandstone with minor interbeds of siltstone and shale (Towner & Gibson, 1983). It has no outcrops, and is limited to the Kidson Sub-basin, where it has a maximum thickness of 733 m in Kidson No. 1, and part of the Barbwire Terrace, where it is only 72 m in Matches Springs No. 1 and 94 m in Barbwire No. 1 (Fig. 12).

The depth of cover of the Tandalgoo Sandstone ranges from 721 m (Kemp Field No. 1) to 1837 m (Kidson No. 1) in the Kidson Sub-basin (Fig. 13), and from 1706 m (Matches Springs No. 1) to 364 m (Barbwire No. 1) on the Barbwire Terrace.

Estimation of hydraulic heads

In this study, no potentiometric data were available for Palaeozoic aquifers, so hydraulic heads were estimated from information available in well completion reports.

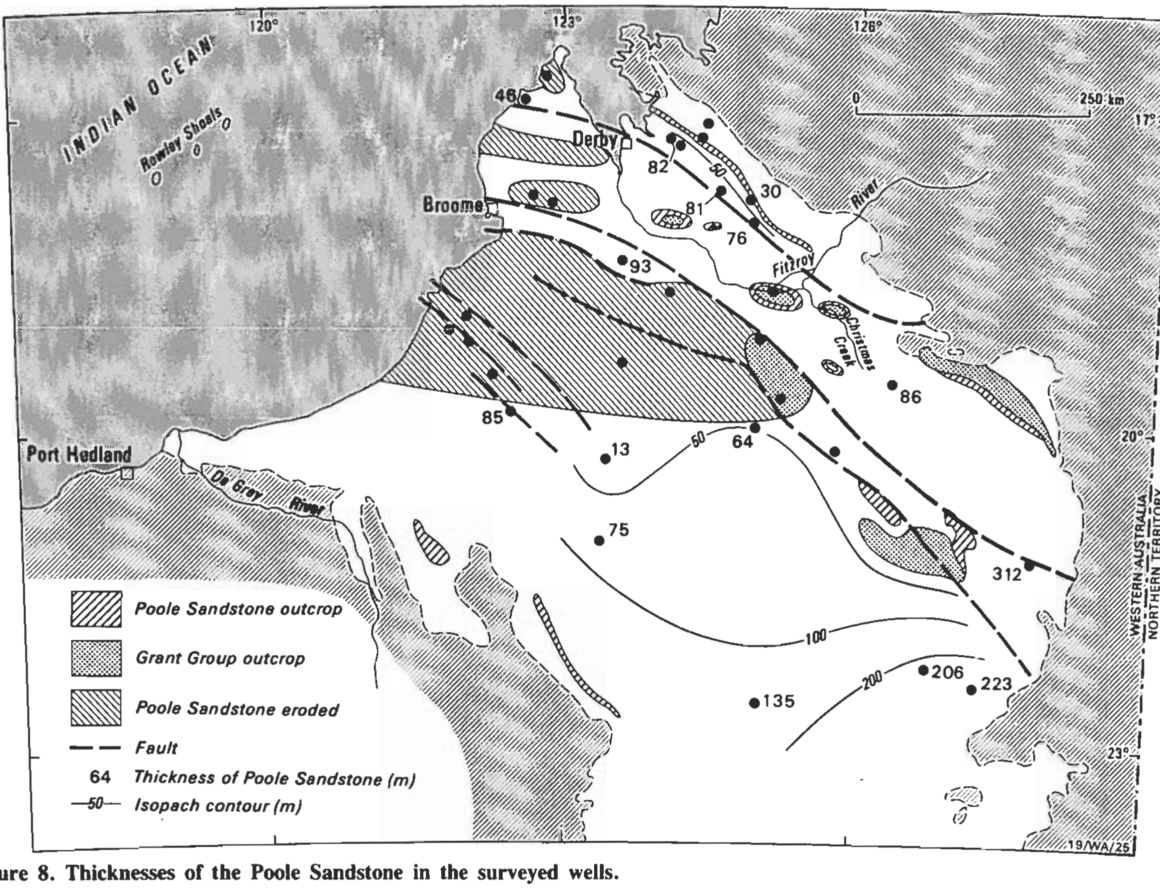

Figure 8. Thicknesses of the Poole Sandstone in the surveyed wells.

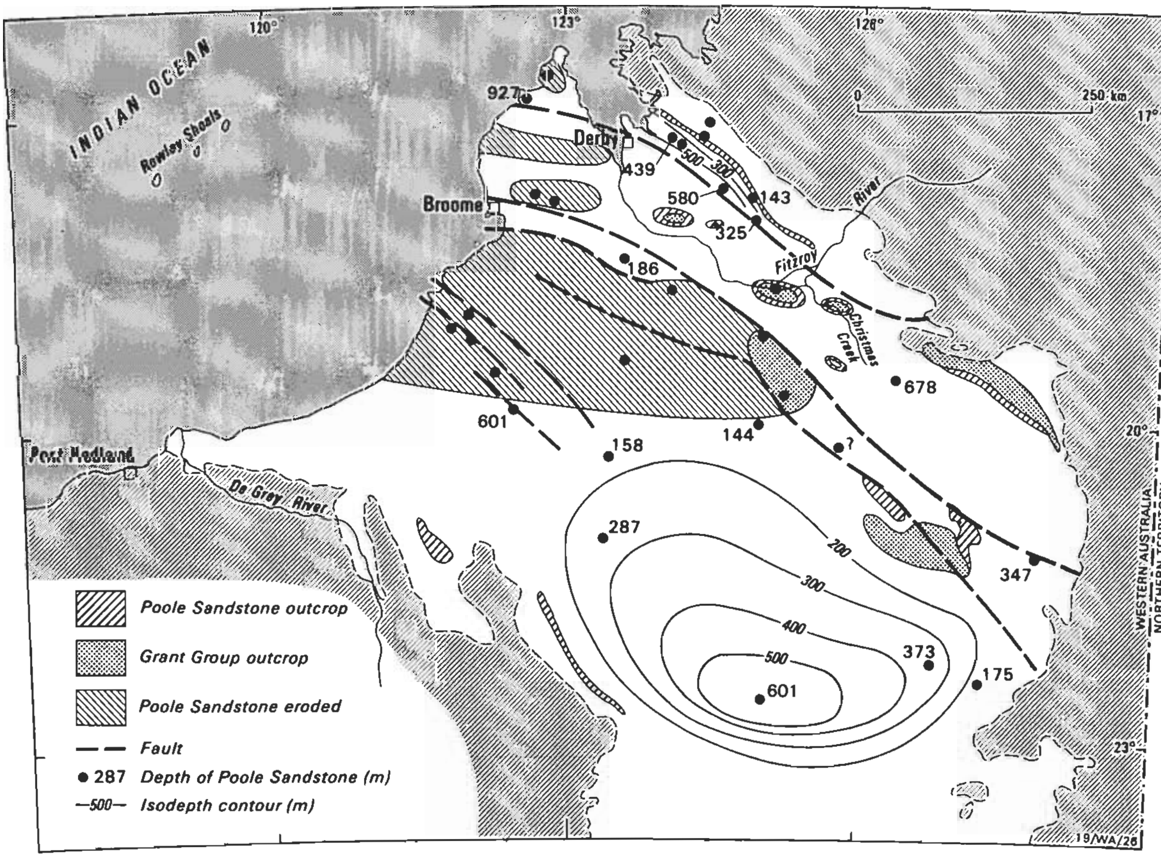

Figure 9. Depths of the Poole Sandstone in the surveyed wells.

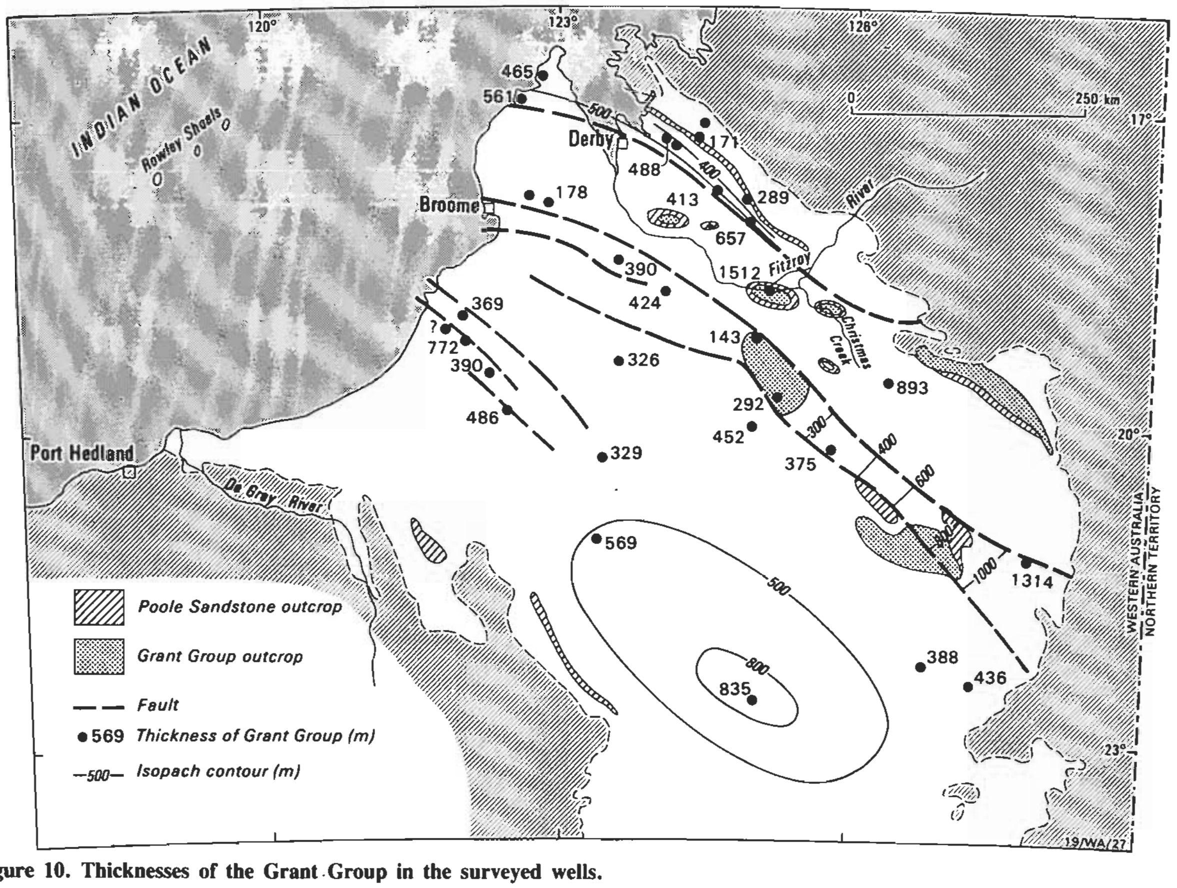

Figure 10. Thicknesses of the Grant Group in the surveyed wells.

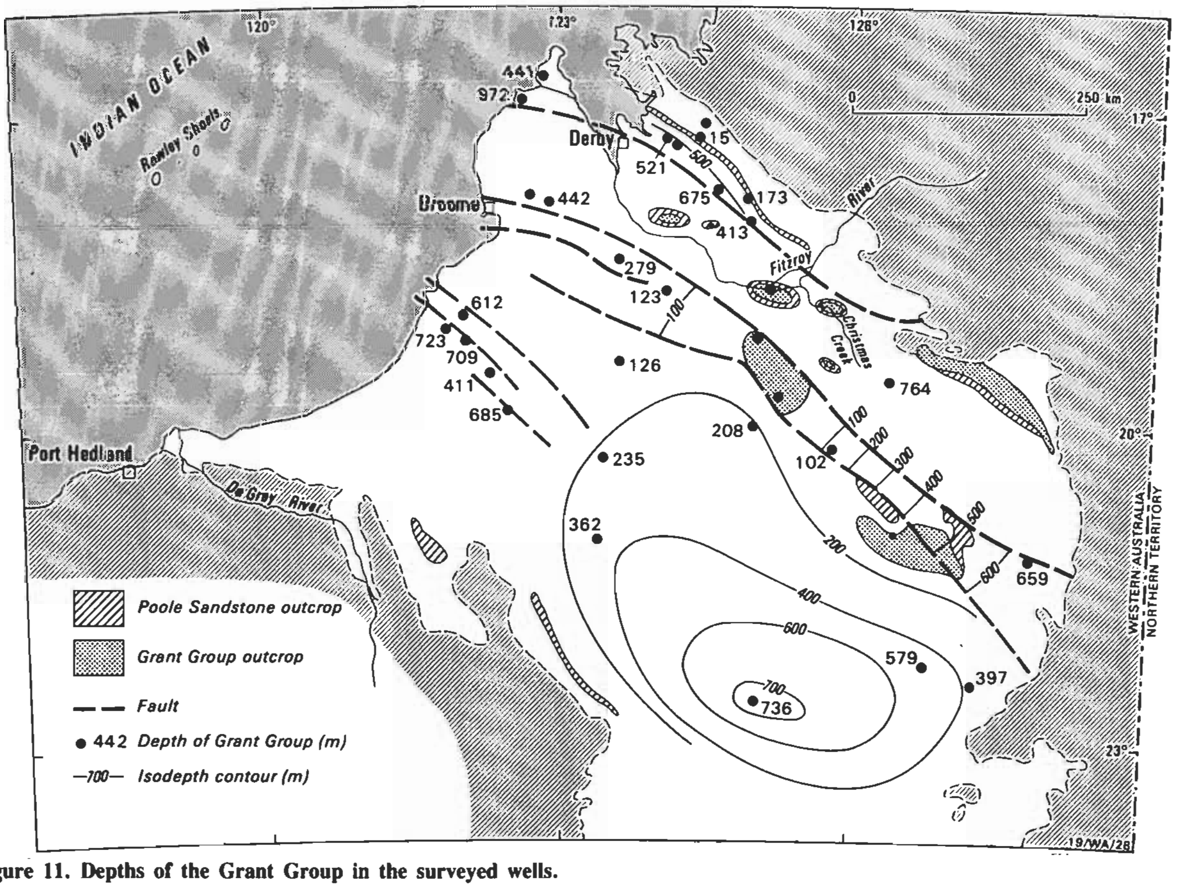

Figure 11. Depths of the Grant Group in the surveyed wells.

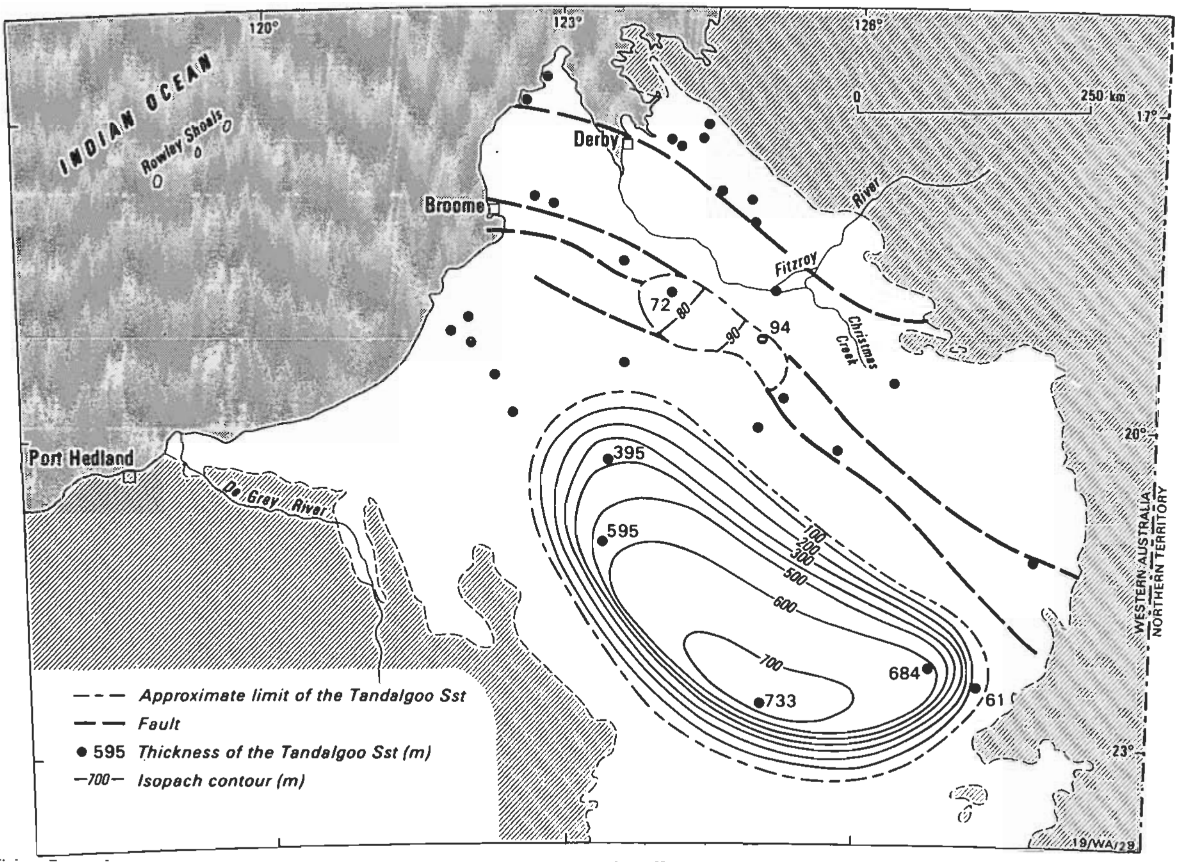

Figure 12. Thicknesses of the Tandalgoo Sandstone in the surveyed wells.

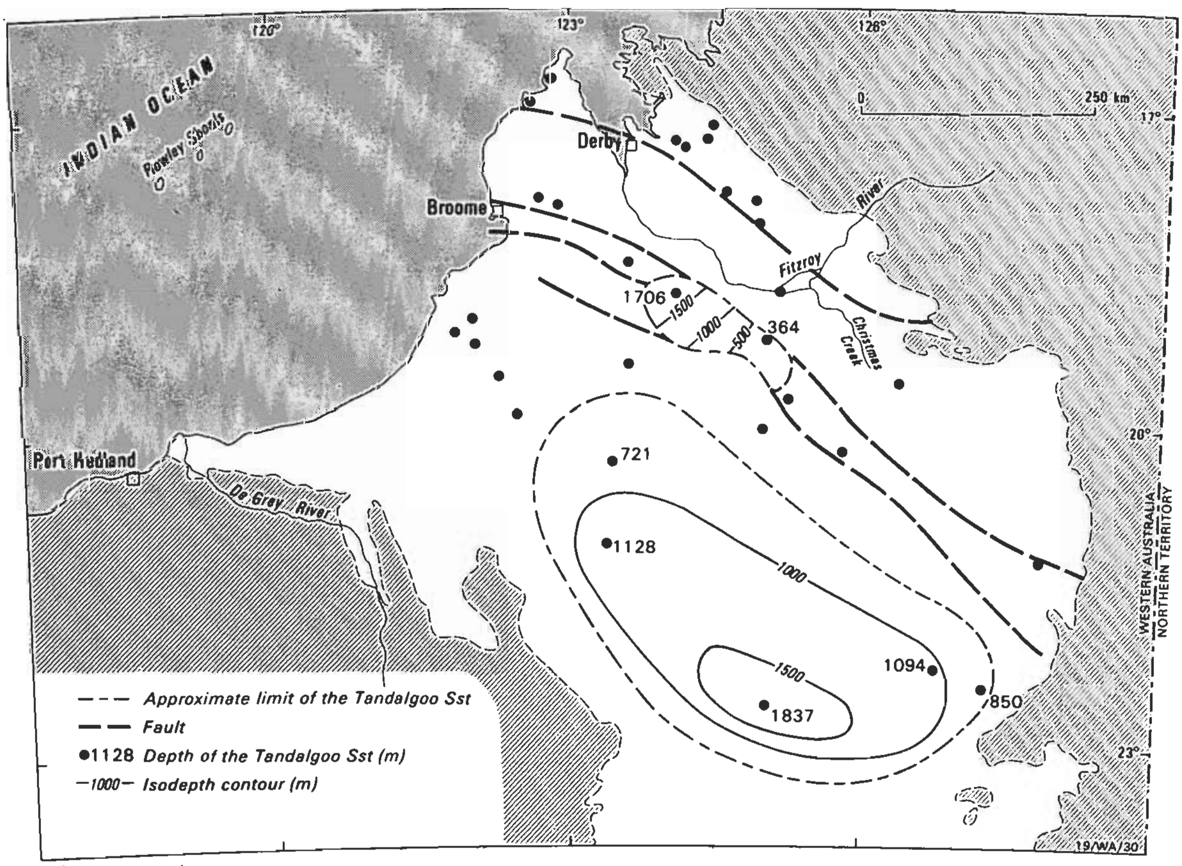

Figure 13. Depths of the Tandalgoo Sandstone in the surveyed wells.

According to Freeze & Cherry (1979), the hydraulic head, h, at point p in a porous medium is defined by the relation:

$$h = z + \frac{P}{\rho g}$$

where:

h = hydraulic head (L)
z = elevation of point p with respect to a reference datum (L)
P = fluid pressure at point p ($M\ L^{-1}T^{-2}$)
ρ = density of the formation fluid ($M\ L^{-3}$), and
g = gravitational constant ($L\ T^{-2}$)

The elevation head, z, is readily available, and, if the formation pressure is also known, then the value of the hydraulic head, h, can be calculated.

As a first approximation in our investigation, the formation pressure at a particular depth was considered to be in equilibrium with the pressure exerted by the column of drilling fluid at the same depth. This was based on the assumption that drillers usually adjust the drilling fluid density to the formation pressure encountered or expected. Application of this method produced very high and unrealistic hydraulic heads in the order of a few hundred metres above the ground surface, because the drilling fluid must be of higher density to fulfil other functions, such as preventing caving-in of the formations (Chilingarian & Vorabutr, 1981).

