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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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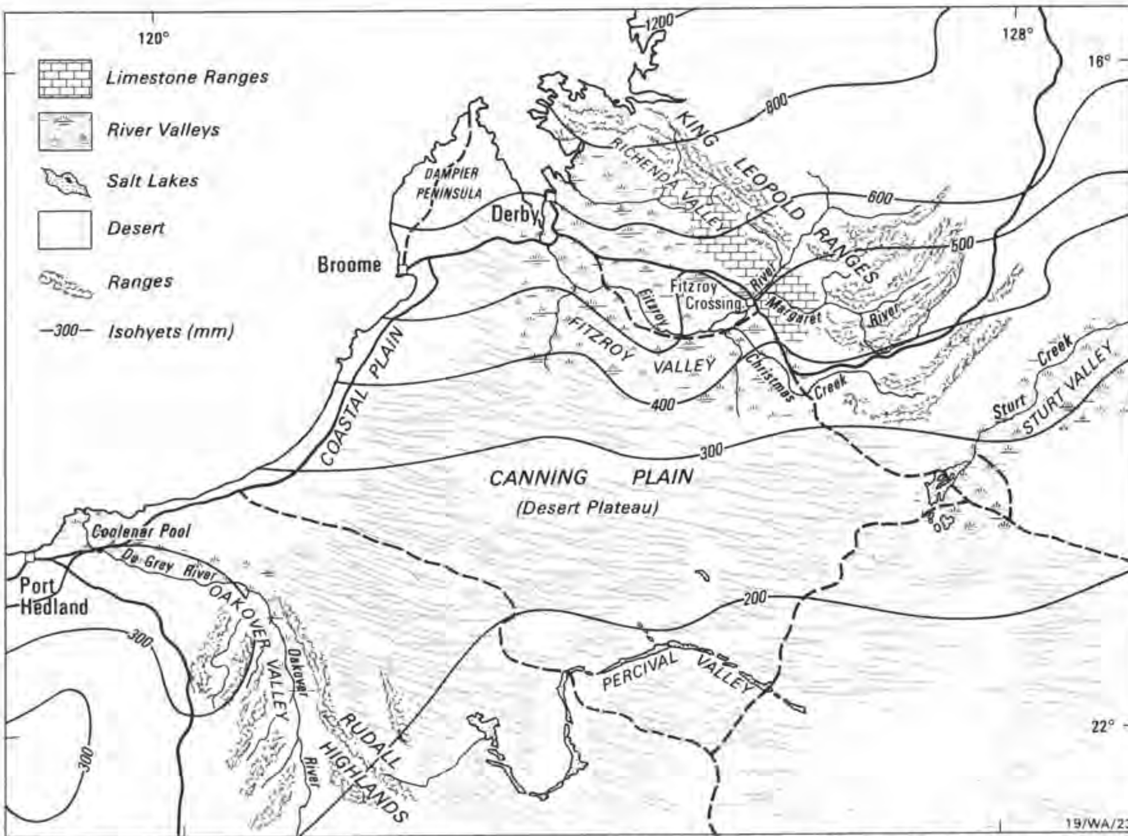

Figure 1. Physiography (from Purcell, 1984) and median annual rainfall (from Parkinson, 1986) in the Canning Basin region.