To obtain a realistic estimate of the hydraulic heads, formation pressures measured during drill stem tests (DST) have been analysed (Table 4), and plotted against depth (Fig. 14). The measured pressures are generally below the hydrostatic gradient line of 0.433 psi ft^{-1} (10 kPa m^{-1}). The only exception is Yullero No. 1, which has a pressure of 6600 psi (45.51 MPa) at a depth of 11 100 ft (3383.3 m), representing a pressure gradient of 0.6 psi ft^{-1} (14 kPa m^{-1}). This exceptionally high pressure has been measured in a deep lens of sandstone surrounded by siltstone and shale, and containing natural gas.

Further analysis shows that, on average, a column of drilling fluid with a hypothetical density of 7.81 lb gal^{-1} (0.94 g cm^{-3}) would compensate the formation pressure in the combined Poole Sandstone and Grant Group aquifers, while a higher density of 8.19 lb gal^{-1} (0.98 g cm^{-3}) is required for the Tandalgoo Sandstone. On the basis of this analysis, hydraulic heads equivalent to fresh water have been calculated using a simple computer code. Table 5 provides an example of the computations for the Poole Sandstone and Tandalgoo Sandstone in Contention Heights No. 1 (see the Appendix for the computational procedure).

Groundwater-flow pattern

Based on the estimated hydraulic heads described in the previous section, potentiometric maps of the combined Poole Sandstone and Grant Group aquifer and the Tandalgoo Sandstone have been prepared in order to provide an impression of the groundwater flow directions in each aquifer.

In the combined Poole Sandstone and Grant Group aquifer, the pattern of the groundwater flow system is complex owing to faulting and erosional effects. However, the following trends are clear (Fig. 15):

- in the Kidson Sub-basin, groundwater flow is from the

Table 4. Measured formation pressures for a number of tested stratigraphic units (see Fig. 14)

No.	*Unit*	*Well name*	*DST*	*Depth (ft)*	*Depth (m)*	*Formation pressure (psi)*	*Formation pressure (MPa)*	*Equivalent drilling fluid density* (lb gal⁻¹)*	*Equivalent drilling fluid density* (g cm⁻³)*
1	Poole Sst	Point Moody No. 1	3	1773	540.4	693	4.78	7.52	0.90
2	Grant Gp	McLarty No. 1	1	940	286.5	352	3.42	7.20	0.86
3	Grant Gp	Willara No. 1	1A	2576	785.2	1142	7.87	8.52	1.02
4	Grant Gp	Point Moody No. 1	2	4693	1430.4	1946	13.42	7.98	0.96
5	'Yulleroo Fm'	Yulleroo No. 1	6	11100	3383.4	6600	45.51	11.45	1.37
6	Van Emmerick Cgl	Napier No. 5	1	2840	865.6	1025	7.07	6.94	0.83
7	Reef complex	Matches Springs No. 1	1	1846	562.7	730	5.03	7.60	0.91
8	Reef complex	Hawkstone Peak No. 1	2	2539	773.9	1087	7.49	8.23	0.98
9	Reef complex	Hawkstone Peak No. 1	3A	3135	955.5	1346	9.28	8.26	0.99
10	Poulton Fm	Napier No. 5	2	5257	1602.3	2025	13.98	7.41	0.89
11	Tandalgoo Sst	Kemp Field No. 1	2	2741	835.5	1174	8.09	8.24	0.98
12	Tandalgoo Sst	Matches Springs No. 1	2	5764	1756.9	2435	16.79	8.13	0.97

*Fresh-water density = 8.34 lb gal^{-1}
The 'Yulleroo Formation' is an equivalent of the Laurel Formation (Fairfield Group; Forman & Wales, 1981, appendix 3).

Table 5. Example of the computational procedure for the hydraulic heads for the Poole and Tandalgoo Sandstones in Contention Heights 1.

Well name: Contention Heights 1
Location: lat. 22°25'36"S, long. 127°13'31"E
Elevation: ground surface — 1377.0 ft, 419.7 m; rotary table — 1392.0 ft, 424.3 m (1)

Formation	*Lithology*	*(2) Depth (ft)*	*(3) EDFD¹ (lb gal⁻¹)*	*(4) Geostatic ratio (Psi ft⁻¹) (3) × 0.052*	*(5) Fluid pressure (Psi) (2) × (4)*	*(6) Elevation head (ft) –(2)*	*(7) Pressure head EFW² (ft) (5)/0.433*	*(8) Hydraulic head from: rotary table (ft) (6) + (7)*	*(9) Hydraulic head from: rotary table (m)*	*(10) Hydraulic head from: Australian Height Datum (m) (9) + (1)*
Poole Sst	Sandstone	573.0	7.81	0.406	232.7	–573.0	537.4	–35.6	–10.8	413.4
Tandalgoo Sst	Sandstone	2790.0	8.19	0.426	1188.2	–2790.0	2744.1	–45.9	–14.0	410.3

¹EDFD = equivalent drilling fluid density; ²EFW = equivalant fresh water

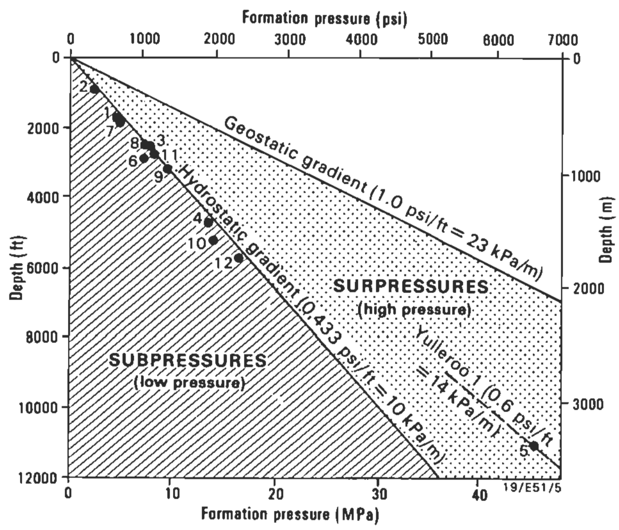

Figure 14. Measured formation pressures in drill stem tests *v.* depths (see Table 4).

southern margin toward the centre of the Canning Basin, and Dummer Range Fault;

- in the Lennard Shelf, groundwater flows toward the Fitzroy Trough;
- in the Fitzroy Trough, groundwater flows from southeast to northwest;
- in the Willara Sub-basin, the aquifer is cut by a number of faults, providing a complex pattern which is not possible to define clearly; and
- potentiometric heads are negative (below the Australian Height Datum, AHD) in some parts of the coast; consequently sea-water intrusion has been facilitated, and groundwater salinity is high in these regions (see *Groundwater salinity* below).

This aquifer is probably generally recharged directly through its outcrops, and indirectly from the overlying Mesozoic aquifers (Figs. 5 to 7). Fault systems play a major role in the discharge of groundwater toward the Indian Ocean.

The Tandalgoo aquifer is much less affected by faults. The general direction of the groundwater flow in this aquifer in the Kidson Sub-basin and Barbwire Terrace is from southeast to northwest (Fig. 16). The aquifer does not crop out; it is recharged indirectly via the Grant Group, and discharges into the same unit (Figs. 5 to 7).

Groundwater velocity

Groundwater velocity can be estimated from the relation:

$$V = \frac{Ki}{\Theta}$$

where:

V = average groundwater velocity (LT^{-1})
K = hydraulic conductivity (LT^{-1})
i = hydraulic gradient (dimensionless)
Θ = porosity (dimensionless)

For the combined Poole Sandstone and Grant Group aquifer, the average hydraulic conductivity of 0.088 m per day (Table 3), porosity of 12%, and hydraulic gradient of 1/1500 results in an estimated velocity of about 0.2 m y^{-1} or a travel time of 5000 y km^{-1}.

The Tandalgoo aquifer has a hydraulic conductivity of 0.426 m per day, porosity of 17%, and hydraulic gradient of 1/1700, which compute to an average estimated groundwater velocity of about 0.5 m y^{-1} and a travel time of 2000 y km^{-1}.

It should be noted that as the hydraulic conductivity, hydraulic gradient, and porosity vary from one part of the aquifer to another, and particularly as the hydraulic conductivity and hydraulic heads have been estimated rather than being measured, values provided for the groundwater velocity and travel time should be regarded as rough estimates, and treated cautiously.

Groundwater salinity

Groundwater salinity was estimated from well logs by Archie, Ratio, and SP methods (Schlumberger, 1972). These estimates were supplemented by a limited number of measurements on formation water samples taken during DSTs and from oil production wells on the Lennard Shelf. Salinity (Figs. 17, 18, and 19) generally is moderately low in recharge areas, and increases along the flow lines (Figs. 18 and 19) and, with depth (Fig. 20).

In the Grant Group, salinity close to the Willara Sub-basin has been increased locally by the dissolution of the evaporites from the Carribuddy Group (e.g., in Munro No. 1; Figs. 5 and 18). Salinity is also high near the shore (Pender No. 1, Tappers Inlet No. 1, and May River No. 1) because of the combined effects of intrusion of sea water and salinity increase along the flow lines. Groundwater in the Grant Group in Lake Betty No. 1 and Point Moody No. 1 has high salinity (6500 mg L^{-1} and 17 000 mg L^{-1} respectively), but the reasons why are not clear.

Groundwater salinity in the Tandalgoo Sandstone increases along the flow lines from 2800 to 7110 mg L^{-1} in the Kidson Sub-basin, and from 3700 to 8500 mg L^{-1} on the Barbwire Terrace.

Groundwater temperature

Burne & Kantsler (1977) studied the geothermal gradient in the Canning Basin using temperature data derived from bottom-hole temperatures (BHT) taken routinely during the logging of petroleum exploration wells. According to their analysis, the Canning Basin has a geothermal gradient range of between 10 and 30°C km^{-1}, which is comparable with the normal world-wide gradient range of 18–29°C km^{-1} (Klemme, 1975) and the world mean gradient of 25°C km^{-1} (Lee & Uyeda, 1965). Four small areas in the basin have a high gradient of 40–46°C km^{-1}, and broader areas have low gradients. This distribution was considered to correspond closely to variations in depth to magnetic basement: high gradients occur in areas of shallow basement.

In this analysis, groundwater temperatures have been estimated using linear correlation of the measured BHT*v*. depth, assuming an average surface temperature of 30°C for the basin (Cull, 1978), and taking into account the depth of each aquifer.

Maps of the estimated groundwater temperatures in the Palaeozoic aquifers (Figs. 21–23) show the gradual increase of the groundwater temperature from the top of the Poole Sandstone to the base of the Tandalgoo Sandstone. According to Table 6 the maximum temperatures occur at the base of the Tandalgoo Sandstone at a depth of 2750 m in Kidson No. 1.

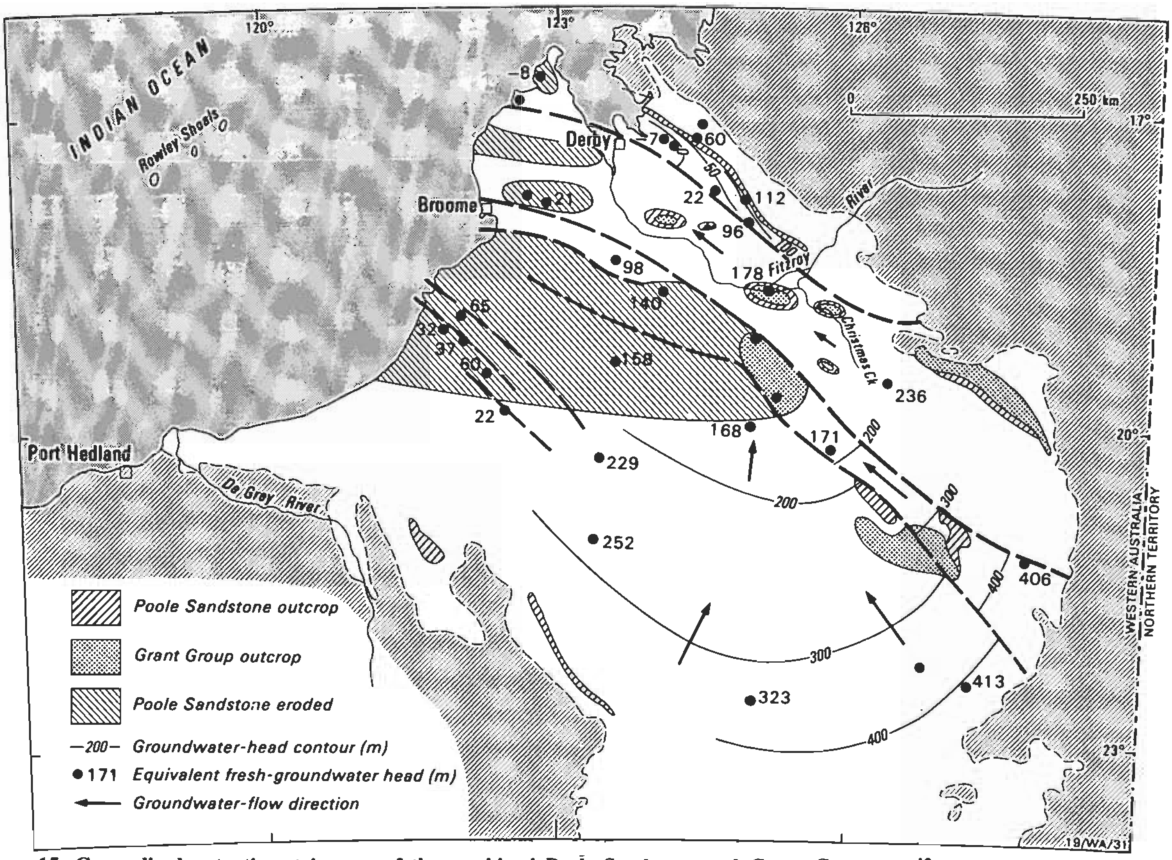

Figure 15. Generalised potentiometric map of the combined Poole Sandstone and Grant Group aquifer.

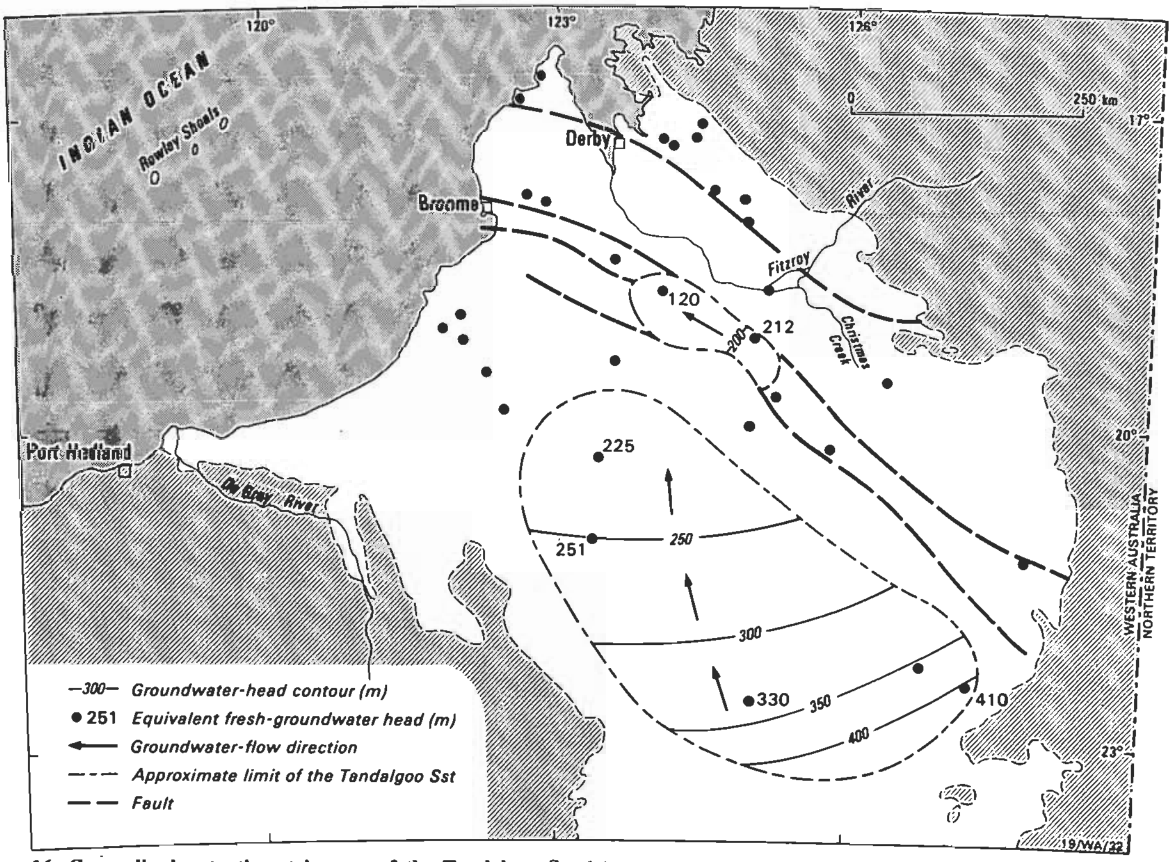

Figure 16. Generalised potentiometric map of the Tandalgoo Sandstone.

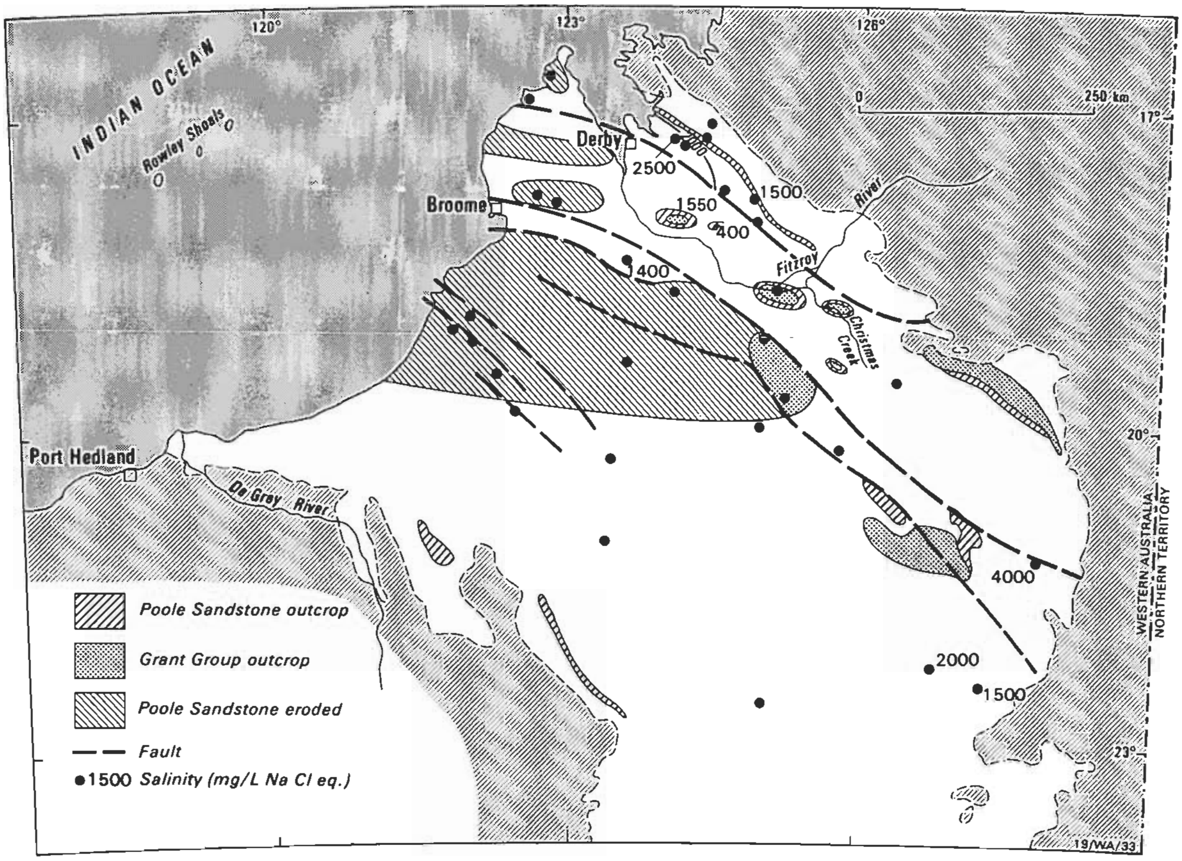

Figure 17. Groundwater salinity of the upper part of the Poole Sandstone for a limited number of wells.

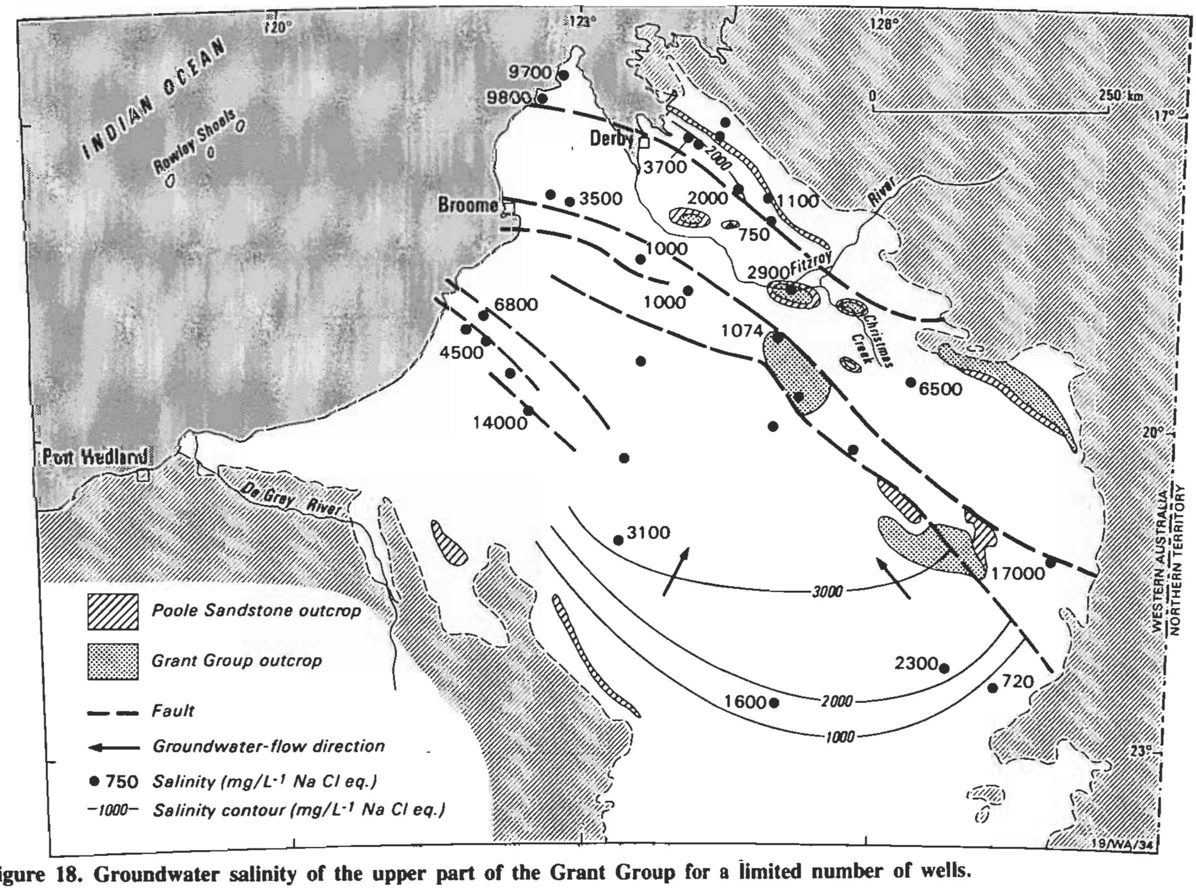

Figure 18. Groundwater salinity of the upper part of the Grant Group for a limited number of wells.

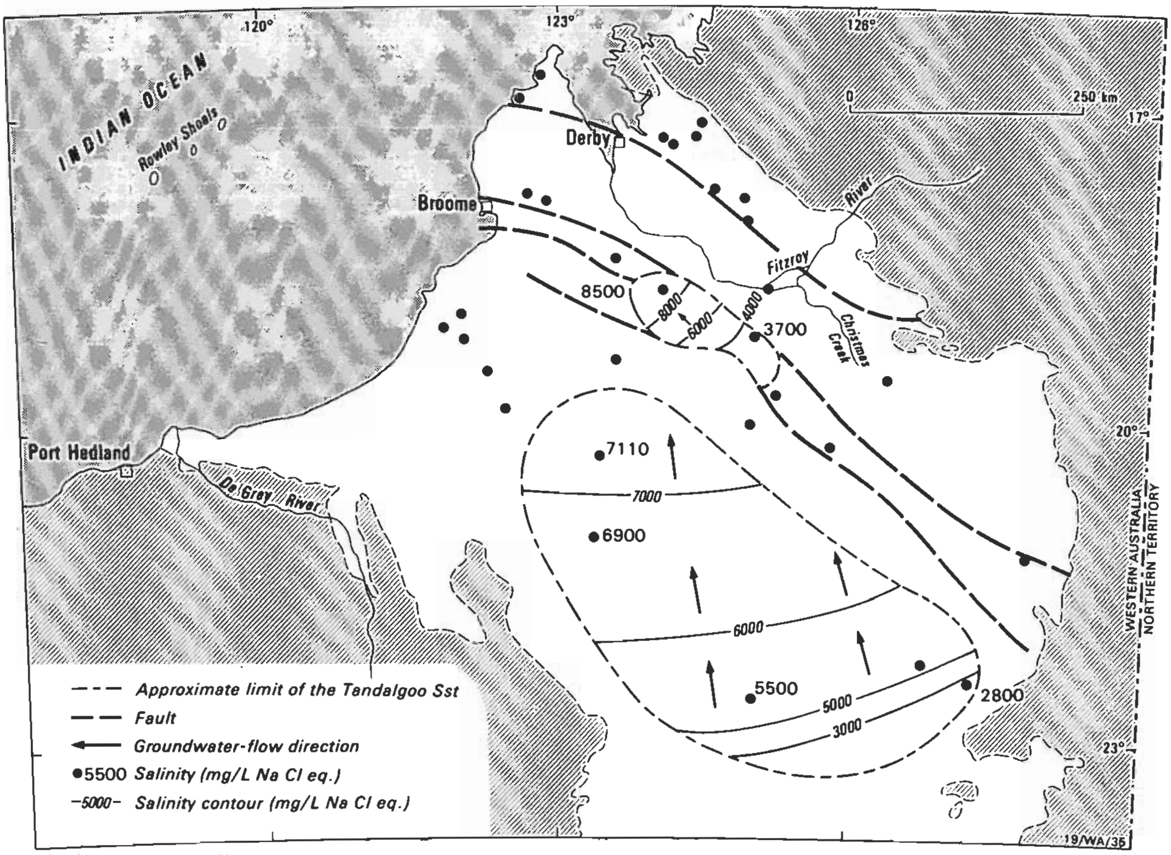

Figure 19. Groundwater salinity of the upper part of the Tandalgoo Sandstone for a limited number of wells.

Table 6. Maximum estimated temperatures for the Palaeozoic aquifers

Aquifer	*Max. temp. (°C)*	*Location*	*Depth (m)*
Poole Sandstone	49	Munro No. 1	686
Grant Group	74	Point Moody No. 1	1973
Tandalgoo Sandstone	83	Kidson No. 1	2750

Zinc–lead mineralisation

MVT epigenetic Zn–Pb sulphide deposits throughout the world are hosted by carbonate rocks ranging from Precambrian to Mesozoic in age. Fluid-inclusion studies suggest that they formed from metalliferous basinal brines in the temperature range of 50–150°C. Most of the known deposits are found at the edges of sedimentary basins, and a fluid source in the deeper portions of the basin is usually invoked. Current genetic models imply two main driving forces for fluid migration leading to concentration of Zn–Pb sulphides. They are:

- compaction-driven fluid flow, either stratifugic fluid flow, or episodic-dewatering fluid flow; and
- gravity-driven fluid flow.

The stratifugic model involves the movement of deep fluids toward basin margins as a result of sediment compaction during normal basin evolution (Noble, 1963; Jackson & Beales, 1967). Episodic dewatering has been described as the result of decompression of geopressured zones (such as those observed in the US Gulf Coast; Dickinson, 1953), which is dissipated by episodic bursts of the pressured deep brines towards basin margins (Sharp, 1978; Cathles & Smith, 1983). The gravity or topography-driven flow model is based on tectonic uplift as the driving force for fluid flow (Garven & Freeze, 1984).

In the Canning Basin, Zn–Pb sulphide deposits occur in the Lennard Shelf and along the Admiral Bay Fault. In the Lennard Shelf, the host rock is the Devonian reef complex, and the ore deposits contain mainly sphalerite (ZnS) and galena (PbS). The

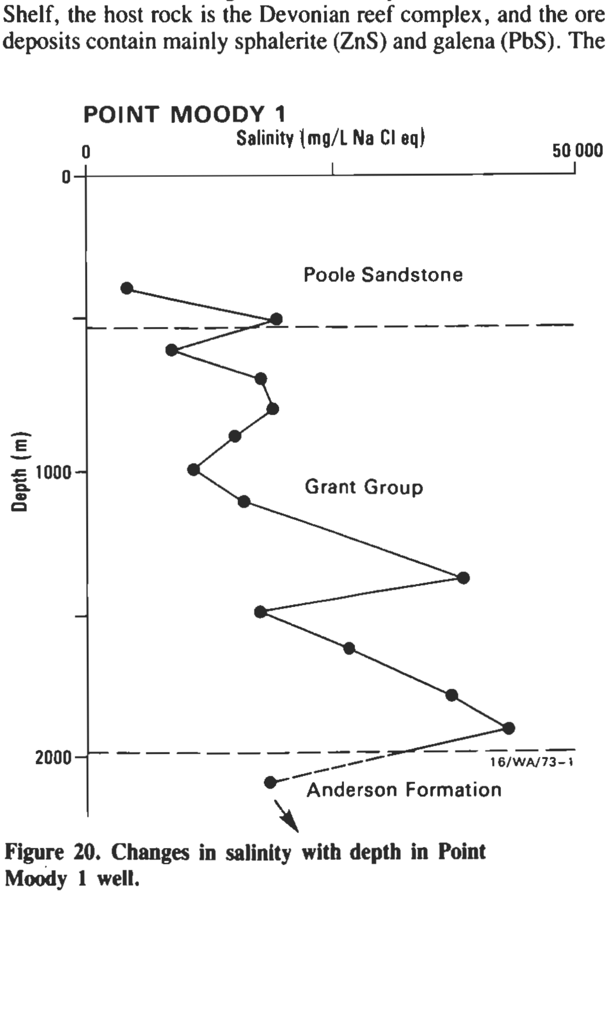

Figure 20. Changes in salinity with depth in Point Moody 1 well.

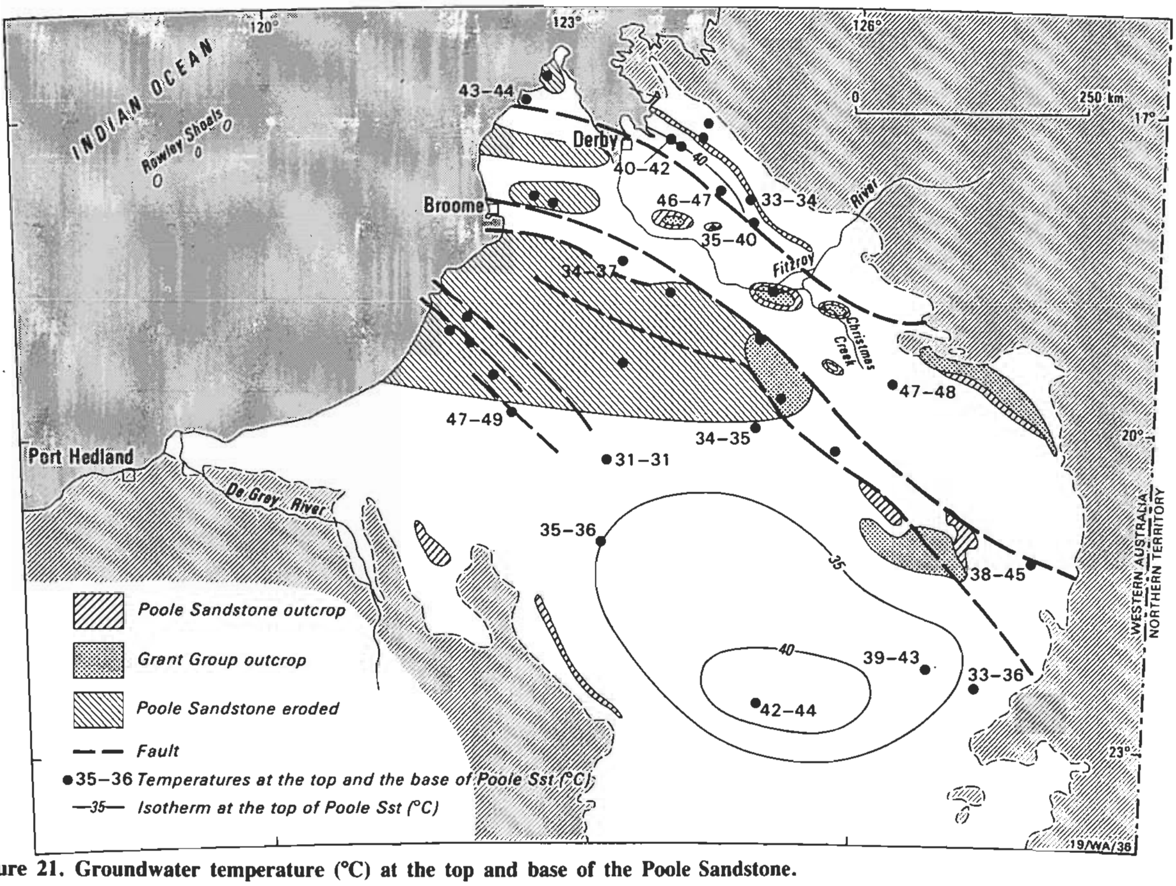

Figure 21. Groundwater temperature (°C) at the top and base of the Poole Sandstone.

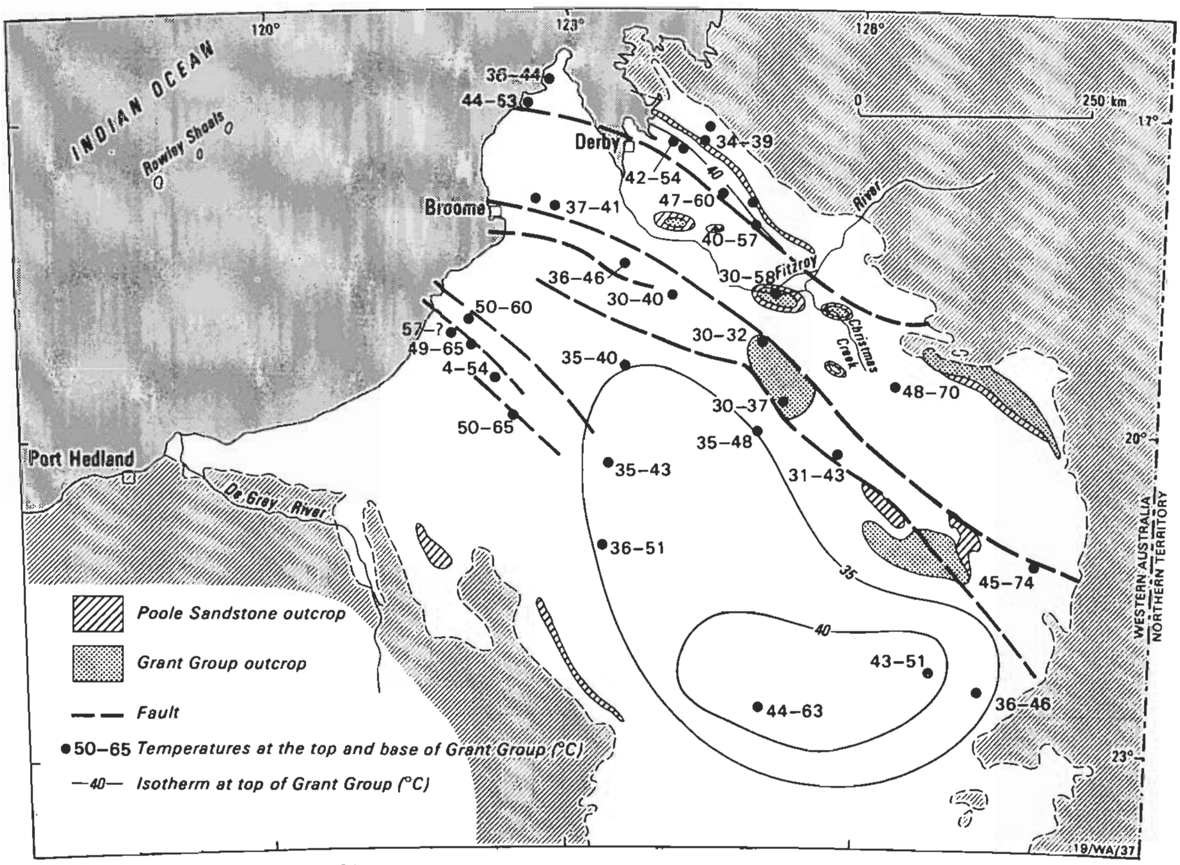

Figure 22. Groundwater temperature (°C) at the top and base of the Grant Group.

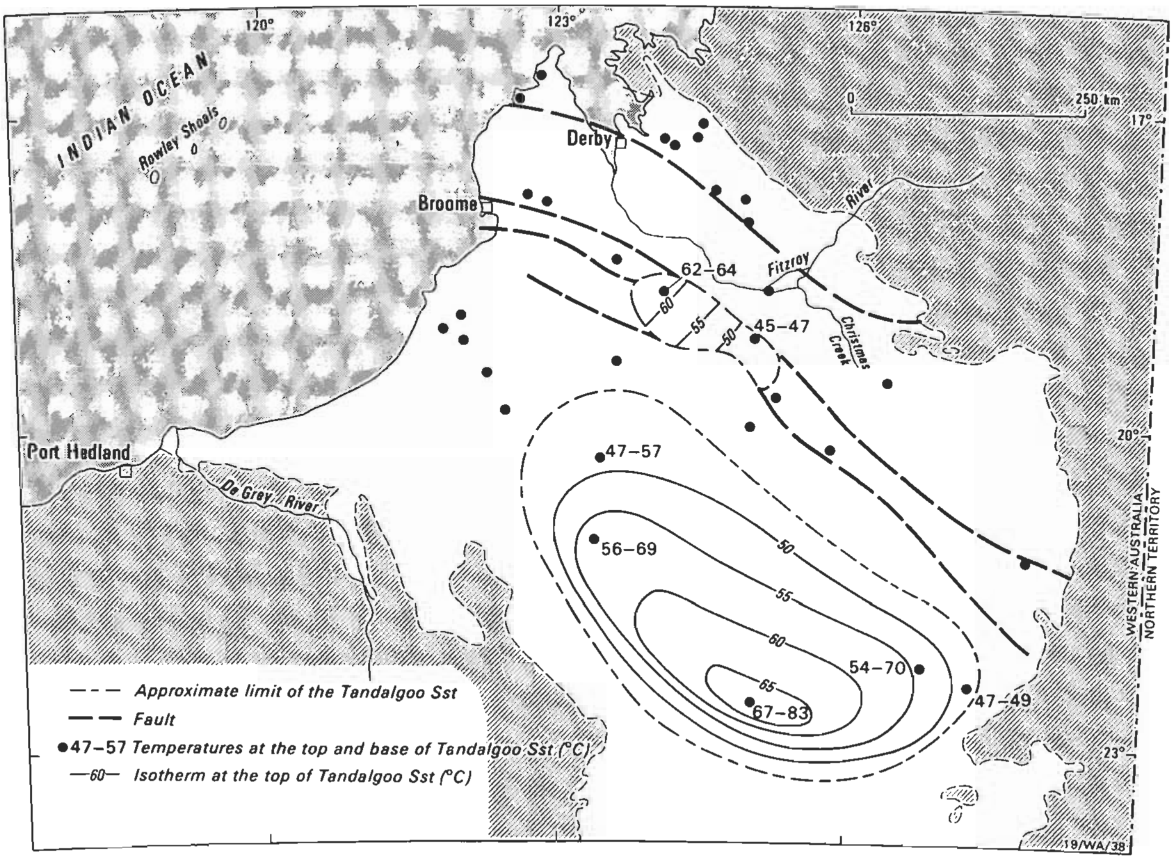

Figure 23. Groundwater temperature (°C) at the top and base of the Tandalgoo Sandstone.

largest deposit found to date in this area is at Blendevale (Fig. 3), which contains an estimated 20 Mt ore at 8.3% Zn and 2.5% Pb; the smaller Cadjebut deposit has a reserve of 3 Mt ore at 13.8% Zn and 4.4% Pb (Murphy, 1990). In the Admiral Bay Fault area, massive sulphide deposits occur at a depth of about 1500 m (Connor, 1990) in the Goldwyer Formation, Nita Formation, and Carribuddy Group, which range in age from Ordovician to Silurian (Fig. 2).

Fluid-inclusion studies (Lambert & Etminan, 1987; Etminan & Hoffman, 1989) of sphalerite indicate that the temperature at the time of deposition was around 100–110°C, and that the fluids were highly saline (>200 000 mg L^{-1} NaCl eq.).

As a general observation, the distribution of the Zn–Pb deposits in the Lennard Shelf might indicate that ore-forming fluids travelled northward and northeastward from the Fitzroy Trough. Also, the location of the Admiral Bay Zn–Pb deposit might reflect fluid flow from the Willara Sub-basin toward its north and northeast margins.

We tested the applicability of the fluid-flow models to the Canning Basin data. The episodic-dewatering model appears to be applicable, at least locally, to the formation of banded sphalerite in the Lennard Shelf MVT deposits. A geopressured zone (the only one observed in our investigation) was identifed in Yulleroo No. 1. There, the abnormally high pressure, high temperature, and high salinity of the groundwater, together with its hydrochemical characteristics, suggests that the ore-forming fluids could have been expelled from marine evaporites partly into deep-seated sandstone lenses. These geopressured lenses might then have been faulted, and the potential ore-forming fluids released.

With regard to the stratifugic and gravity-driven fluid-flow models, precise data on the age of the mineralisation, tectonic history, and palaeotopography during the Silurian to Permian interval (when Zn–Pb mineralisation is considered to have occurred in the basin) is not available. However, BMR is currently carrying out a sedimentary basin analysis of the Canning Basin. This is expected to provide a more comprehensive database relevant to a palaeofluid-flow model for the Zn–Pb mineralisation.

Conclusions

Based on a limited number of petroleum exploration wells, our reconnaissance investigation has identified the Poole Sandstone, Grant Group, and Tandalgoo Sandstone as major Palaeozoic aquifers in the Canning Basin, and attempted to provide an estimate of their hydraulic characteristics.

The temperature and salinity ranges in these aquifers are currently much lower than those required for the formation of the Zn–Pb deposits. Moreover, the general pattern of the present-day groundwater movement is from the margins toward the centre of the basin, and from there towards the sea. This information suggests that the present hydrogeological regime is basically different from those active in the Silurian to Permian. This implies that the high-temperature, high-salinity ore-forming fluids were probably generated in the deeper parts of the basin, and travelled towards the basin margins and/or along major faults, where they deposited Zn–Pb sulphides in favourable conditions.

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Appendix: Computational procedure for the estimation of the hydraulic heads (see Table 5).