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-

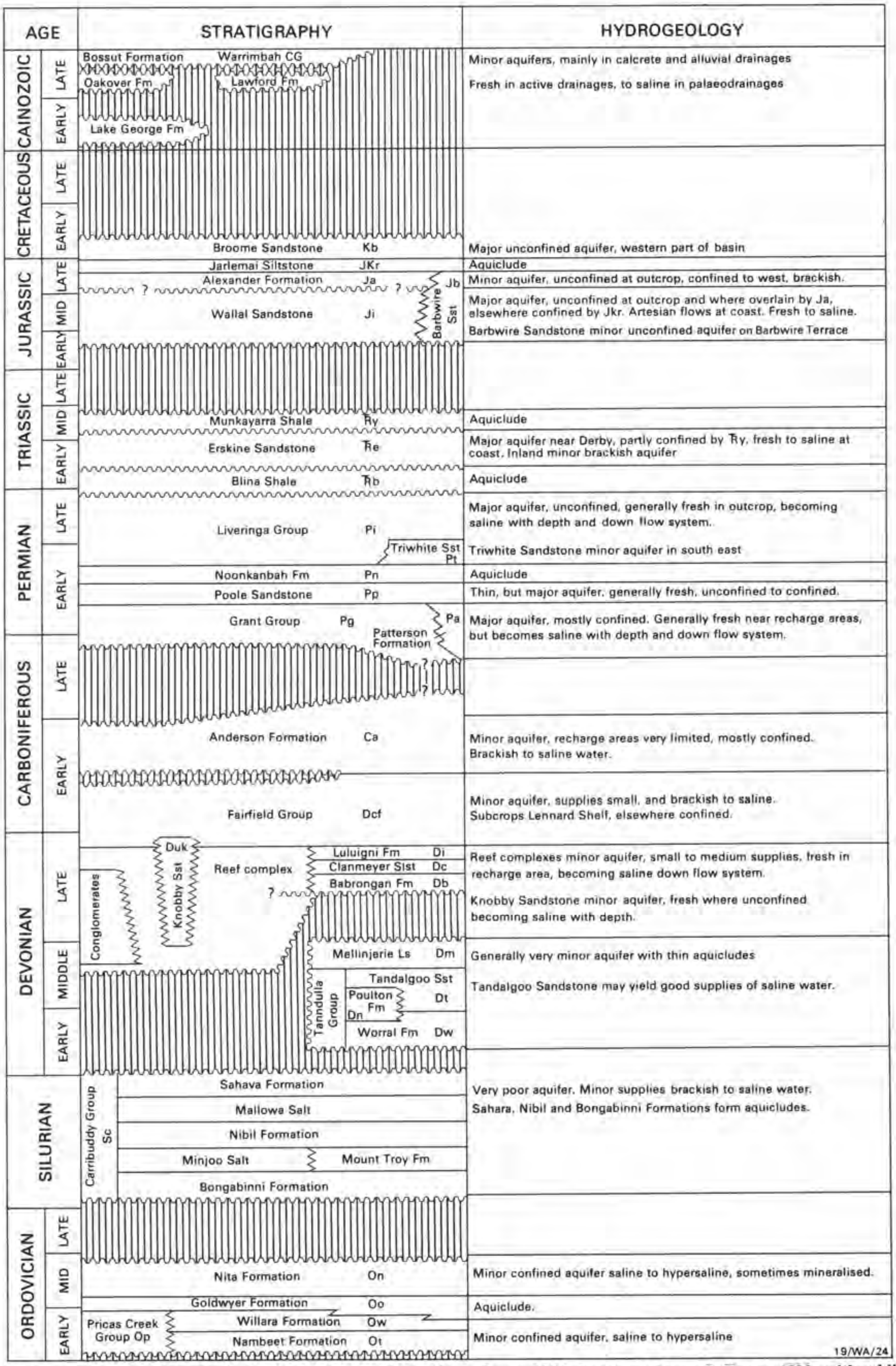

Figure 2. Stratigraphy and hydrogeology of the Canning Basin (from Laws, 1991; based on Mory & Dunn, 1990, with additions).