1. The computer code reads the well name, location, and ground-surface and rotary-table elevations.
2. For each geologic unit, the computer code reads the name, lithology, depth, and value of equivalent drilling fluid density which would compensate the pressure (column 3).
3. In column (4), the value of column (3) is multiplied by 0.052, which is a factor converting lb gal^{-1} to psi ft^{-1} (Whittaker, 1985).
4. In column (5), the fluid pressure is computed by multiplying columns (2) and (4).
5. Column (6) shows the elevation head, or the value of column (2) with negative signs.
6. In column (7) the equivalent fresh-water (EFW) pressure head is computed by dividing column (5) by 0.433, which is the normal pressure gradient for fresh water in psi ft^{-1} (Whittaker, 1985).
7. In column (8), the hydraulic head is computed in feet by adding columns (6) and (7).
8. In column (9), the computed hydraulic head in column (8) is converted to metres.
9. In column (10), the computed head with respect to the rotary table is computed with respect to the AHD by adding column (9) to the elevation of the rotary table in metres (1).
10. The procedure is repeated from 2 to 9 for the other stratigraphic units in the same well.
11. A table similar to Table 5 is printed for each well.
12. The procedure is repeated from 1 to 11 for other wells.

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Hydrogeological modelling for an arid-zone borefield in Amadeus Basin aquifers, Alice Springs, Northern Territory

P.B. Jolly[1] & D.N. Chin[1]

Water supply for the town of Alice Springs is obtained from the Roe Creek Borefield, 15 km to the south-southwest. This borefield currently consists of 20 production bores which pump water from four discrete aquifers in three formations in the Amadeus Basin: Mereenie Sandstone, Pacoota Sandstone (2), and Shannon Formation. Annual extraction is of the order of 10×10^6 m^3, of which more than 80 per cent comes from the Mereenie Sandstone. Peak daily extraction rates are 55 000 m^3. Regional investigations show that the Mereenie Sandstone will continue to be the major source of Alice Springs water supply.
Models have been developed to determine the economically sustainable yield from the Roe Creek Borefield. These models indicate that borefield abstraction is primarily from local aquifer storage, and, as such, drawdown is linearly related to total withdrawal from the aquifers.

Introduction

Alice Springs is close to the geographic centre of Australia (Fig. 1). It lies on a small plain on either side of the Todd River. With a mean annual rainfall of 285 mm, Alice Springs is only moderately arid. Most of the rainfall occurs during the summer. Temperatures are moderate to high throughout the year, above 30°C for half of it during the day. Potential evapotranspiration is high, and has been estimated at between 1250 and 1500 mm per year (Mabbutt, 1977).

The water requirements for Alice Springs (population about 24 000) are fulfilled by the Roe Creek Borefield, 15 km to the south-southwest. This borefield is situated at the eastern end of an easterly trending broad fold (Fig. 1) in the Amadeus Basin. This fold covers an area of 50 000 km^2, and comprises a continuous series of discrete or poorly interconnected aquifers with a regional groundwater flow from west to east.

The borefield currently has production bores in four separate aquifer systems in three formations: Mereenie Sandstone, Pacoota Sandstone, and Shannon Formation; the Mereenie Sandstone produces more than 80 per cent of demand.

The Roe Creek Borefield

Alice Springs was first established in 1871. Until 1964 the town obtained its water supply from alluvial sediments of the Todd River. In 1964 the Roe Creek Borefield was commissioned, to draw water solely from the Mereenie Sandstone. In 1984, the borefield was expanded by the commissioning of two production bores in the Pacoota Sandstone.

Current annual extraction from the Roe Creek Borefield is in the order of 10 million m^3 obtained from 20 production bores pumping from up to 170 m below ground level. Peak daily consumption approaches 55 000 m^3.

Production bores P1 to 21 and P24 and 25 (Fig. 2) extract water from the Mereenie Sandstone, though production bores P1 to 7 have been decommissioned. Production bores P22 and 23 extract water from the upper part of the Pacoota Sandstone, and P26 from the lower part. Production bore P27 extracts water from the upper Shannon Formation. All production bores, except P27, extract water from aquifers developed in porous sandstone. P27 extracts water from solution-enlarged fractures within a dolomite aquifer. The quality of water from all aquifers is good: total dissolved solids are in the range 350 to 650 mg L^{-1}, and hardness is in the range 130 to 230 mg L^{-1}.

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Hydrogeology of the borefield

The Alice Springs Orogeny, 350 Ma ago, is believed to have provided the environment for fracturing and deep chemical weathering, which resulted in the formation of the high-yielding aquifers in each of the formations exploited by the Roe Creek Borefield (Jolly & others, 1991). Aquifer development in the borefield has been controlled by the extent of fracturing and weathering associated with:

- *for the Mereeenie and Pacoota Sandstones* — the erosion feature south of Iwupataka (Fig. 1), where the Pertnjara Group transgresses the Mereenie Sandstone and Pacoota Sandstone (Larapinta Group); and
- *for the Shannon Formation* — the Tertiary basin (containing up to 300 m of lacustrine and fluvial sediments) to the southeast of Alice Springs (Fig. 1).

The major producing aquifer is and will continue to be that in the Mereenie Sandstone. This formation has a true thickness of about 365 m (drilled thickness 425 m) in the borefield. Jolly & others (1991) have divided it into three hydrogeological units — A (base), B, and C. The approximate true thickness of each of these units is: unit A, 150 m; unit B, 100 m; and unit C, 115 m.

Variations in yield and competence of the Mereenie Sandstone have been attributed to a combination of how the sandstone was originally deposited and the weathering processes to which it has been since subjected. Unit A represents the transition from a marine to an arid terrestrial environment. Unit B was deposited under extremely arid conditions. Unit C represents the transition from an arid to a very wet, humid environment. Unit A is moderately low-yielding. Unit B is the least competent of the units; formation stability problems encountered in this unit are associated with deep chemical weathering that took place during the Alice Springs Orogeny and later on during the early Tertiary (about 50 Ma ago). Unit C is also moderately low-yielding, except in a small area to the west of Roe Creek. It is, however, in this area that most of the production bores are located.

High yields in unit C in this area are a consequence of large open fractures that are believed to have resulted from the more brittle nature of the sandstone in this area. This brittleness probably resulted from the redistribution of iron during physical and chemical weathering of the Mereenie Sandstone during the Alice Springs Orogeny, when the formation formed the flanks of the valley which is now manifest as the erosion feature south of Iwupataka.

The Pacoota Sandstone consists of interbedded marine sandstone and mudstone that are apparent as shoaling-upward

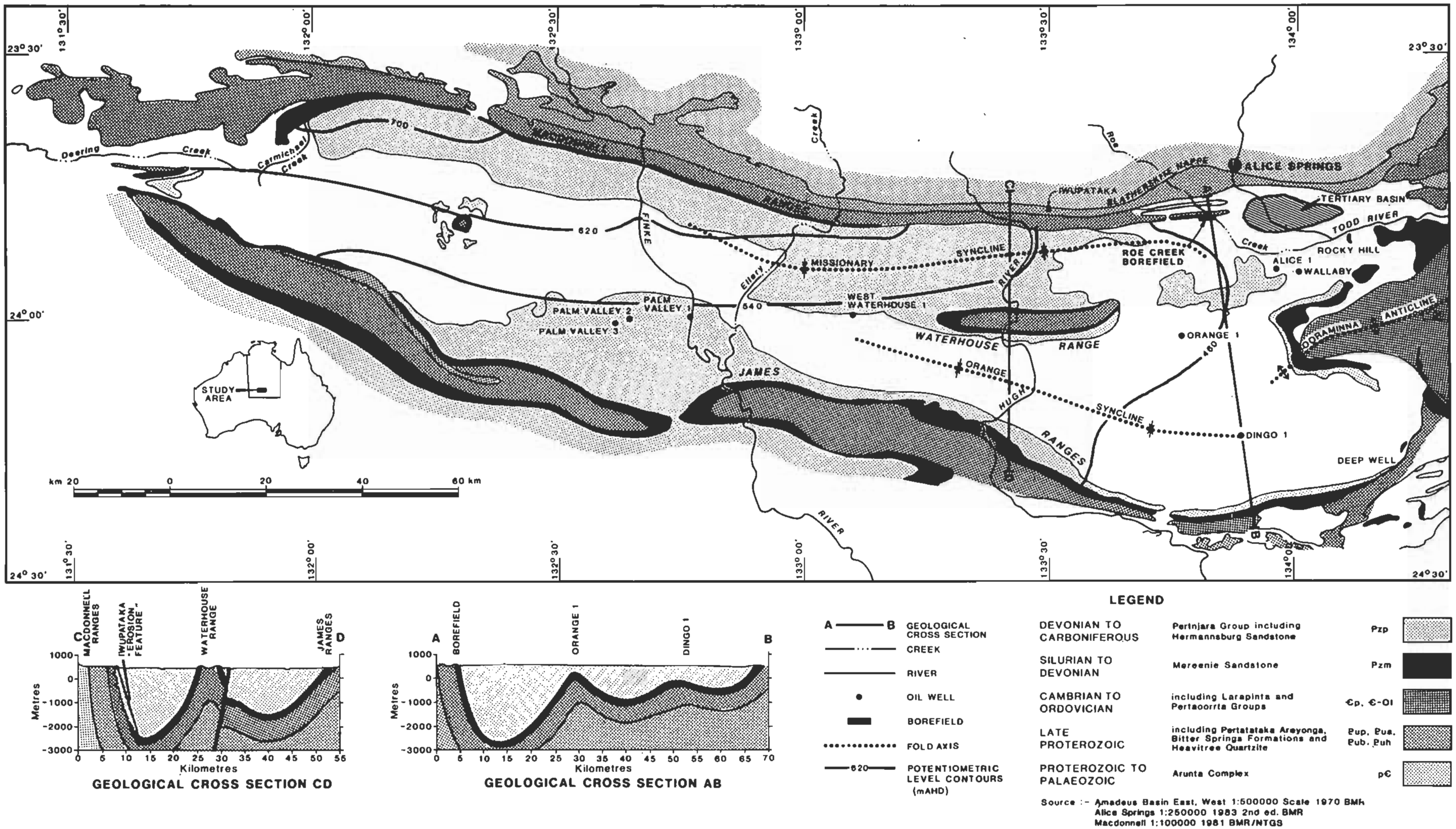

Figure 1. Regional hydrogeology of the study area.
All figures for this paper have been supplied by the authors.

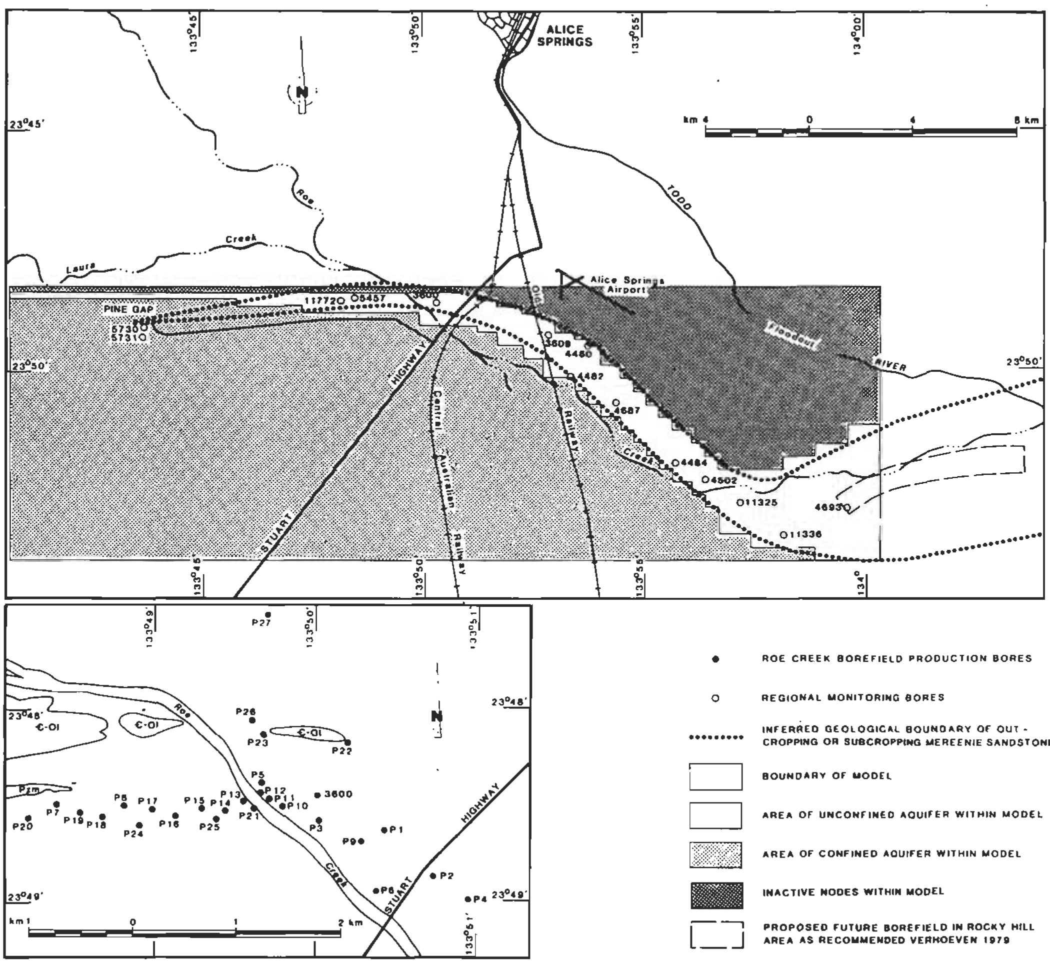

Figure 2. Roe Creek Borefield and local model.
Note that the reference to Verhoeven (1979) in the legend should read 'Verhoeven & others (1979)'.

cycles on geophysical (downhole-gamma) logs (Lau, 1989). Two poorly interconnected aquifers have been identified in mainly sandstone beds separated by a mainly mudstone unit. Secondary porosity in the sandstone is due to solution of carbonate shell fragments (Lau, 1989).

The upper Shannon Formation comprises interbedded dolomite and shale. Production bore P27 intersects an aquifer in a mainly dolomite section where fractures have been enlarged by chemical weathering. Higher yields from the upper Shannon Formation east of Roe Creek are due to early Tertiary deep chemical weathering adjacent to the Tertiary basin (Fig. 1). The erosion feature south of Iwupataka does not transgress this formation.

The permeability and porosity of each of the formations is at its maximum near outcrop. Permeability and porosity markedly decrease with increasing depth because fractures are not as open (owing to the weight of the material above) and chemical weathering is subordinate.

Permeability and porosity characteristics in the borefield have been studied in detail only for the Mereenie Sandstone. These studies have shown that the aquifer in the Mereenie Sandstone is controlled by fracture permeability with hydraulic conductivities in the range 0.02 to 0.1 cm s^{-1}. Porosity values average more than 22%. Examination of data for the Mereenie Sandstone encountered at depth in oil wells indicates that significant permeability and porosity values occur only in unit B, in which hydraulic conductivities are of the order of 10^{-4} cm s^{-1} and average porosities are 10%.

Regional water balance for the Mereenie Sandstone

Regional potentiometric-level contours have been constructed for the Mereenie Sandstone aquifer (Fig. 1) from limited available data, including the hydraulic parameters (presented above), and the results of regional computerised groundwater-flow modelling (outlined briefly below). Available data indicate that recharge is primarily from small rivers and creeks that run along strike of outcropping or subcropping Mereenie Sandstone; discharge is by evapotranspiration from the major rivers which cut across outcropping or subcropping Mereenie Sandstone. The control on the discharge is the present ground surface elevation. Water-chemistry data indicate that there is little if any interconnection with aquifers in adjacent formations.

Carbon-isotope chemistry has been used to assist in deriving a regional water balance for the Mereenie Sandstone. According to the parameters presented above, the total volume of water in storage in the system is estimated to be in the order of 3×10^{11} m^3. Carbon-dating data (Jacobson & others, 1989) indicate that the mean age for the groundwater in the system exceeds 20 000 years. This equates to an average annual recharge over 600 km^2 of outcropping Mereenie Sandstone of less than 2.5 cm per year. Recent water-level monitoring in the Roe Creek floodout area indicates an average annual recharge in the order of 0.8 to 2.0 cm per year.

Historical biological–climatic data for north Australia (Kershaw, 1976, 1980) suggest that the mean annual rainfall has varied considerably during the last 123 000 years (Fig. 3). Preliminary modelling implies that the most likely effect of such a variation would be a variation in the amount of discharge by means of evapotranspiration at the penecontemporaneous base-level of erosion. According to available data, this base-level has changed little, at least over the last 70 000 years.

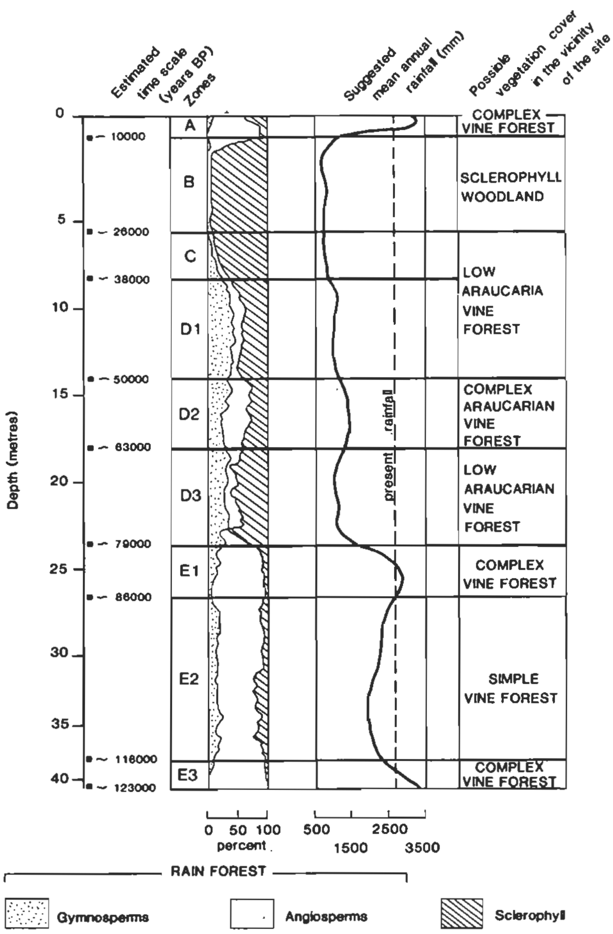

Figure 3. Pollen record over the last 123 000 years for Lynch's Crater, Queensland (after Kershaw, 1976, 1980).

Modelling the Roe Creek Borefield

Computerised models — one local and one regional — have been developed to predict the future performance of production bores in the Mereenie Sandstone and the upper Shannon Formation in the Roe Creek borefield. They are based on MODFLOW, a three-dimensional modular finite-difference groundwater-flow model (McDonald & Harbaugh, 1984). A description of the modelling approach for the Mereenie Sandstone follows.

The approach adopted was firstly to establish a local model that would reproduce the measured drawdowns within the area of pumping influence of the Roe Creek Borefield. The local model covers an area of 351.75 km^2 (33.5 km E–W × 10.5 km N–S). Where the watertable intersects it, the Mereenie Sandstone was modelled as unconfined; the rest of it is confined (Fig. 2). The first eleven years of extraction and water-level data were used to calibrate the model, and the second ten years of data were used to verify it. This was necessary because only limited unstressed water-level data are available.

The remaining parameters were: a specific yield of 0.20, a storage coefficient of 0.003, and transmissivities of 10 000 m^2 per day in the borefield area (east–west), 3000 m^2 per day in the remaining unconfined area, and 300 m^2 per day in the confined area. The ratio of east–west to north–south transmissivity was 5:1. Selected outputs of this model are presented in Figure 4 as log-distance and log-time *v.* drawdown plots. A significant prediction of the model was the small contribution from up-dip flow and across-strike flow from Rocky Hill (in the order of 0.5 × 10^6 m^3) to the borefield annual extraction of 10 × 10^6 m^3.

After the modelling of the hydraulic performance of the borefield was completed, a regional model for the combined Missionary and Orange Synclines (Fig. 1) was developed. This model reproduces the regional potentiometric levels which result from natural recharge and discharge from the system, and its purpose was to confirm that permeability diminishes with depth.

The regional model covers an area of 9600 km^2 (240 km E–W x 40 km N–S). Again, where the watertable intersects the Mereenie Sandstone (i.e., adjacent to outcrop), the aquifer was treated as unconfined, and the rest of it as confined. Natural recharge (stream concentration and infiltration) and discharge occur only over unconfined areas of the aquifer, so, conceptually, recharge was input over outcrop, and discharge was output by transpiration from subcropping Mereenie Sandstone to the east and as base-flow to the Finke River where it dissects outcropping Mereenie Sandstone.

This model was calibrated only by reproducing the known regional water levels as shown in Figure 1. Various recharge rates were tried with various hydraulic parameters for a period of 1000 years, and the best fit was achieved with a recharge rate of 1 cm y^{-1}, specific yield of 0.20, storage coefficient of 0.003, unconfined transmissivity east–west of 3000 m^2 per day, confined transmissivity east–west of 100 m^2 per day, and an east–west to north–south transmissivity ratio of 10:1. The regional model indicated that regional throughflow into the Rocky Hill area was in the order of 5000 m^3 per day.

Discussion

The apparent hydraulic flow regimes of the two models showed that extraction of water from the Roe Creek Borefield was not in effect intercepting the regional throughflow, which would imply a sustainable resource, but — rather — that the extracted water was coming from local storage. Therefore the hydraulic performance of the Roe Creek Borefield can be equated with that of a tank model. To confirm this, borefield drawdown was plotted against borefield cumulative extraction (Fig. 5). Extrapolation of the linear drawdown *v.* cumulative extraction plot, and the inclusion of historical and estimated future extraction rates, resulted in a simple graphical relationship. This simple graphical relationship can be used to predict the long-term performance of the Roe Creek Borefield, hence no further refinements were made to the local model.

Conclusion

A simple tank model has been developed for the major aquifer system exploited by the Roe Creek Borefield. This aquifer system, developed in the Mereenie Sandstone, is being mined, and the simple linear relationship between drawdown and cumulative extraction derived for the tank model can be used to assist in determining the economically viable life of the borefield. Similar models probably can be developed for the three other aquifers exploited by the Roe Creek Borefield.

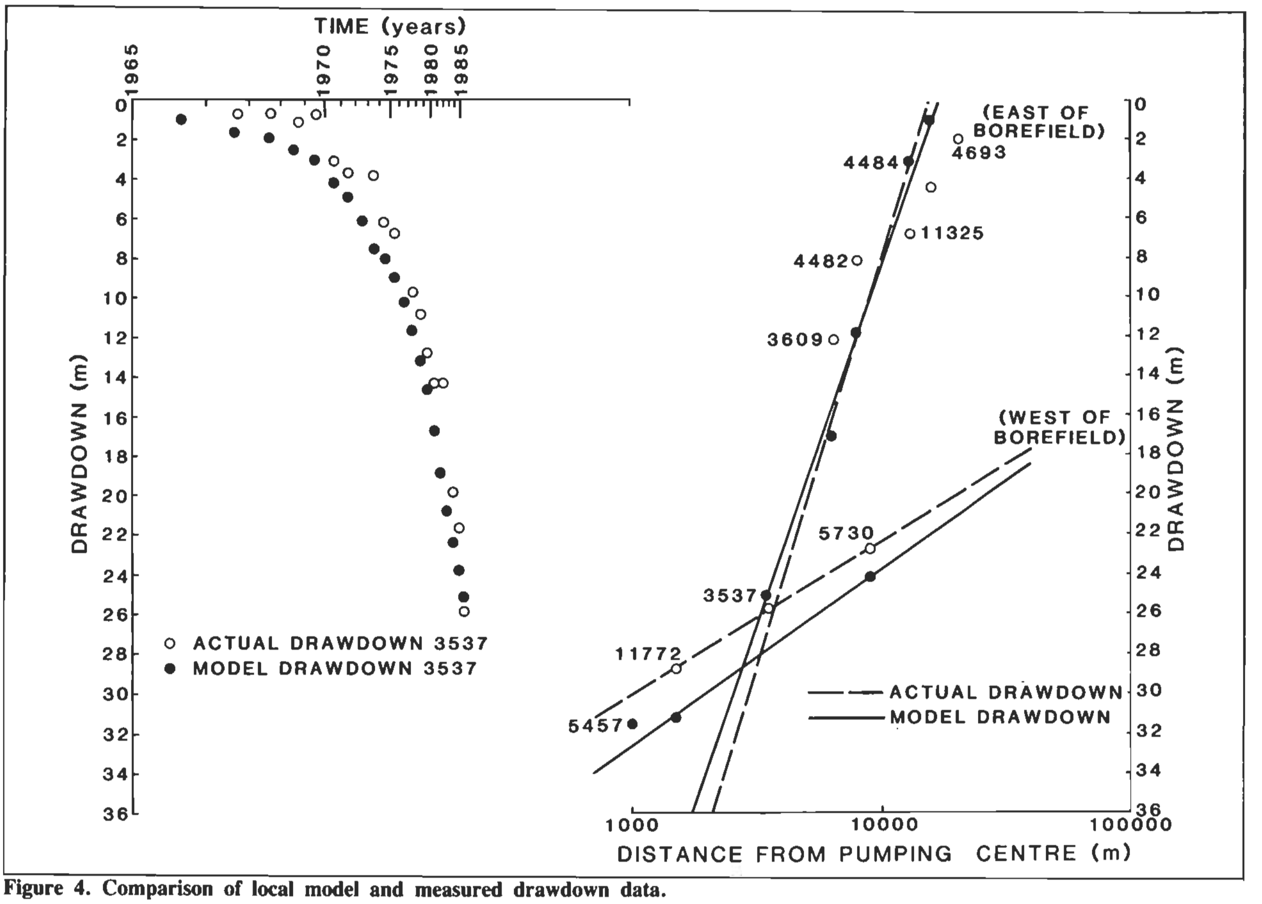

Figure 4. Comparison of local model and measured drawdown data.

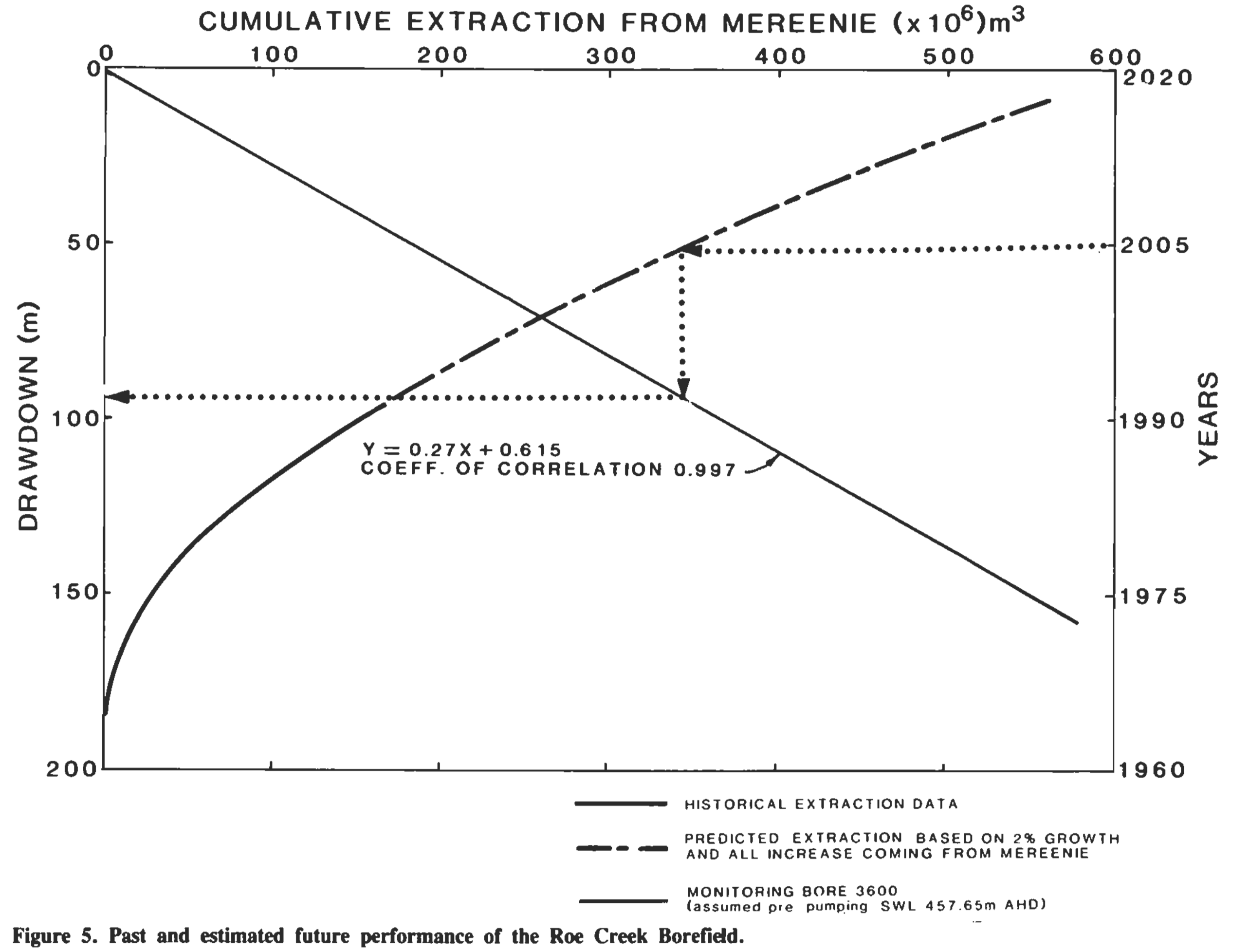

Figure 5. Past and estimated future performance of the Roe Creek Borefield.

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Water resources development in the Northern Territory's arid zone

Peter McDonald[1]

The arid zone of the Northern Territory is one of the world's more sparsely populated areas, with an estimated population of only 45 000 in 12% of Australia's land mass. The region depends mainly on groundwater for provision of water supplies. Annual water usage for all purposes is estimated at 45 000 ML. Compared with the estimated divertible groundwater resources of 2 870 000 ML, the rate of extraction is insignificant. Problems of resource overuse are of growing concern, due to the spatial distribution of readily usable water sources, and the difficulty of matching these to development requirements and community expectations. Climatic realities make the concept of 'greening the red heart' unattainable, but intensive and sustainable water-dependent development is possible, given rigorous assessment of both water source potential and site economics, and sound resource management.

Introduction

Aridity affects the landscape, demographics and economic base of central Australia. Rainfall over the region is generally low, ranging from less than 200 mm in the south, to 400 mm, with a high degree of variability. Much of the region is desert; Mabbutt (1977) cites Alice Springs as an example of an arid continental desert climate, although by another definition (Simmers, 1990) much of central Australia is semi-arid.

The arid zone of the Northern Territory (Fig. 1), with an area of over 800 000 km^2, is around 12% of Australia's land mass. Of the region's estimated population of about 45 000 (<0.3% of Australia's total: Tables 1, 2), 25 000 live in Alice Springs, the regional administrative centre. Apart from the tourist village of Yulara and the Tennant Creek township of some 3000 people, the rest live in several minor centres and in numerous widely scattered small communities based on pastoral holdings, mines, tourism or Aboriginal traditional lands. A high proportion of the region's population is Aboriginal, and many Aborigines live in small groups within traditional homelands or pastoral leases.

For the purposes of this paper, the arid zone is considered to be that area where average pan evaporation exceeds median rainfall by a factor of 10 or more (Fig. 2). Because of the high rate of evaporation, combined with the generally low relief of the region, surface water diversion is minimal, although for environmental reasons and limited recreational use natural water holes are locally important. Small dams are commonly used for stock purposes but abandoned in dry times.

Groundwater is generally essential to all significant development in the arid zone. Availability of an adequate source of groundwater of appropriate quality is always a fundamental economic consideration in the establishment or augmentation of any project, whether community, farm, mine or roadhouse.

In most cases, from necessity, the search for sources of water and provision of a supply has preceded development. Commonly, however, the adequacy of the source to sustain the infrastructure which followed has not been established. There are many examples of problems arising from this, such as the profound water deficiencies at some of the roadhouses which are vital to the Northern Territory transport and tourism industries, and at a number of expanding Aboriginal communities.

The central Australian community must come to terms both environmentally and economically with the arid land in which we live. Our planners must also take the longer term view that sustainable water resources are critical to our continuing presence here recognising that 'a higher level of competence, not only technical but social and political, is needed in arid zones than in humid zones to achieve sustained progress' (FAO, 1981).

History

Water supplies used by the Aboriginal people of central Australia included shallow soaks and wells. Some of these sources, fed from regional groundwater flow or slow seepage, would have been critical to survival during drought as the only available water. It is interesting to speculate on the presence or otherwise of any water supplies at all in the region during the severe periods of aridity that are known to have occurred during Aboriginal presence in Australia.

The 'native wells' were frequently enlarged and enhanced when the country was taken up for pastoral purposes. Constructed wells, sunk in some hard and unrewarding terrain along the Telegraph Line, date from the 1880s. The first drilling to take place in the region was the sinking of Anacoora Bore, on the southern edge of the Simpson Desert, to a depth of 381 m in 1901. Steam driven boring plant was known to be in use before 1920 on the Barkly Tableland. Although there are records of drilling continuing from this time, much of the remaining pastoral land was taken up after World War II, and many new tenures established. Drilling activity flourished, with firm Government encouragement for the provision of new water supplies for primary producers. The drilling of bores for community water supplies also began in earnest at this time, at Hermannsburg in the 1950s, and later in other Aboriginal reserves. The arrival of rotary percussion rigs in the 1970s enabled the cost-effective drilling of the fractured rock areas, although success rates here were not good, and still are not.

There have been numerous attempts to establish viable horticulture in central Australia, in Alice Springs, and as a commercial venture at Aboriginal communities, including Warrabri (now Ali Curung) and Santa Teresa. Commercial production of fodder crops has also been trialled. Most projects have met with, at best, limited success as a small supplier of local market produce: many have failed, for reasons other than lack of water, although water supply has been a significant cost factor.

Success in producing a range of marketable produce at Ti-Tree, 200 km north of Alice Springs, in the 1970s, demonstrated the potential of the region to grow high quality fruit, particularly grapes. Although site infrastructure and transport costs are high, central Australia has a distinctly advantageous early

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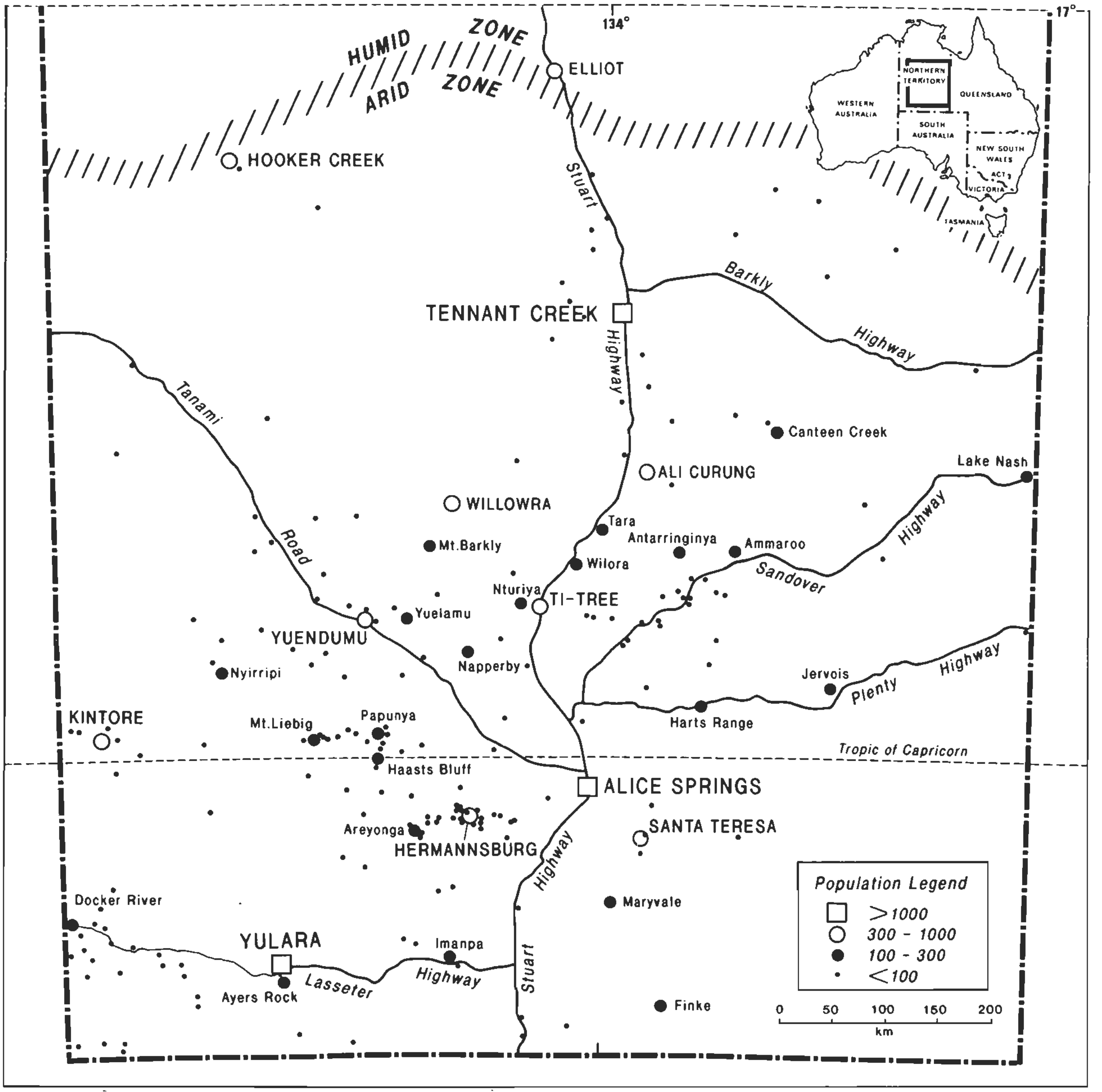

Figure 1. Arid zone of the Northern Territory.
All figures for this paper have been supplied by the author.

growing season compared with more southerly growing areas. This early success in the Ti-Tree Basin was followed up by substantial plantings of grapes in 1987. Despite some set-backs caused by storms during harvesting the project has shown very encouraging results.

Shortage of water has always been a severe constraint to the economics of mining, such as the Arltunga goldfield, active in the 1890s, the Granites in the 1930s, and Tennant Creek. Current mining activities in each of these areas is served by supplies pumped from borefields remote from the mines.

Current water use

Water use (Tables 2, 3) can be categorised as domestic/urban supplies (including a small but largely indistinguishable tourism and industrial component), agricultural (pastoral and irrigation), and mining industry requirements.

Table 1. NT water, land and population resources as percentages of Australia.

	Arid zone	Total Northern Territory
Streamflow	4%	26%
Fresh groundwater	6%	43%
Total water	5%	29%
Land area	12%	17%
Population	0.3%	1%

Domestic/urban

Larger Centres. By far the largest water user in the region is the Alice Springs community, with a 1989/90 consumption of 11 500 ML for a population of 25 000. Most of this water is used for irrigation of private and public lawns and gardens. Included is an estimated 1000 ML of Town Basin water used almost exclusively on public recreation/sporting areas. Average daily per capita consumption is 1260 L, and peak usage is twice this.

The continuing growth of the town has been facilitated by progressive development of new water supply sources. The

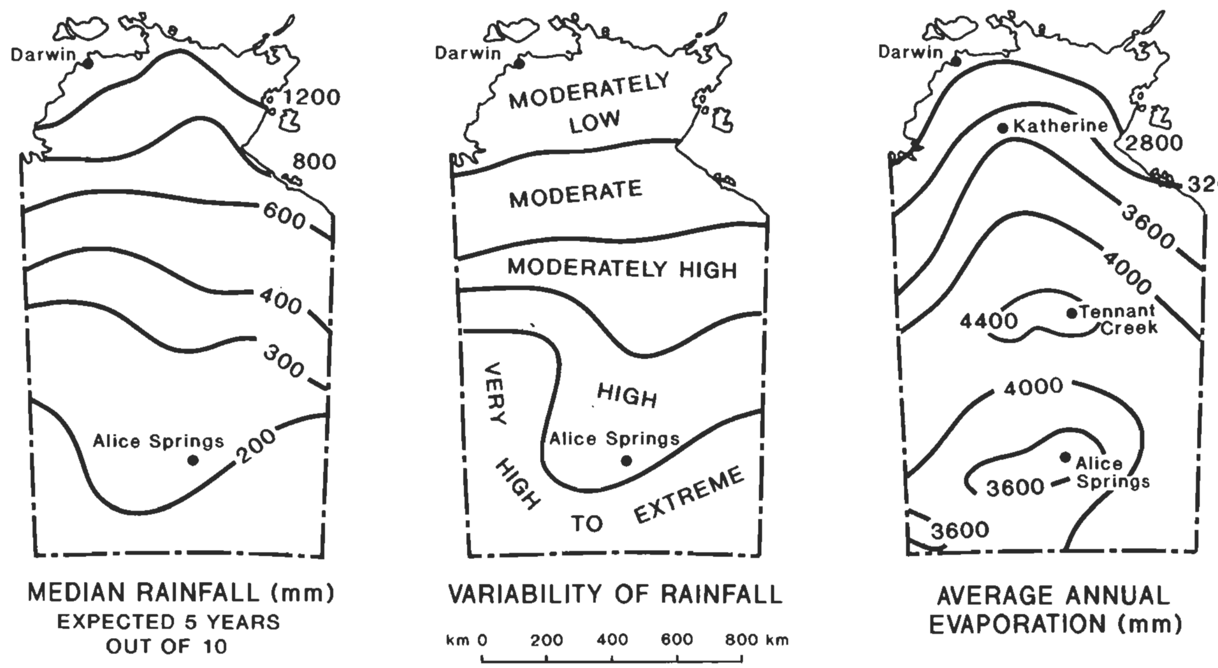

Figure 2. Northern Territory rainfall and evaporation.

original 'springs' were at the Telegraph Station. The supply for the town, drawn from the alluvial basin under the town area, was assessed and developed in the 1940s, and used as sole supply until commissioning of the present Roe Creek Borefield in 1964.

Water level in the aquifer at Roe Creek has declined steadily since extraction commenced, with escalating capital and energy costs. Rate of recharge to the source aquifer here is believed to be much less than the current rate of extraction, which is not sustainable on a long term basis (Jolly & others, 1990). Work on a new borefield is projected within the next decade. The capital investment associated with a new borefield dictates that future strategy must be directed at curbing demand, and development of alternatives including effective use of waste water and the Town Basin aquifers.

Tennant Creek draws its supply from Wiso Basin aquifers southwest of the town. With population now stable, projections are that the current borefield will probably service the community for some years to come. Substantial recharge to the source aquifer occurred in 1974/5, and a similar occurrence might further extend the life of the borefield infrastructure. An alternative source area has been identified, but it is highly desirable to defer opening up a new borefield for as long as possible.

Yulara, a totally planned tourism-based community, is notable in that water source assessment preceded establishment. Source aquifers are adequate, and recharge has been recorded. Quality is not good, however, and water for domestic purposes is treated to reduce salinity. Dual reticulation is used and both raw and waste water are used for irrigation.

Aboriginal communities. There are around 200 Aboriginal communities in the arid zone of the Northern Territory, and many others within the surrounding areas in Western and South Australia. Most of these are small homeland outstations of the larger communities, the largest of which is Yuendumu, with an estimated population of 910. Populations of the larger communities, and water supply data, are shown at Table 2, and community locations in Figure 2. Water consumption rates and supply quality vary considerably (Knott & McDonald, 1983). All of the larger communities have established borefields, with storage facilities and reticulated supply. The supply facilities at the smaller communities range from reticulated supply to windmill or solar pump and tank, or in some cases a simple hand pump. The larger communities have all had water supply source assessments carried out to some degree, and this process continues. Where facilities are in place, total abstraction, water levels, and quality are monitored.

Some communities have high levels of per capita consumption (Table 2). This is often not evident in improved living standard and environmental health of the residents. Provision of reticulated supply of good quality too often results in extreme levels of wastage, without regard to the depletion of what may be a very limited source. Local media attention was attracted to one example in January 1991, where demand at a major community could not be satisfied even with all production facilities running continuously. Detailed site investigation of the total system showed that the problem experienced was due to wastage of some 90% of available supply. This sort of situation is not uncommon.