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

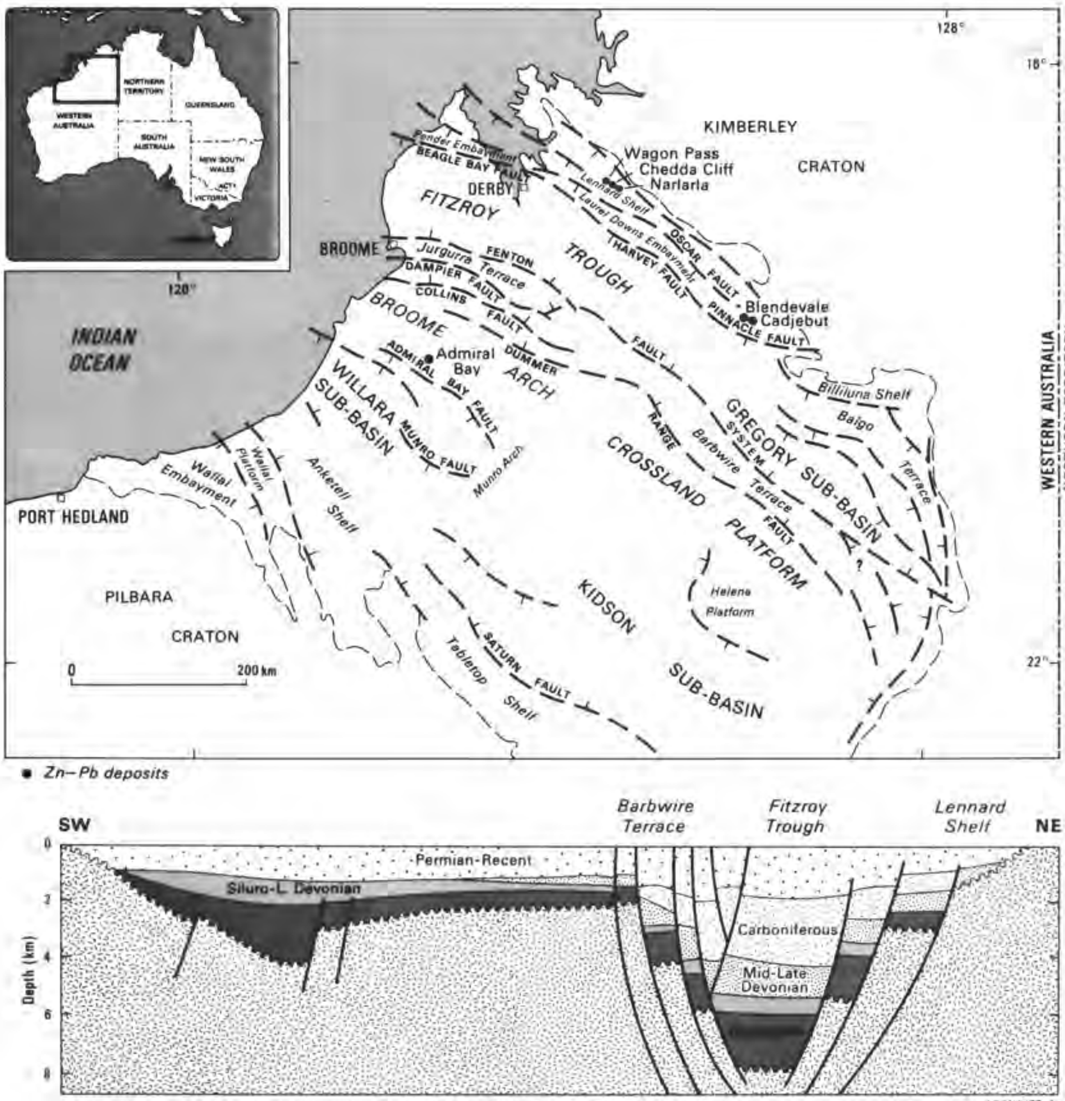

Figure 3. Main structural units of the Canning Basin, and locations of Zn–Pb deposits (after Purcell, 1984).

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 No. of samples	Porosity Min. %	Porosity Max. %	Porosity Mean %	Permeability No. of samples	Permeability Min. (md)	Permeability Max. (md)	Permeability 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	<O.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.