Addressing this key issue is difficult and complex, involving a wide range of aspects such as administrative/management responsibilities for local supplies; availability, distribution and access to technical skills; training and education; cost recovery/tariff considerations; and community participation in local activity. However, potable water sources are frequently finite, and existing levels of extraction and/or expectation at some communities unsustainable.

Financial constraints upon supply investigation and augmentation are becoming increasingly severe, but exploration continues for water supplies for small communities. Recent legislation and agreements to establish living areas within pastoral leases and on stock routes throughout the Northern Territory have boosted the program.

Agricultural

Pastoral. Since the first wells for stock purposes in central Australia were sunk in the 1880s, there have been more than 5 000 stock bores drilled. Most of the land available for pastoral

Table 2. Domestic urban water use.

Community	Alternative Community Name	Population	Annual Water Consumption (ML)	Supply Quality (TDS in mg/L)	Source Adequacy
Communities with population over 1000					
Alice Springs		25000	11500	450–500	Current borefield extraction not sustainable. New borefield proposed.
Tennant Creek		3000	1870	615	Currently mining borefield, but potentially sustainable subject to high rainfall.
Yulara		1200	544	~2000 Treated for domestic use	Adequate for current needs, but review in progress to aid future development.
Communities with population between 300 and 1000					
Yuendumu		910	170	1100–1500	Borefield being mined. Review in progress.
Lajamanu	Hooker Creek	550	347	700–800	Sustainable.
Ltyentye Purte	Santa Teresa	550	160	300–340	Sustainable.
Walangurru	Kintore	500	44	660–800	Intermittent recharge will support increased extraction, but careful monitoring essential.
Ntaria	Hermannsburg	500	234	430–970	Source requires investigation to determine lon-term sustainability.
Ali-Curung	Warrabri	350	332	700–1000	Sustainable.
Willowra		350	87	790–1050	Sustainable.
Ti-Tree (town and 6 Mie camp)	Pmara Jutunta (Ab Comm)	300	100	670–780	Sustainable, but nitrate content may increase with time and increased pumping.
Communities with population between 100 and 300					
Papunya		275	126	860–1380	Sustainable.
Mt Liebigq		260	64	590–680	Probably sustainable, but aquifier monitoring essential.
Laramba	Napperby	250	40	650–700	Sustainable.
Kaltukatjara	Docker River	250	80	350–520	Sustainable.
Lake Nash		250	No data	825–1070	Thought to be sustainable, but review planned.
Nyirrippi		220	88	610	Potable water limited in extent, requires monitoring and probably more work in the future.
Yuelumu	Mt Allan	200	19 (plus dam water)	2065 (groundwater)	No potable groundwater, and existing source in fractured rock and probably severely limited in extent. Dam supply ephemeral.
Apatula	Finke	180	46	370–440	Probably sustainable, but review in progress.
Ampilawatja	Ammaroo	180	16	970–1130	Sustainable.
Mutitjulu	Ayers Rock	160 (plus park staff)	59	730–800	Sustainable.
Areyonga		160	50	460–560	Sustainable.
Imanpa		150	15–20	965	Potable water severely limited. Aquiter management critical.
Nturiya	Ti-Tree Station	150	No data	1550	Sustainable, but water quality poor.
Titjikala	Maryvale	130	21	380–420	Sustainable.
Atitjere	Harts Range	130	52	565–1450	Sustainable.
Owaitilla	Canteen Creek	130	No data	640–845	Considered sustainable, although quality may fall with time.
Tara	Neutral Junction	125	No data	1095	Potable groundwater very limited and requires careful management.
Ikuntjl	Haasts Bluff	115	25	1100–1335	Probably sustainable at current extraction rate, but extent of potable source unknown.
Mt Barkly		110	No data	450	Sustainable.
Antarringinya		110	No data	890	Sustainable.
Wilora	Stirling	106	13	1250–1480	Source is marginal in quality and limited in extent.
Bonya	Jervois	100	No data	100–2265 (variable)	Little potable water in groundwater storage, but recharge is recorded.
Communities with population less than 100					
More than 150 small Aboriginal communities scattered throughout the region.		Not all are permanently occupied.	No records kept	Varies. Most supplies meet health criteria for chemical quality.	Varies, but generally source evaluation has not been done.
Pastoral lease homesteads	More than 100 in the region	Genrally 5–10 people at each	No data	Varies	Not assessed.
Roadhouse/tourism network	15–20 roadhouses or tourist based establishments	High numbers of travellers/	No records kept	Varies widely	Varies, but usually no source assessment done. Some have a shortage of potable water limiting commercial expansion.

1. Population data from Office of Local Government and PAWA estimates. Mining centres included in Table 3. Production data is latest available metered and projected from PAWA records. Quality varies depending on bores in use. Based on current population except where indicated.

Table 3. Agriculture and mining water use .

User	Product	Annual water consumption (ML)	Supply quality (TDS in mg/L)	Source adequacy
Pastoral Industry	Beef cattle	20 000	300—10000	Generally adequate. Occasionally fractured rock aquifers fail or fall in quality.
Irrigated agriculture				
Territory grape farms	Early table grapes	520	550—650	Adequate for projected expansion
Central Australian produce	Grapes, vegetables	400	800	Adequate for projected expansion
Other ventures (combined)	Grapes, dates, vegetables, lucerne	200 (no reliable data)	500—1100	Adequate for current users with much scope for expansion
Mining				
The Granites	Gold	1580	1200—2500	Minimal impact on aquifer, and evidence of seasonal recharge
Tanami	Gold	800	1100	Considered adequate, but some dewatering has occurred. Aquifer management essential
Warrego (Peko-Wallsend)	Copper	950	2200	Sustainable. Mine water and tailings decant used
ADL (mill operations at Nobles Nob)	Gold	128	Poor	Sustainable supply from abandoned shaft
White Range	Gold	365	770—1600	Adequate, but aquifer storage. Supply operated at capacity

purposes is watered, although some 'problem' areas remain where repeated attempts have failed or struck salty water. It is an irony of the region that much of the best grazing land is on soils developed over rocks poorly prospective for groundwater, while the large sedimentary basins tend to develop poor sandy desert soils unsuitable for grazing. The pastoral areas of the region are shown in Figure 3.

Almost all stock water is used at, or close to, the bore site. There are no bore drains such as those used in other States in the Great Artesian Basin, and few examples of piping water to unwatered areas, although this is an increasing trend as pipeline and pumping economics change.

The development of new supplies for stock watering continues, following fencing for disease control and better management, and economics which dictate that pastoralists extract maximum value from their grazing land. Exploration for stock water in the Northern Territory has been greatly facilitated by the 'dud bore scheme' under the Water Supplies Development Act.

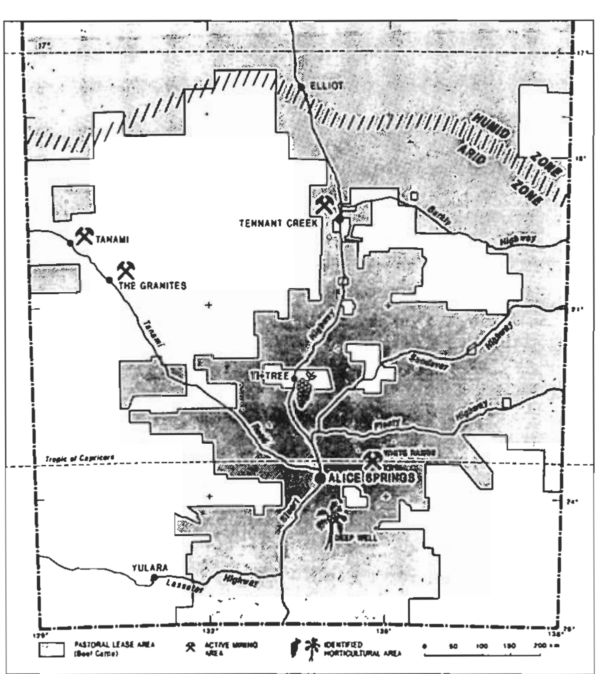

Figure 3. Northern Territory arid zone land use.

Irrigation. The horticultural industry in central Australia is in its infancy. As discussed above, early season grapes have been grown successfully at Ti-Tree, and there is a great deal of potential for expansion here and in other areas. While availability of water is a major factor in these developments, the overriding constraints are market economics and absence of the infrastructure support (roads, electricity, communications) taken for granted in other parts of the nation. There are no government funded irrigation facilities in the Northern Territory.

Groundwater assessments in recent years have identified water resources suitable for large scale horticulture in the Ti-Tree Basin, at Singleton Station (south of Tennant Creek), and Deep Well (southeast of Alice Springs), where a date industry is planned. Each of these areas has proven groundwater storage which could support large scale horticulture for at least decades, and periodic recharge combined with effective management may extend this indefinitely.

Currently, identified resources exceed planned developments, although work remains to be done on borefield planning and computer modelling to support resource management. Total abstraction (Table 3) is only around 1100 ML/year, and although this is insignificant in regional terms, networks have been established to monitor the effects of continued pumping on the source aquifers. A cautious approach to large scale extraction is essential to minimise the risk of overexploitation and salination.

Mining

The mining industry is a major user of water, mainly for processing and dust control purposes. The Granites Gold Mine, 500 km northwest of Alice Springs, is the region's third largest single user of water after the Alice Springs and Tennant Creek communities.

Mineralisation in the region is largely confined to the older basement rocks , which are typically highly unprospective for groundwater. The search for water supply aquifers must concentrate on geological environments distinct from and usually distant from the mine, the position of which is obviously fixed by the location of the orebody.

Each of the current mining operations shown in Table 3 draws supplies from sources some distance from the mine. The Tanami and Granites mines draw from palaeochannel aquifers, largely identifiable using remote sensing methods (Domahidy, 1990). The Tennant Creek mines are served by Wiso Basin aquifers, and White Range by an Amadeus Basin source. To reduce demand and costs process water is re-used, but water shortage is not a constraint to current mining operations.

Available groundwater

The key to an understanding of central Australia's water resources, as in other arid areas, is knowledge of the geology. As the Government Geologist of South Australia wrote in 1926, 'the storage of underground water is controlled entirely by geological structure; and, with every change of structure, the conditions of occurrence vary so that varying considerations must govern the choice of new sites for boreholes or wells' (Ward, 1926). The region's diverse geology includes a variety of aquifer types. Supplies are drawn from major sedimentary basins capable of yielding large supplies of often good quality water, shallow semi-consolidated or unconsolidated basins, and fractured rocks of generally low yield and often poor quality. Extreme variability of both yield and water quality is characteristic of the region, and there are still very large areas where we have little knowledge of the presence of groundwater. Quantitative water resource assessments have been carried out in only a few areas of current or projected intensive extraction.

Studies of the origin and renewal of groundwater in the region have demonstrated low flow gradients, and very slow flow rates of fossil waters whose age can be measured in tens of thousands of years. Offsetting this is the considerable volume of water stored in the larger sedimentary basins. While modern recharge is demonstrably occurring, it appears confined to particular areas where geology and topography are favourable, and there has not yet been any comprehensive quantitative research on recharge to groundwater in central Australia.

The 1985 review of Australia's water resources (Australian Water Resources Council, 1987) compiled and tabled the estimated divertible water resources of the nation's groundwater provinces (Fig. 4). From those estimates, a rough summary of the renewable water resources of the Northern Territory's arid zone has been derived (Table 4). This is an estimate of sustainable extraction, based largely on assumptions of recharge, and does not consider the immense storage of fossil groundwater in the extensive aquifers of the region.

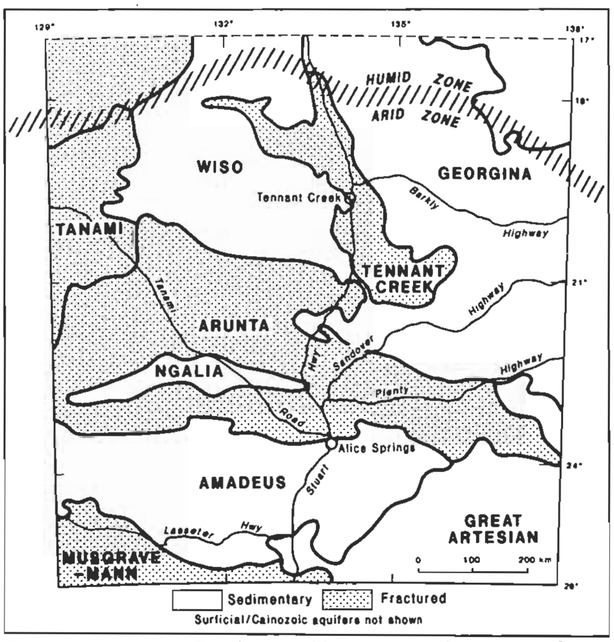

Figure 4. Northern Territory arid zone groundwater provinces.

It is apparent from Table 4 that estimated divertible resources are considerably greater than current water usage. Overall resource availability is not a constraint to expanded water extraction. It is also apparent that the region's resources includes a very large proportion of water which is marginal, brackish, or saline in quality. Unfortunately, the poor quality water often occurs at sites where better water is sought.

Water quality variation has been a profound obstacle to groundwater use throughout the region, with frequent marginal or high levels of salinity in both shallow and deep aquifers. Problem ions, especially high concentrations of naturally occurring nitrate, have frequently restricted use for drinking, and many bores drilled are abandoned on completion of drilling due to poor supply or unacceptable quality. Of approximately 4000 bores drilled for water supply for all purposes in the area since 1960, just over half were successful. Lack of success was mainly due to unsatisfactory yield (80% duds, 20% unacceptable quality). Indications are that the percentage of unsuccessful drilling is increasing despite a growing data bank and better technology. This is due to a combination of higher expectations of yield and quality, land tenures which restrict siting options, and political imperatives which dictate that drilling proceed in areas known to be poorly prospective or at least marginal.

The Northern Territory is fortunate in that, with a small population and a limited industrial base, there has been little chemical or bacteriological pollution of water. However, the potential for salination in an arid climate is great, as shown by problems developing in the Alice Springs Town Basin. We must ensure that our agricultural activities do not induce the salinity that is destroying much of rural Australia.

Water is perceived to have no intrinsic value until we need to use it. It is essential, however, to an orderly resources strategy, that we continue to build on our knowledge of water resources. We must quantify the process of renewal to ensure that our developments are sustainable.

Role of government

The development of new water supplies throughout the Northern Territory, and particularly in the southern region, has in large part involved Government initiatives and incentives.

The sinking of wells along the Telegraph Line, and later the establishment of stock routes along chains of new bores, were Government initiatives of the time. During World War II, the army added many new water supplies, and drilled the Alice Springs Town Basin as a source aquifer, work that was later built on by the Commonwealth Works Department.

Government has continued to support new water supplies for primary producers, through the provisions of the Water Supplies Development Act. Under this legislation, which is still in force, the cost of unsuccessful drilling for pastoral or horticultural water is reimbursed. Some 250 bores have been drilled under the provisions of this Act in the southern region since 1986.

The process of regional exploration and assessment of Northern Territory Water Resources was initiated by the Commonwealth Government, through the agencies of the CSIRO, the BMR, and the local offices of the Northern Territory Administration. Identification and assessment of resources to support horticulture have been actively pursued since that time. Recently hydrogeological mapping of key Northern Territory mining regions has been carried out in support of the mining industry in mineralised areas in both the northern and southern regions.

The Water Resources Branch of the Northern Territory Administration was set up in 1955, and took on the role within

Table 4. Divertible Water Resources

Province Name	Percentage in NT Arid Zone	Major Divertible Resources in the NT arid zone (ML x 1000)					Minor Divertible Resources in the NT arid zone (ML x 1000)				
		Fresh	Marginal	Brackish	Saline	Total	Fresh	Marginal	Brackish	Saline	Total
Tanami	70	0.0	1.4	2.1	1.4	4.9	4.9	23.8	25.2	11.2	65.1
Wiso	80	0.0	3.2	0.0	0.0	3.2	1.6	4.2	17.7	3.5	27.0
Tennant Creek	100	0.0	2.0	1.0	0.0	3.0	300.0	136.0	83.0	37.0	556.0
Georgina	50	112.0	410.0	0.0	0.0	522.0	33.5	208.5	131.5	26.5	400.0
Arunta	100	0.0	3.0	2.0	1.5	6.5	34.0	179.0	195.0	99.0	507.0
Ngalia	100	0.0	2.0	2.0	1.0	5.0	1.0	4.0	4.0	5.0	14.0
Amadeus	90	17.1	98.1	26.1	9.9	151.2	48.6	185.4	128.7	75.6	438.3
Musgrave-Mann	20	0.0	0.2	0.2	0.8	1.2	0.0	8.0	9.8	6.2	24.0
Great Artesian	5	35.3	29.5	17.5	4.9	87.1	16.4	5.1	4.9	23.5	49.8
Total		164.4	549	51	19	784	440	754	600	287	2,081

	Fresh	Marginal	Brackish	Saline	Total
Total Major + Minor	604	1,303	651	307	2,865

1. Divertible Water Resource-amount which can be removed from developed or potential sources on a sustained basis without causing adverse effects or long term depletion

2. Minor Source-not capable of yielding enough for a small town or irrigation system

3. Fresh: TDS<500mg/L Marginal: TDS>500mg/L but <1500mg/L Brackish: TDS>1500mg/L but <5000mg/L Saline: TDS>5000mg/L

4. Table derived from AWRC (1987); resource volumes derived from proportion of area of each basin falling in the NT arid zone.

Government of water resources assessment and management, maintaining an active role in the development of water supplies. The Northern Territory is fortunate by comparison with other States in that one body, the Power and Water Authority, is responsible for all water related activities, including ground and surface water data collection, assessment, and dissemination; water supply development; water resource management and licensing; and urban water supplies.

The water resources function in the arid southern region is carried out by a Water Resources Branch in Alice Springs, which maintains a staff of over 30 professional, technical and support staff. With head office support, the Branch is responsible for all local data collection and dissemination, regional assessment, and water supply development projects. Both in-house and contract drilling facilities are used.

The management/licensing role in the Northern Territory is administered under the Control of Waters Act, which establishes baseline water rights, means of enforcing water conservation and pollution prevention, and restrictions on diversion of natural waters . Extraction requires licensing only within declared Water Control districts (Fig. 5) where, due to specific development requirements, source aquifers must be protected. The existing water resources legislation is to be replaced by the impending Water Act, which is expected to be passed into legislation during 1991.

Future directions

With the change in pace in new development projects in the Northern Territory, and the contracting economic outlook generally, where should water resources activities be heading? In other States the emphasis has shifted away from resource assessment and development to resource management, particularly with reference to environmental concerns. The establishment of the Territory's infrastructure however was much later than in other States. Over past decades the provision of new water supplies, particularly community/urban supplies, has been paramount, and much effort has also been put into resource exploration and assessment. Work in this area of activity will continue; new water supplies are still required, and a great deal of the Territory, particularly the arid portion, is virtually unexplored for sources of water.

Some of the areas where an expansion of activity is needed are apparent. Increasing importance is being placed on the quality, reliability, and cost effective operation of existing community water supplies, particularly of those at Aboriginal communities. Guidelines for the provision of essential services (Department of the Chief Minister, 1988) are based on population size and stability. Meeting the standards for quantity and quality of water supply, and supporting the general level of capital infrastructure being created, depend on the sustainability of source aquifers, which cannot be taken for granted (Table 2).

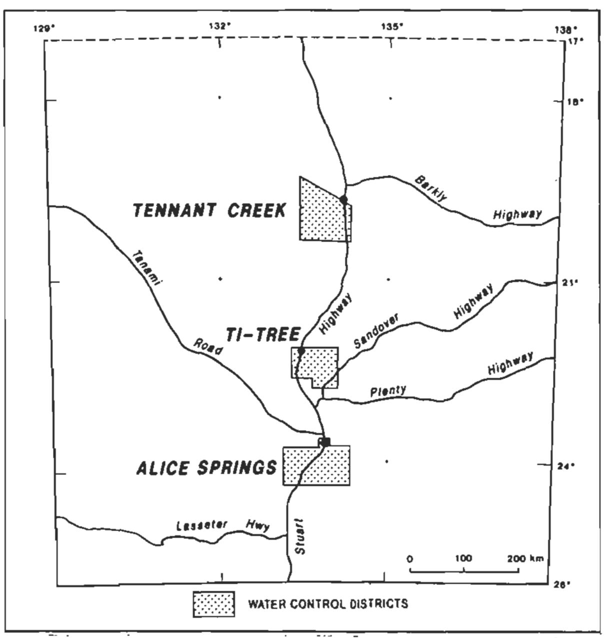

Figure 5. Northern Territory arid zone water control districts.

We must identify priorities in determining source sustainability for existing community users, or clearly identify those communities that will face limits to growth imposed by absence of suitable water supply. Providing sustainable sources of potable water to meet guideline values is, at some centres, a formidable task.

With financial constraints, there is an increasing need to collect uniform data for the specific needs of the region. In the longer term recharge, natural or artificially enhanced, is the key to the environmental and economic sustainability of all of our larger water supplies. Quantitative study of groundwater recharge mechanisms requires long term collection of water level data, and use of available technology such as isotope studies for water dating, and satellite telemetry in collecting rainfall and flow data.

Better data storage, and especially the continuing computerisation of hydrological and hydrogeological data, is fundamental to cost effective resource assessment, planning and management. The Northern Territory has lagged behind the other States in implementing a computerised water database, but now, with all water functions within the Northern Territory Power and Water Authority, we can implement a comprehensive system based on 1990s technology.

Better dissemination of water information to the community stakeholders, particularly the planners, is essential. Hydrogeological maps, as a means of presenting and disseminating groundwater information, are particularly suitable for the arid zone when all water supplies are groundwater. The map produced for the Granites/Tanami mining region (Domahidy, 1990), one of two prepared to assist the mining industry in the Northern Territory, is the forerunner of an expected series of hydrogeological maps prepared by the Northern Territory Power and Water Authority.