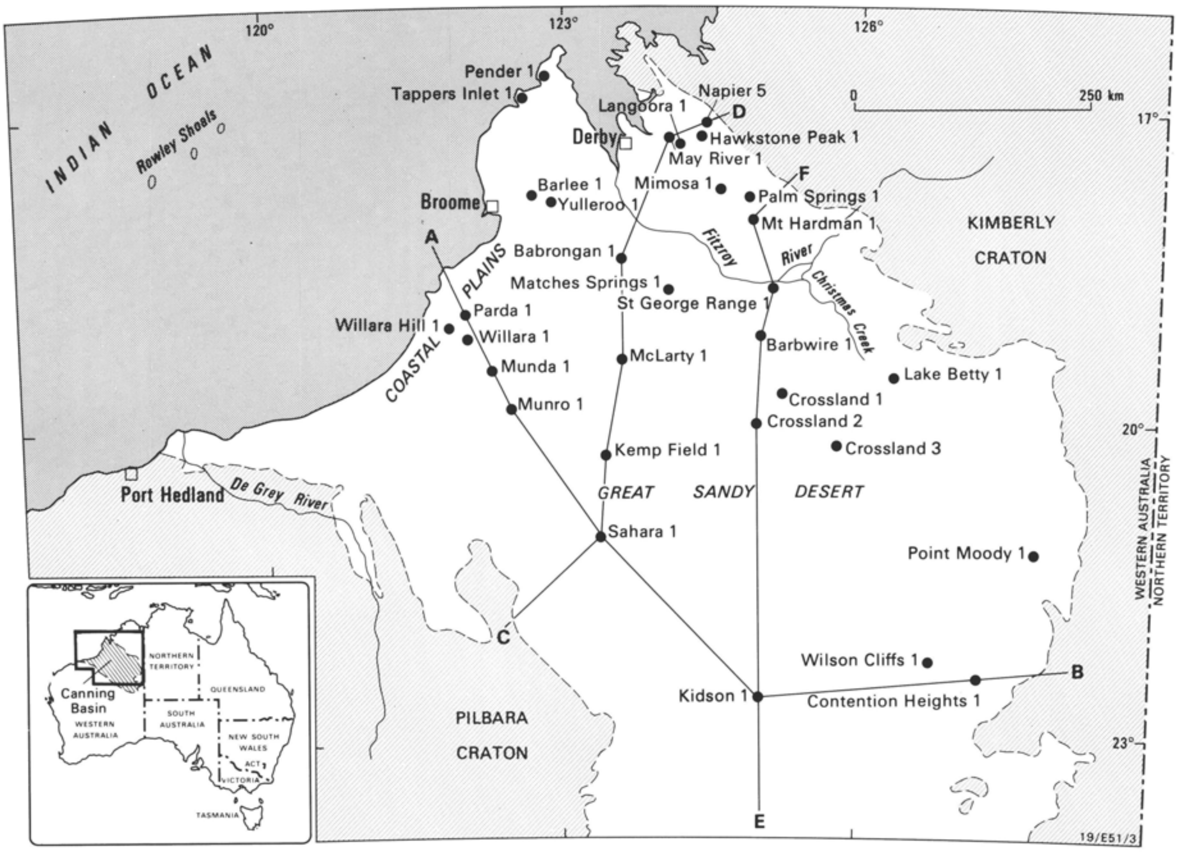

Figure 4. Locations of selected oil exploration wells in the Canning Basin, and hydrogeologic cross-sections shown in Figures 5 to 7.