Environmental monitoring and regulation will demand increasing attention. While regionally, Northern Territory arid zone water resources can be considered pristine, the Alice Springs experience demonstrates that we have to take more account of our impact on the hydrological regime, assuring that baseline conditions have been established, monitoring initiated, and where necessary regulatory means used for management.

Acknowledgements

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Progress in the development of a water-care ethic for the Pilbara region of Western Australia

Steven Vellacott[1]

Mining towns in the Pilbara region of Western Australia have daunting problems that hamper efforts to apply water-conservation techniques: compacted heavy clay water-shedding soils, an evaporation rate ten times the mean annual rainfall (less than 300 mm), summer temperatures above 40°C, and long periods without rain. Town water supplies are drawn mainly from underground sources. Until recently, domestic consumption was heavily subsidised, and water was used copiously to create gardens reminiscent of a less harsh environment. Since the boom times, mining companies have adopted more realistic policies on private and public water use. With the introduction of home-ownership schemes, they replaced water subsidies with generous incentives to convert gardens to low-water use. Major reductions in water consumption were achieved: 50 per cent in Dampier (entire town) between 1985 and 1990; 38 per cent in Karratha (households only) between 1980–81 and 1990; and 39 per cent in Wickham (households only) between 1984 and 1990.
Some important community-based initiatives were developed in the 1980s: native-plant nurseries, arid landscaping for remote Aboriginal communities, demonstration garden projects, and horticultural courses and programs to help disadvantaged people to acquire work skills. Recent government water-care initiatives have included establishing the Pilbara Water Conservation Advisory Committee, the first of its kind in Western Australia. With support from the Water Authority in Karratha, the committee is undertaking a community education program.
The support of industry, through funding and personal involvement, contributes to the success of local projects. Professionals could contribute further by applying their skills and experience to public education, research, trials, demonstrations, and workshops. The funding of regional and local projects and research, the establishment of water-conservation committees, liaison with local groups, and promotion of a holistic environmental ethic are all appropriate activities for the State and Federal Governments.
The approach to land care provides a good model for the development of a water-care ethic for the Pilbara region. The problems which made land care, and now water care, necessary have their roots in attitudes to the whole environment. The issue of water conservation cannot be tackled in isolation from other conservation issues.

Introduction

Frugal human use of water is essential everywhere today because it can reduce the economic and environmental costs of diverting natural waters and modifying natural hydrological cycles. This is especially so in Australia's arid zone.

Efficient design of our built environment and the lawns and gardens within it can have a dramatic impact on water-consumption levels. Water applied to lawns and gardens accounts for between 40 and 80 per cent of domestic consumption in Western Australia (Western Australian Water Resources Council, 1986), where the challenge of conserving water on a large scale while maintaining or even improving the amenity value of the built environment is being met. This paper outlines how communities in the arid Pilbara region are meeting that challenge.

The term 'water care' is used in this paper to describe a holistic approach to water management, whose primary aim is to maintain as far as possible a sustainable hydrological condition for any given area. Water conservation is one aspect of water care; in urban environments it is a critical component.

On the north coast of the Pilbara region, the town of Karratha (Fig. 1) enjoys an arid tropical climate, experiencing an annual evaporation rate of 3 m and an unreliable rainfall with an annual mean of less than 300 mm (Bureau of Meteorology, 1972). As an example of the variability about that mean, Karratha received less than 50 mm of rain in the 11 months between April 1990 and March 1991 (Bureau of Meteorology, 1990a–i, 1991a–c), yet the equivalent of the town's mean annual rainfall may deluge the town within a few days (Bureau of Meteorology, 1989). Around two-thirds of Karratha's rain is precipitated in falls of less than 30 mm (Nicholson & Edgecombe, 1986).

Towns of the Pilbara region, and much of arid Australia for that matter, typically have heavy clay water-shedding soils, evaporation rates ten times that of mean annual rainfall, and summer temperatures consistently above 40°C. In any 12-month period, they might receive almost no rainfall at all.

Most Pilbara towns, including Karratha, are moderately new, rely on employment provided by a few major resource-de-

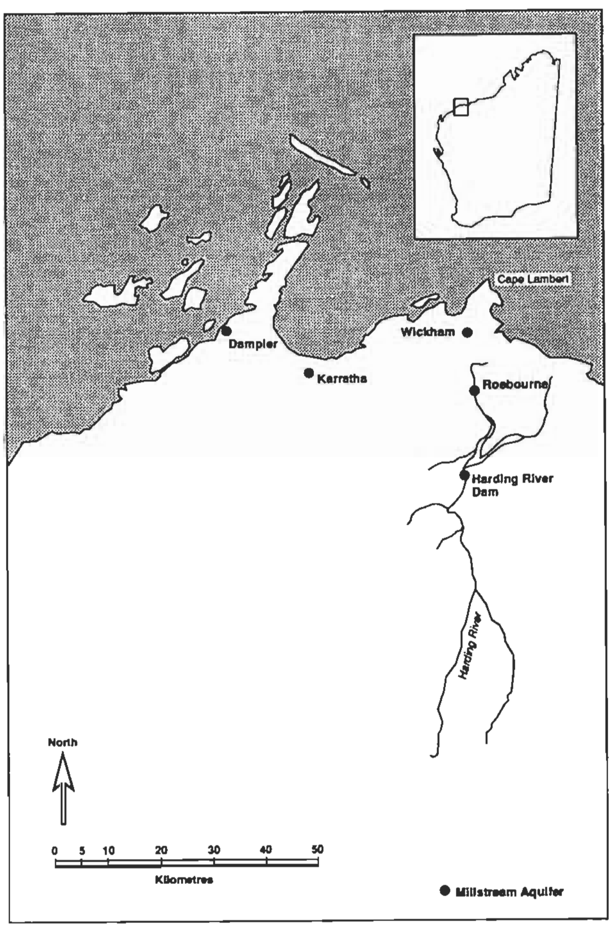

Figure 1. Location of Karratha and nearby towns of the Pilbara region.
All figures for this paper have been supplied by the author.

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velopment companies, and have transient populations. The Pilbara towns of Karratha, Wickham, and Dampier (Fig. 1) and others farther south and southeast — such as Paraburdoo, Tom Price, Pannawonica, Newman, and Telfer — have been entirely developed within the past 25 years. The mean age of the population is much younger than the national average, and residents live in these towns commonly less than four years. Attractive salary packages have lured people to the region. In many of the towns, water was provided free of charge to employees until the last few years.

Significant water resources have been developed to service Pilbara towns. Until the early 1980s, the west Pilbara towns of Karratha, Dampier, Wickham, and Roebourne relied entirely on water from the Millstream aquifer to the south (Fig. 1). This aquifer supports an important wetland system which lies in the Millstream–Chichester National Park. Drawdown in the aquifer eventually led to vegetation mortality, and posed a risk to spring-fed pools and wetlands. The reaction to this problem was to construct the Harding River Dam (Fig. 1), which now supplements the Millstream supply. In all other Pilbara towns, water is supplied from underground aquifers close to major river systems. In Newman, groundwater recharge has been assisted by the construction of a barrage across the Fortescue River. All these water-resource developments have involved not only a substantial capital cost but also an environmental cost.

More recently, greater export competition in the mining industry has led to a close examination of costs. One of these costs is that which is associated with developing new water resources. Consequently there has been a marked concentration of effort on reducing the demand for water resources.

Some of the recent changes in policy and attitude discussed in this paper would have been considered quite remarkable when Nicholson & Edgecombe (1986) described the Pilbara in the early 1980s with average household water consumption 30 to 40 per cent higher than today. However, there is a danger that the recent reductions in water use may not be enduring, or as great as they could be, if they are not occurring for the right reasons.

This paper not only boasts about the real achievements in water conservation in Karratha and, to some extent, other Pilbara towns, but also provides an understanding of why this occurred, where improvements can be made, and what must be done to achieve sustainable water conservation in the arid zone.

Overview of water-conservation techniques for arid landscapes

The greatest opportunity for conserving water without loss of human amenity, is through minimising the artificial irrigation of our lawns and gardens. Considerable water savings can be achieved through appropriate landscaping and gardening techniques.

The application of water-harvesting (capturing and retaining run-off water during natural rainfall events) and water-management techniques for water conservation in arid landscapes are now well documented (National Academy of Sciences, 1974; Nicholson, 1986; Nicholson & Edgecombe, 1986; Western Australian Water Resources Council, 1986; RMIT, 1989).

Effective water management at the micro- and macro-catchment levels is fundamental to the achievement of water-conservation objectives in urban design. Macro-catchment (town, residential size) management for water conservation can be achieved with good town and residential planning, design, and construction (RMIT, 1989). At the micro-scale, the essential elements are:

- harvesting water during rainfall events by directing run-off from roofs and pavement areas into shallow depressions in which plants are established;
- soil preparation;
- species selection; and
- type of artificial irrigation (at least for the initial establishment of plants).

Water harvesting is a technique which has been used by the Israelis for centuries, and is now being adopted in Australia. At the macro-scale it has been used for growing tree crops and for restoring degraded pastoral lands. At the micro-scale it is now a critical element in urban and residential design. Where run-off from roofs, paved areas, and roads is directed onto gardens, and if a prescribed amount of that water is trapped, supplementary watering of plants can be dramatically reduced.

Soil preparation appears to be one of the most overlooked aspects of arid-garden development in the Pilbara region. Many well intentioned arid-garden projects initiated by mining companies, shopping-centre owners, residents, and local governments have been rendered almost ineffective because of the lack of attention to soil preparation.

It is essential to maximise the efficiency of water and nutrient retention in arid urban soil environments. This most often requires mechanical disturbance (particularly in clay soils), which should be carried out in association with water-harvesting works. Key points in creating the best possible soil environment are:

- breaking up compacted clay soils by ripping or digging (preferably with the aid of a backhoe) to improve water infiltration, root development, and nutrient retention (Fig. 2);
- incorporating dry sewage sludge, other organic matter, and/or coarse sand in clay soils to enhance soil functions; and
- covering the soil surface with a thick mulch (stony or vegetative) to minimise capillary action and evaporation from the soil surface while providing an excellent barrier to weeds.

Insufficient attention to soil preparation can result in poor growth response, which might prejudice residents against the use of indigenous plant species in home gardens. This is a tragedy to be carefully avoided, especially when considerable ground has already been made in converting gardeners of exotic species to using our own water-conserving local species.

The use of local indigenous plant species is one of the most commonsense and practical ways of conserving water. Indigenous species have evolved within the local rainfall regime, and with good soil preparation and a little attention they flourish in the home garden with very little need of artificial irrigation.

Species selection and the details of irrigation design and equipment are important, particularly since there is a belief in some quarters that native-plant species are shortlived, and most native gardens therefore become senile within a few years. This has no doubt come about through experience with some *Acacia* species which grow quickly and become woody if not pruned properly.

Another difficult challenge in getting everything right for an almost self-sustaining attractive garden landscape (or townscape) is to convince the owner (or users) that medium-to-long-term success seldom can be achieved without some short-term sacrifice. For arid gardens, this means planting small seedlings

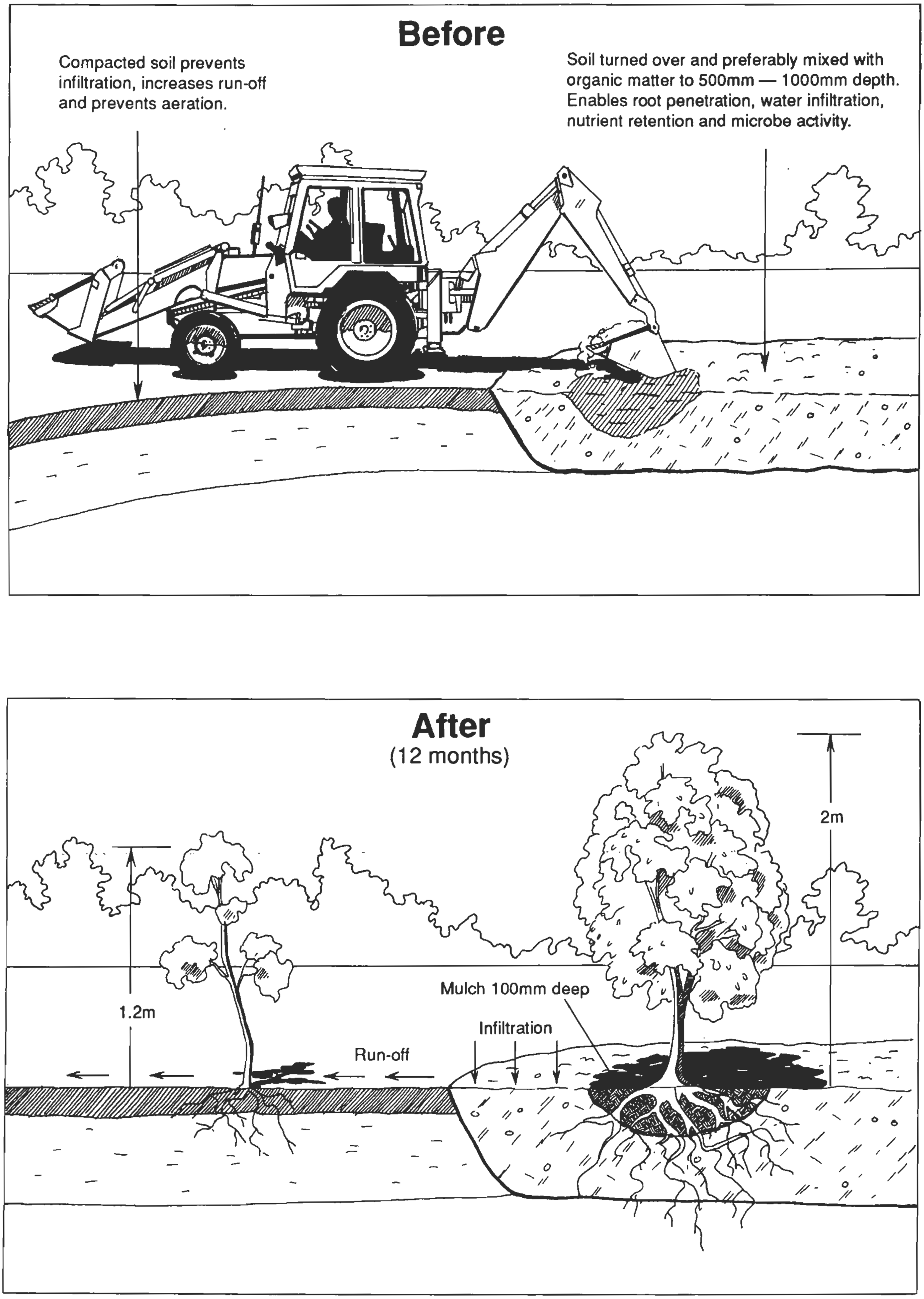

Figure 2. Essential soil preparation for compacted soils.

Table 1. Industry initiatives in Pilbara water conservation.

Company	*Town*	*Policy change*	*Result*
Hamersley Iron	Dampier (69% of former company houses now under home-ownership scheme)	Home-ownership scheme introduced in 1983, later made compulsory for new employees. On entry to scheme, $1000 provided per home to convert gardens to low-water maintenance	Town water consumption in 1990 less than 50% of that in 1985; 33% fall in consumption in 1987–88
Hamersley Iron & Woodside Offshore Petroleum	Karratha (almost 50% of houses in the town are company-built)	Hamersley Iron policy cf. Dampier. Woodside policy was free garden landscaping (low-water design), incorporating trickle-feeding of plants, small lawns, free tap timers, and reimbursement for paving and pergolas	Average household consumption fell 38% from 933 kL in 1980–81 to 578 kL in 1990
Robe River Iron Associates	Wickham	Water subsidies halved, assisted low-water garden conversions, and water-conservation campaign introduced	Average household consumption fell 39% from 1260 kL in 1984 to 760 kL in 1990

Sources: W.S. Kelly (Hamersley Iron Pty Ltd, personal communication 1991); S. Waller (Woodside Offshore Petroleum Pty Ltd, personal communication, 1991); N. Gay (Robe River Iron Associates, personal communication 1991); P. Roberts (Water Authority of Western Australia, personal communication 1991).

instead of pot-bound, half-matured, force-fed shrubs and trees. The right approach to this problem is to show to the diehards examples of where the right technique has worked, and to convince them that the early days of their new landscape need not be painful if the physical landscaping itself has been thoughtfully designed.

Recent trends in water consumption for some Pilbara towns

Nicholson & Edgecombe (1986) described a Pilbara scene of intensely water-consuming mining towns occupied by heavily subsidised tenants. Fortunately, this scene is changing owing to the tendency for mining companies to review costs in an increasingly competitive industry. Some have taken the bold step of removing or cutting subsidies for water bills. Others have introduced home-ownership schemes which shift the responsibility of payment for water from the company to the employee. In all instances, however, these changes have been accompanied by generous compensation from the companies to their employees in the form of free conversions to low-water gardens, or reinbursement for low-water conversions. Examples of changes in company policy and the results achieved are listed in Table 1.

Private-industry policy initiatives, such as those outlined in Table 1, have brought about dramatic falls in average annual household water consumption in some of the Pilbara mining towns, particularly Karratha and Wickham (Fig. 3). By comparison, average annual consumption has changed little during the same interval in the non-mining town of Roebourne (Fig. 3).

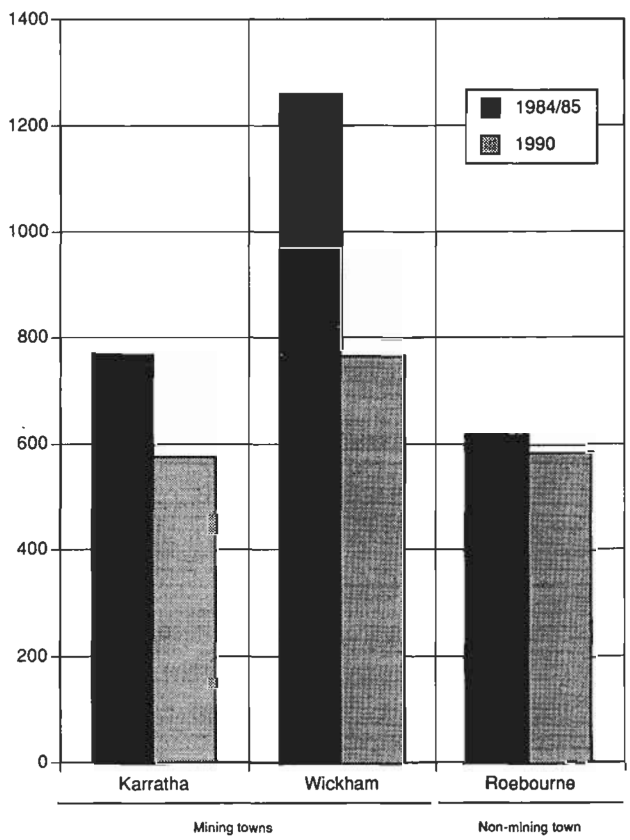

Figure 3. Average annual household water consumption kL in three west Pilbara towns.
Source: Water Authority of Western Australia (1991).

Reduction in water consumption has not been totally confined to households. For example, Robe River Iron Associates has reduced water consumption in its port operations (crushing and stockpiling) at Cape Lambert by 25 per cent with the commissioning of a water-recirculation system (N. Gay, Robe River Iron Associates, personal communication 1991).

It appears unlikely that any more significant reductions in water consumption will be achieved in the foreseeable future. Indeed, the challenge will be to prevent a growing demand for water. In many people, the longing for an exotic high-water garden persists, and older houses are bringing about problems of leaking toilet cisterns, taps, and pipes. In housing where tenants are still subsidised (for up to 1000 kL of water per annum), there is little incentive to reduce these water losses due to leakage.

In favour of water conservation is the trend towards less transience in Pilbara workforces, and hence a greater propensity for investment by residents in better landscaping for long-term benefit.

Filling information gaps for water care in the Pilbara

Nicholson & Edgecombe (1986) identified several gaps in basic information on landscaping for water conservation. These included: publication of designs and guidelines for planners and architects; more data for engineers to assist in appropriate engineering design of low-water landscapes; more demonstration projects; more detailed figures on costs of alternative techniques; and specific horticulture and landscape training courses. With the help of public and private funding, and a substantial amount of voluntary labour, most of these gaps have been filled over the last five years. Recent relevant publications and unpublished reports on water conservation include those by the Western Australian Water Resources Council (1986), Nicholson (1986), Tyler (1988), Hill & Nicholson (1989), RMIT (1989), EPA (1989), and Water Sensitive Urban Design Research Group (1990).

Various pamphlets on low-water gardens and other water-conservation techniques were distributed by most local mining companies and the regional offices of the Water Authority and the Department of Conservation and Land Management (DCALM) in Karratha. A videorecording that summarises the message in the Western Australian Water Resources Council (1986) publication was also released.

Even though the gaps in available information identified by Nicholson & Edgecombe (1986) have been largely filled, much of it is not accessible to the public; the effective dissemination and application of this information are today's challenges.

Direct community action for water care

Responses to resource depletion are often complicated. At the very least, there are considerable (and unforgiving) time lags between resource depletion (or over-use), economic response, and community response. It is therefore essential that all sectors of the community understand that water conservation not only makes sense but also has diverse and immense benefits in the form of:

- maximising our capacity to cope with environmental stresses such as drought and/or climatic change;
- improving our understanding and appreciation of the natural environment through the use of indigenous xerophytic plants;
- maximising our efficiency in energy use (e.g., reduced need for water-pumping, and less energy expended on water-resource development); and
- minimising the need for environmentally costly water-resource developments.

The adoption of low-water landscaping and gardening techniques using local indigenous plants can compound the benefits of water care. Embracing a water-conservation ethic can facilitate progress of the community towards a more holistic environmental ethic. Without the development of such ethics in the community, the direction that we take, and the degree of success that we achieve, in water care will at best be limited and at worst non-sustainable.