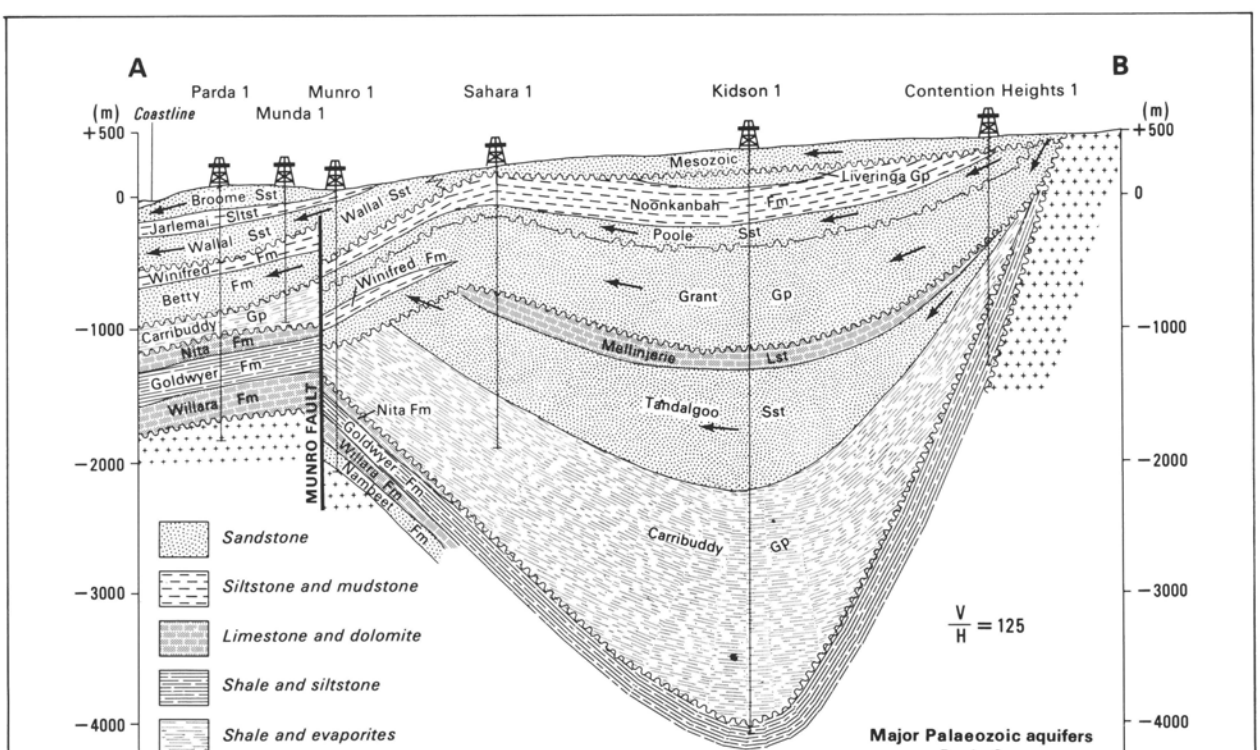

Figure 5. Generalised hydrogeologic cross-section A–B (see Fig. 4 for line of section).