The growth in available information on water-conservation techniques is evidence of a developing water-care ethic in the Pilbara region. The availability of this information has promoted the instigation of a considerable number of important community-based initiatives (Table 2), particularly in the town of Karratha. All these initiatives have been developed by highly motivated individuals both within and outside government and industry. The keen individuals have diverse backgrounds, but all are entwined in the common thread of the water-care ethic. Once entwined, these individuals retain the ethic, and take it with them when they — like many other transients in the arid zone — travel to other parts of Australia and the world.

Table 2. Community-based water-conservation projects.

Group	*Town*	*Objectives, projects*
Arid Gardens Group	Karratha	Operate a nursery now holding thousands of local plants representing ca 100 species. Plants and seeds are available to visitors for a small donation. Current projects include planting public native gardens around Karratha. Future projects include establishing a showpiece public garden near the town centre
Community Work Skills	Karratha	Private organisation helping disadvantaged. Established a native plant nursery with a range of local species
Community College	Karratha	Offers educational courses, including one on horticulture, which are designed for the practical application of techniques for arid landscapes
Community College & Roebourne Aboriginal Community	Karratha	Established an ethnobotanical garden at the college in 1985. Water-harvesting and trickle irrigation are incorporated in the design. It features plants grown for food, and for the manufacture of artefacts and ceremonial accessories
Community College	Karratha	Established (in 1984) the Pilbara Regional Herbarium, now managed by DCALM, which strongly emphasises community ownership
Pundulmurra College & Murdoch University	Port Hedland	Joint project developing arid landscaping for remote Aboriginal communities. Emphasis is on the use of sewage effluent for growing shade and shelter trees. Many local species are available
Local Environment Affinity Force	Port Hedland	Voluntary conservation group planting native species in and around Port Hedland. It has attracted considerable assistance from local government and private sources for some substantial landscaping projects
Bindi Bindi Aboriginal Community	Onslow	Arid-plant nursery re-established in 1991. Plants and seeds of indigenous species are available to mining companies, residents, and land-care groups within a radius of *ca* 300 km

Recent government action for water care

A greater public awareness and community participation in conservation issues, including water care, has influenced environmental management. The concept of sustainability also has been incorporated into planning policies for new developments. Examples of this are the adoption of a new planning policy for groundwater resources on the Swan Coastal Plain (Department of Urban Planning and Development, 1991), and the Draft Environmental Protection Policy for the Gnangarra Mound (EPA, 1991).

At the local-government level the Shire of Roebourne (which includes the towns of Karratha, Wickham, Dampier, and Roebourne) has recently developed a low-water-landscaping policy. This policy makes low-water landscaping a condition of approval for all new development proposals in the Shire. This is a novel approach, and, if it proves successful, may influence other shires to introduce such planning initiatives.

In 1987, the Port Hedland Town Council engaged consultants to assist them in preparing a five-year plan (Price Waterhouse Urwick, 1987). The aim of this plan was to enhance the appearance and public perception of Port Hedland, whilst improving the efficiency and effectiveness of its administration. Landscape architects, planners, environmental scientists, horticulturists, and conveners developed townscape-concept plans in consultation with the local community. The concept plans were founded on the principles of water conservation, and emphasised the need to build on the natural character of the area. Implementation of the townscape principles and designs is now in progress.

In early 1987, the Western Australian Water Authority set up a community-based Pilbara Water Conservation Advisory Committee. The Committee developed a list of objectives and strategies aimed at reducing total water consumption in Pilbara towns. By late 1987, the Committee was invited to operate under the umbrella of Section 17 of the Water Authority Act, 1984, which formally recognises community-based advisory committees (Western Australian Government, 1984). The Committee, the first of its kind in Western Australia, has since acquired the support of a working group within the Water Authority's Karratha office. This working group comprises officers with formal responsibility for assisting the Committee in achieving its objectives.

The specific objectives of the Committee are to:

- minimise waste of scheme water (i.e., water provided by the State for domestic and industrial uses);
- encourage consumers to adopt techniques which conserve water use from all sources;
- maximise the use of alternative water sources; and
- encourage the recycling and re-use of scheme water previously used for industrial purposes.

The Committee's functions are:

- to advise on the implementation of conservation strategies, and to monitor results; and
- to develop and implement a community-wide water-conservation education program, adopting both long- and short-term goals.

A number of long- and short-term goals were set, and the Committee meets every six months or so to review the progress of the working group and steer it into the following six months. Among the achievements of the Committee over the past four years are:

- the establishment of water-conservation libraries in Water Authority offices and Shire libraries;
- the compilation of Pilbara water-consumption figures for Pilbara towns;
- the compilation of a list of low-water demonstration gardens already established throughout Pilbara towns;
- the transfer of information direct to schools and mining companies;
- various publicity campaigns funded and co-ordinated by Water Authority Headquarters in Perth, but adapted to the Pilbara environment; and
- the distribution of pamphlets to households advising of the correct watering times (i.e., early morning and late evening).

The Committee and its working group could do more — such as providing assistance to community groups involved in native-plant nurseries and the planting of arid gardens, and targeting media campaigns more directly at the Pilbara population. Even so, there is no substitute for direct personal contact between people in small communities for promoting an environmentally beneficial concept such as low-water gardening. In this context, a well managed, well resourced native-plant nursery with well presented gardens, a large stock of cheap native plants, and accessible, informal, friendly, free advice provides the ideal surroundings for encouraging such contacts.

Such a service was available to Pilbara residents in the nursery owned and managed by CALM in Karratha. Originally established under the 'Northwest Tree Scheme', whose objective was the greening of the new mining towns of north Western Australia, the nursery grew into an establishment which could boast remarkable credentials in propagating hundreds of indigenous plant species. Free plants were given to residents establishing gardens, and most extra plants were sold for around $1.00.

In July 1987, the nursery was closed as part of a rationalisation scheme that centralised all nursery activity for north Western Australia in the established government nursery in Broome. The same service to Pilbara residents was offered via the Broome nursery, but the loss of the focal point in Karratha, delays of up to three months to acquire some species, and now a freight charge of $1.00 per plant sent to the Pilbara are obvious reasons why a nursery 800 km from one's garden is not as practical as one less than 8 km from one's home. Since the closure of the Karratha nursery, nearly all potential native-plant customers seem to have resorted to purchasing non-indigenous species from commercial nurseries.

The delivery of first-hand advice on low-water gardening techniques, without the focus of the nursery, is extremely difficult if not impossible to maintain. Any amount of media promotions and extension from the office cannot come close to the effectiveness of service delivery in a nursery, especially one whose high level of accessibility and institutionalised credibility has established consumer confidence in the business. The closure of the CALM nursery in Karratha has therefore limited the ability of complementary water-conservation programs to achieve their goals.

Other Western Australian initiatives

Some impressive water-management-based landscape-design initiatives have developed in other dry regions of Western Australia. Two are of particular note.

- 'A case study in water conservation through good design' (RMIT, 1989) proposed how the future development of Broome might incorporate total water management at the house-block, neighbourhood, and regional scales. The concepts applied in this case study are being considered now for development in the Perth metropolitan region. The designs cater for extreme drought and floods, and offer great opportunity for 'designing with nature' as proposed by McHarg (1969).
- The concepts of total water management have been incorporated into open-space design for a natural watercourse — Gribble Creek — which passes through Kalgoorlie's Centennial Park. The report on the project (Arid Area Landscape Group, 1990) is comprehensive, and includes a detailed analysis of catchment characteristics. The plan has now entered an implementation phase.

The future of the water-care ethic in Karratha (and perhaps globally)

The emergence of community-based arid-garden groups in various Pilbara towns, and particularly in Karratha, is encouraging in that it demonstrates the acceptance of the water-care ethic within the general community. Average water consumption in Karratha and other mining towns has fallen significantly over the past six years, and appears to be stabilising around fairly acceptable levels (600–700kL per annum per household). There is also commitment to the principles of water conservation in industry and in State and local governments. The basic recipes for achieving long-term success in arid-garden landscapes have been developed and are being implemented.

The future of the water-care ethic in Karratha depends on several key issues that must be addressed so that we maintain the momentum of our achievements so far. These include the following.

- The water-care ethic must become the prime motivating force behind water-conservation efforts. Economic imperatives are justification enough, but long-term success depends on doing water conservation for all the right reasons.
- Those native-plant enthusiasts, of whom most have already adopted a water-care ethic, need strong encouragement and support so that they might achieve something close to perfection in their own sphere of influence.
- Many more people need to be directly exposed to attractive arid-garden landscapes, and have ready access to expert advice. The landscapes and the advice must be located at the same place (e.g., a nursery or arboretum) to be effective.
- A great deal of expertise in arid-garden landscaping, plant propagation, and soil conditioning is still available in Karratha, but much technical information, experience, and enthusiasm has left the town with the souls of those who have moved on to greener pastures in the south. It is imperative that at least the technical information (if not the enthusiasm and experience) be retained in a form which will be permanently available to those who will surely soldier on to new frontiers in arid-garden landscaping.
- We need to be more effective in promoting (to all sectors of the community) the concepts of conservation and personal responsibility for the environment.
- We must provide support for the converted. This requires financial assistance and extension services to be provided by Federal, State, and local government agencies, perhaps in the same way that this support is provided to land-care groups.

Extension services required for water care could be easily drawn from existing resources in a number of government agencies. In Western Australia, these resources are evident from the lists of contributors to recent publications and reports on the subjects of arid-land gardens and water-sensitive urban design. Ideally, one Federal and one State agency should provide the focus for the extension effort. The extension must be provided, wherever possible, in an environment in which the public will feel comfortable, and where they are likely to accept advice. A nursery is the most obvious environment for this type of contact, although a well presented arboretum or demonstration garden might also be appropriate in some places. The notion of governments being directly involved in the nursery business is one of the perceived obstacles to this approach. However, it may not be necessary for governments to own and manage such businesses, if the same results could be achieved through co-operation with the nursery industry and/or the systematic development of arboreta and demonstration gardens in towns and cities.

The retention of expertise within regions requires vigilance on the part of government and non-government organisations. The focus provided by water-care groups will help to ensure that technical information is stored and made easily accessible.

Conclusions

The Karratha experience, and to some extent the experience of other towns in Western Australia, has taught us that significant water can be saved by using appropriate landscaping and horticulture in arid zones. It has taught us that arid gardens can be attractive. We have also learnt that the community responds well to economic stimuli, but may be a little slower at responding to ecological ones. The ecological problems that we face in arid Australia commonly directly affect water, the finite resource.

To hasten the development of a water-care ethic, I suggest that the land-care approach be used as a model (Department of Primary Industries & Energy, 1991). The cost of water-care should be less than that of land care because most of our water use, and hence the opportunity to reduce it, is within the confines of towns, cities, and small settlements — not the vast open spaces of our rangelands. The skeleton of a water-care movement is already there, so it will not cost much to provide the ligaments to make it work. There are many things that we can do as individuals and as groups to develop a strong water-care ethic. Some of these are:

- *for individuals and community groups*:
  - — organise demonstration projects;
  - — lobby for policies, incentives, research, and project funding;
  - — form water-care groups; and
  - — establish nurseries for the propagation of local indigenous plants with horticultural potential;
- *for scientists, engineers, horticulturists, and landscape architects*:
  - — direct the application of techniques;
  - — undertake further research;
  - — educate all sections of the community;
  - — organise multidisciplinary workshops;
  - — carry out trials and demonstrations; and
  - — participate in water-care groups and water-conservation advisory committees;
- *for local governments*:
  - — encourage engineers, horticulturists, planners, and building surveyors to adopt appropriate landscape design and species selection; and
  - — adopt by-laws, policies, and regulations to ensure that appropriate techniques are applied to all new developments;
- *for State or Territory government agencies*:
  - — adopt policies in planning, environment, water resources, roads, and railways which require the application of water-conservation principles in all new developments;
  - — support regional and local projects and research; and
  - — establish regional water-conservation committees to liaise with local water-care groups;
- *for Federal Government agencies*:
  - — promote the water-care ethic;
  - — promote a holistic environmental ethic;
  - — fund water-care projects and research; and
  - — encourage the States to adopt appropriate policies.

The issue of water conservation cannot be tackled in isolation from other conservation issues, because the problems besetting us have their roots in attitudes about our whole environment. A holistic environmental ethic therefore needs to be adopted by the whole community — one that tackles not only water care but also land care, marine care, and air care.

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Problem constituents in Australian groundwater drinking-water supplies[1]

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Groundwater is a common source of drinking supply in Australia's arid zone. The constituents in groundwater can limit its use either for drinking or for other domestic purposes. This paper discusses those constituents. It also highlights popular misconceptions about water-quality problems associated with groundwater, and encourages radical rethinking to ensure that people in the arid zone can use available water supplies appropriately to maintain a healthy lifestyle.

Introduction

About 80 per cent of all the water reticulated to towns and cities in Australia is of surface-water origin. However the majority of small communities, many of them in drier regions of Australia, are entirely dependent on groundwater. Much of this water is of ancient origin, a relic of past climatic regimes.

The quality of groundwater is related to both the geochemistry and residence time of water underground. The major water-quality problems experienced by small communities reliant on groundwater are reviewed. Options for small-community water supplies were considered by a workshop of the Australian Water Resources Council (1989), and further elaborated in the UNESCO Regional Seminar on 'Technology for Community Development in Australia, South-East Asia and the Pacific', presented in Alice Springs between 9 and 11 July 1990.

Groundwater quality

Undesirable constituents in groundwater can be broadly classified as:

- those of health concern, which are normally present at levels below those that can be detected by sight, smell, or taste; and
- those that have an aesthetic and economic effect, typically present at high levels.

Pesticides, petroleum products, heavy metals, and other introduced chemicals can pollute groundwaters. However, in lightly populated areas, the main constituents of groundwater are those that occur naturally or which have always been associated with human settlement. Health-related parameters include microorganisms (bacteria and viruses), nitrate, and fluoride. Aesthetic and economic parameters include total dissolved solids (TDS — water salinity and water hardness), colour (iron and manganese), and acidity (pH and total alkalinity). The maximum normally accepted levels (National Health and Medical Research Council–Australian Water Resources Council, 1987, guideline levels, in parentheses) are:

• total dissolved solids	1500 (1000) mg L^{-1}
• hardness (as $CaCO_3$)	600 (500) mg L^{-1}
• turbidity	25 (5) NTU[3]
• colour	50 (15) TCU[4]
• iron[5]	1 (0.3) mg L^{-1}
• manganese[5]	0.5 (0.1) mg L^{-1}
• acidity	pH 6.5–8.5
• taste/odour	not offensive

For many domestic issues, such as showering, much higher levels need to be accepted in practice.

Health-related constituents

Microorganisms. The major health concerns associated with nearly all water supplies relate to the levels of pathogenic bacteria, viruses, and possibly protozoans present. Well protected deep aquifers are sometimes the safest to use, and are normally free of harmful microorganisms. Conversely, shallow aquifers are often polluted, especially where they are connected to surface waters or where shallow wells, septic tanks, and other systems directly contaminate the groundwater.

Two categories of microorganisms are recognised:

- those of animal, bird, or human faecal origin; and
- those of environmental, normally soil, origin.

Microorganisms of environmental origin are best known for the problems they cause in swimming pools. Current wisdom doubts that environmental microorganisms are a major health hazard in drinking water. Faecal pathogens in drinking water, on the other hand, are probably contributing factors to both morbidity and mortality (sickness and death) in small poor communities. Communities that lack an adequate water supply — those with poor hygiene — can, however, improve their living standards by washing clothes and bathing in untreated water.

Just which microorganisms most compromise untreated supplies is a matter for conjecture. Bacteria — including *Salmonella, Campylobacter*, and *Shigella* — and enteroviruses are probably important in many situations. The protozoans *Giardia* and *Cryptosporidium* are of uncertain importance in Australian supplies of drinking water, partly because they are extremely difficult to isolate from water and partly because epidemiological evidence of their having an effect is lacking.

Since most groundwaters contain little suspended organic material, they are usually relatively easy to disinfect. Boiling water or, at a community level, treating water with chlorine at around 3 mg L^{-1} will usually render water safe to consume.

Nitrate. The health effects of elevated nitrate levels in groundwater have been recently reviewed by the National Health and Medical Research Council (1990). Despite widespread fears about the presence of nitrate in drinking water, there appears to be no clinical evidence that it has adverse health effects in Australian arid-zone communities. The only individuals likely to be affected are babies under three months of age. It is now accepted that the baby must also be suffering other complications. In practice this amounts to poor nutrition and hygiene. There is firm evidence that poor hygiene is associated with inadequate water supplies.

The National Health and Medical Research Council has encouraged review of the policies of water authorities reticulating

[1] Poster paper presented at conference on 'Arid zone water: a finite resource', Alice Springs, 11–14 April 1991 (*Issues in Water Management* number 6 of the Centre for Continuing Education, Australian National University, Canberra, ACT).
[2] Aquatech Pty Ltd, 52 Jaeger Circuit, Bruce, ACT 2617.
[3] Nephelometric turbidity units.
[4] True colour units.
[5] Both sluggish flow and biological activity in water mains can result in the levels of iron and manganese at the tap being much higher than those that enter the reticulation.

high-nitrate water supplies. Further, most water uses — including drinking-water supplies for all individuals, except young babies — are not compromised by nitrate. Water always should be made available, whatever the nitrate level, and supplementary or treated water provided for drinking purposes where nitrate levels are excessive (Table 1).

Fluoride. Fluoride levels are occasionally elevated in groundwater. This phenomenon appears to be confined to particular districts or regions. Low dietary levels of fluoride are beneficial (National Health and Medical Research Council, 1990) in the prevention of dental caries (tooth decay), whereas highly elevated levels, generally well above 2 mg L^{-1}, can have an adverse effect on bone strength. Elevated levels are unlikely to be a cause of significant health problems in Australia. The United States Environment Protection Agency (1991) confirms the 1987 maximum contaminant level for fluoride as 4 mg L^{-1}.

The treatment of naturally high-fluoride water supplies is expensive. Alternative options include mixing the water with water containing little or no fluoride, or simply providing a low-fluoride water source for drinking and cooking. Uses of water other than for drinking and cooking, such as bathing and washing clothes, are not compromised by high-fluoride levels in the water.

Constituents of aesthetic and economic importance

Total dissolved solids (salinity and hardness). Total dissolved solids (TDS) are what remains when all the water is removed from filtered water by, for example, evaporation. Suspended material — that is, undissolved material such as plant and algal debris — may also be present in water, but is generally only a problem in surface waters.

Salinity. In practice, dissolved solids comprise mainly sodium, calcium, and magnesium salts. Sodium salts give water a brackish or saline taste. High levels of sodium make water unpalatable. Some communities use supplies with up to 5000 mg L^{-1} TDS (mainly sodium salts). Levels above 1000–1500 mg L^{-1} TDS (mainly sodium salts) are, however, considered to be of very poor quality for drinking (Table 2). Such water is still suitable for a wide range of uses such as bathing, and washing clothes and dishes. Taste thresholds for different sodium salts (the minimum level that many people can detect) are listed in Table 3.

Saline waters can be quite aggressive, particularly if chloride levels are high, promoting corrosion of water fittings and mains. They can also be unsuitable for garden watering.

Hardness. Hard waters (those containing calcium and magnesium salts) cause a range of problems. They adversely affect taste, scale hot-water systems and fittings, and increase laundry soap and detergent requirements.

The proportions of calcium and magnesium can vary widely depending on the hydrogeology of the groundwater system. Limestone produces high-calcium waters, whereas dolomite produces water with roughly equal levels of calcium and magnesium. The economic importance of hard waters is well recognised: for many uses very hard waters need to be treated or the effects, such as blocked pipes and poor heat transfer in heating systems, must be accepted.

Fortunately, waters which are temporarily hard are not difficult to treat, and systems such as brine-softening and lime-softening are feasible on a small-to-medium scale. These waters contain calcium and magnesium bicarbonate. Waters containing other calcium and magnesium salts are termed permanently hard, and are expensive to fully treat. A ranking of water hardness levels is provided in Table 4.

Table 1. Guideline values for nitrate in water supplies.

Use pattern	*Guideline level (mg L^{-1} as N)*
Babies under three months	10
Community drinking-water supply	23
General use	no limit

Table 2. Drinking-water-quality rating for total dissolved solids (World Health Organization, 1982).

TDS (mg L^{-1})[1]	*Aesthetic quality*
Less than 300	excellent
300–600	good
600–1000	fair
1000–1500	poor
Greater than 1500	unacceptable

[1] Current Australian guideline level is 1000 mg L^{-1} (National Health and Medical Research Council–Australian Water Resources Council, 1987).

Table 3. Taste threshold at normal temperatures for various sodium salts.

Salt	*Sodium level (mg L^{-1})*
Sodium carbonate	20
Sodium chloride	150
Sodium nitrate	190
Sodium sulphate	220
Sodium bicarbonate	420

Table 4. Water hardness rating (World Health Organization, 1982).

Classification	*Hardness as $CaCO_3$ (mg L^{-1})*
Soft	0-60
Medium hard	60–20
Hard	120–180
Very hard	Greater than 180

Iron and manganese. Iron and manganese are troublesome trace metals, and are a common cause of water discolouration. Iron stains washing and plumbing fixtures reddish brown, whereas manganese typically stains black. These metals can affect taste, and bacteria can concentrate them in sluggish-flow areas of water-supply mains; for example, they are a common problem in cul-de-sacs. Mains-supply design or water treatment can reduce their nuisance value.

Iron and manganese are widespread in nature, and almost any groundwater or bottom water in a storage reservoir is affected by their presence. On contact with air, these metals often form a scum. Even when they remain dissolved or in colloidal suspension, they can adversely affect the appearance and taste of water. Levels of iron around 0.3 mg L^{-1} and manganese around 0.1 mg L^{-1} are marginally acceptable at the tap, though problems may occur if these are the levels entering a water-supply system. Iron and manganese are essential elements, and at the natural levels found in water are of no health concern.

Acidity. Some soft, as opposed to hard, groundwater contains high levels of dissolved carbon dioxide, and is therefore acidic. Communities in some coastal areas of the Northern Territory, for example, have highly acidic supplies with a pH commonly below 5. Such water is highly aggressive, particularly to cement and galvanised iron. Either pH correction or use of acid resistant materials such as plastics is essential for maintaining the integrity of such systems.

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