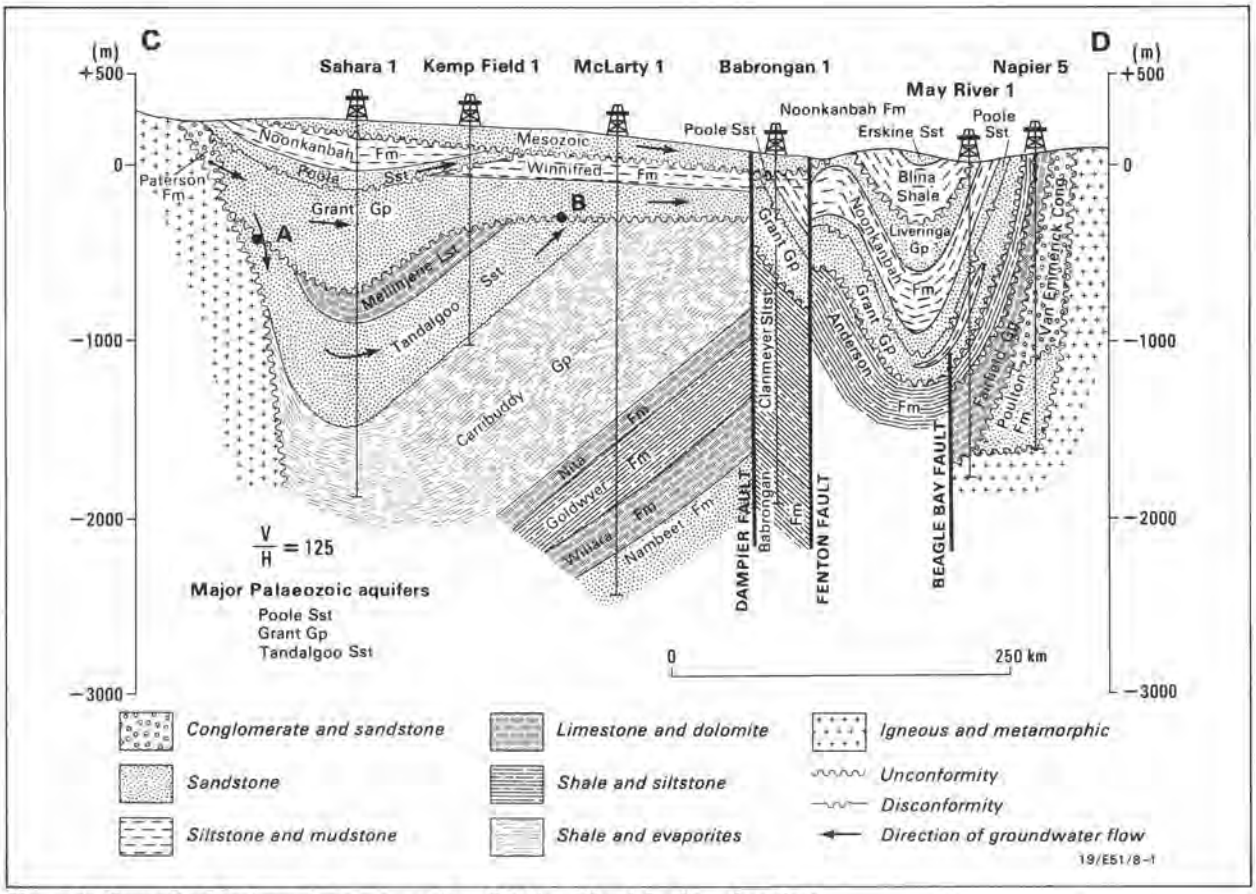

Figure 6. Generalised hydrogeologic cross-section C–D (see Fig. 4 for line of section).

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.

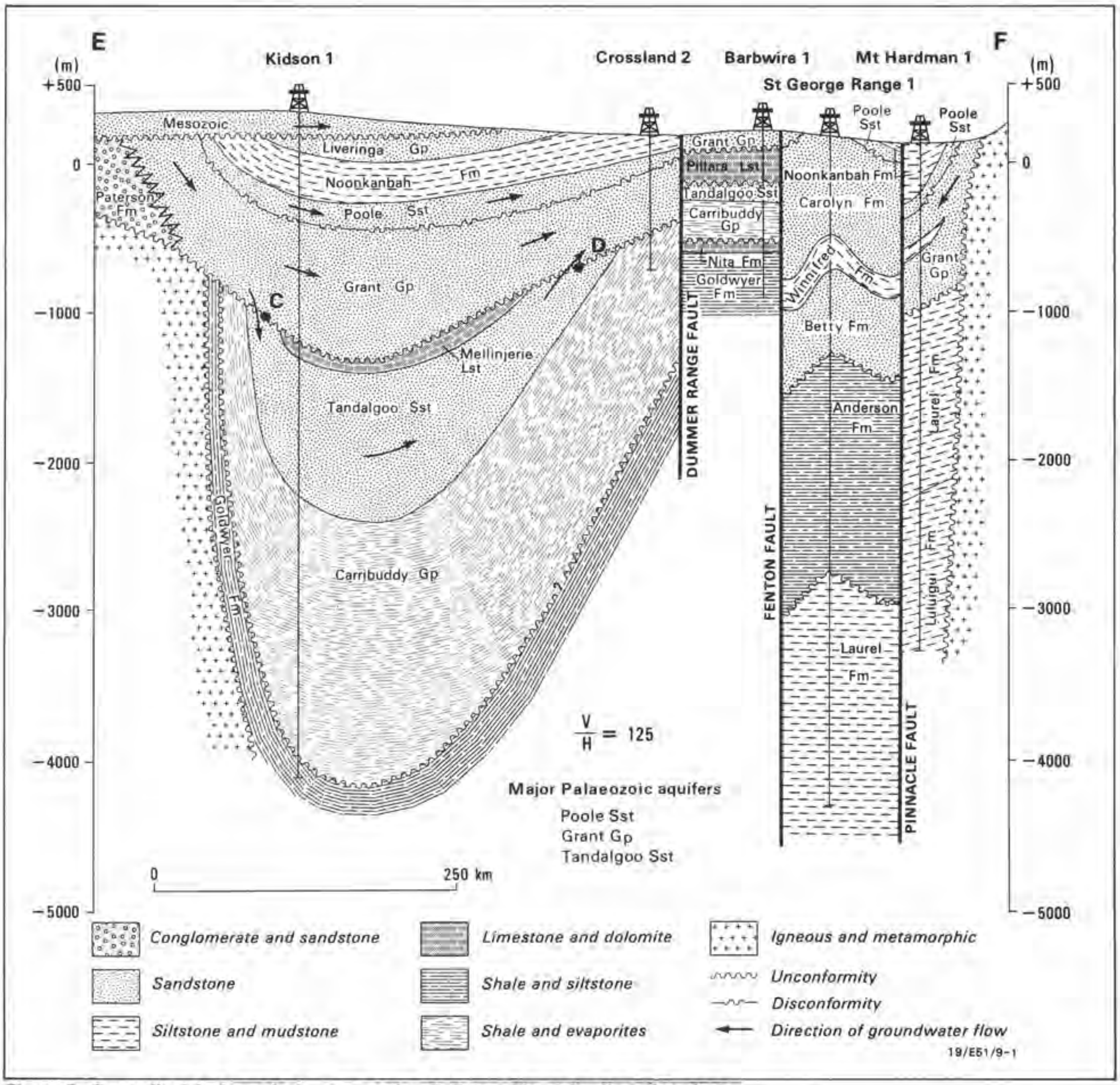

Figure 7. Generalised hydrogeologic cross-section E–F (see Fig. 4 for line of section).

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.

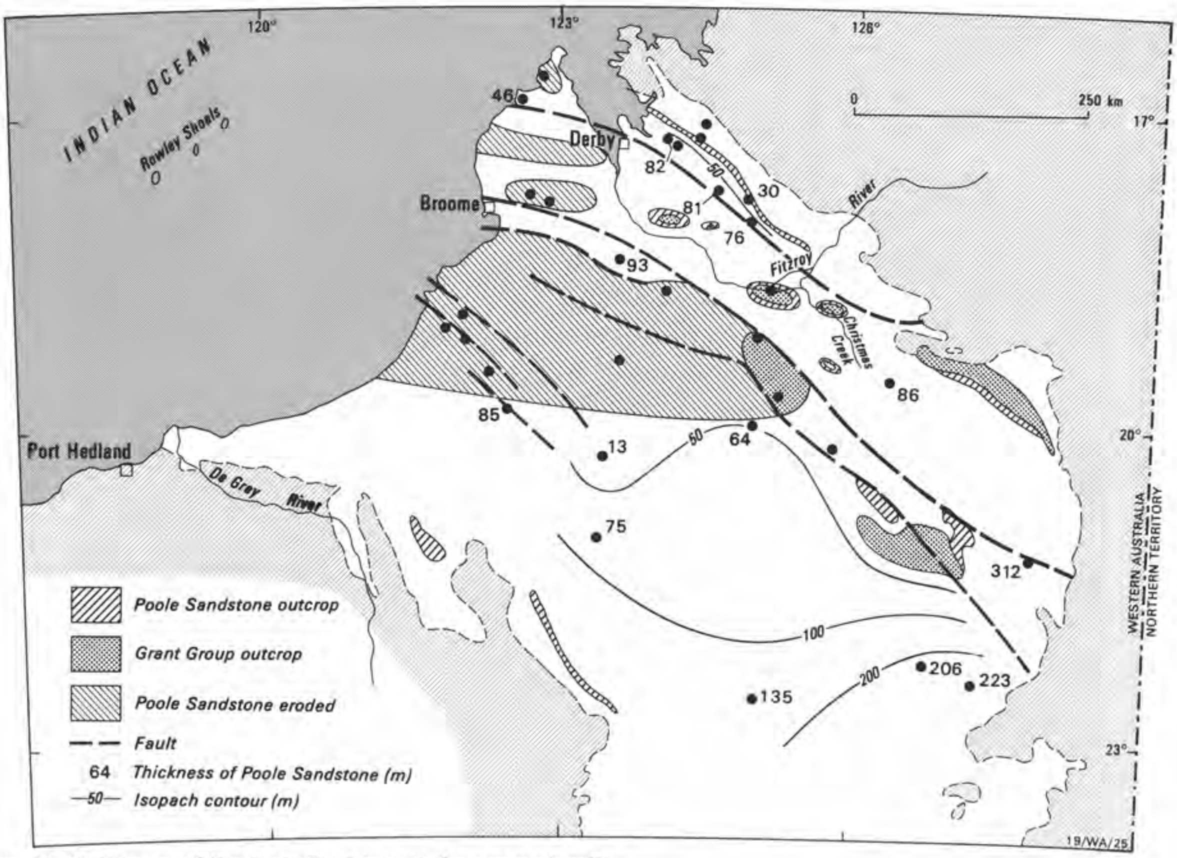

Figure 8. Thicknesses of the Poole Sandstone in the surveyed wells.

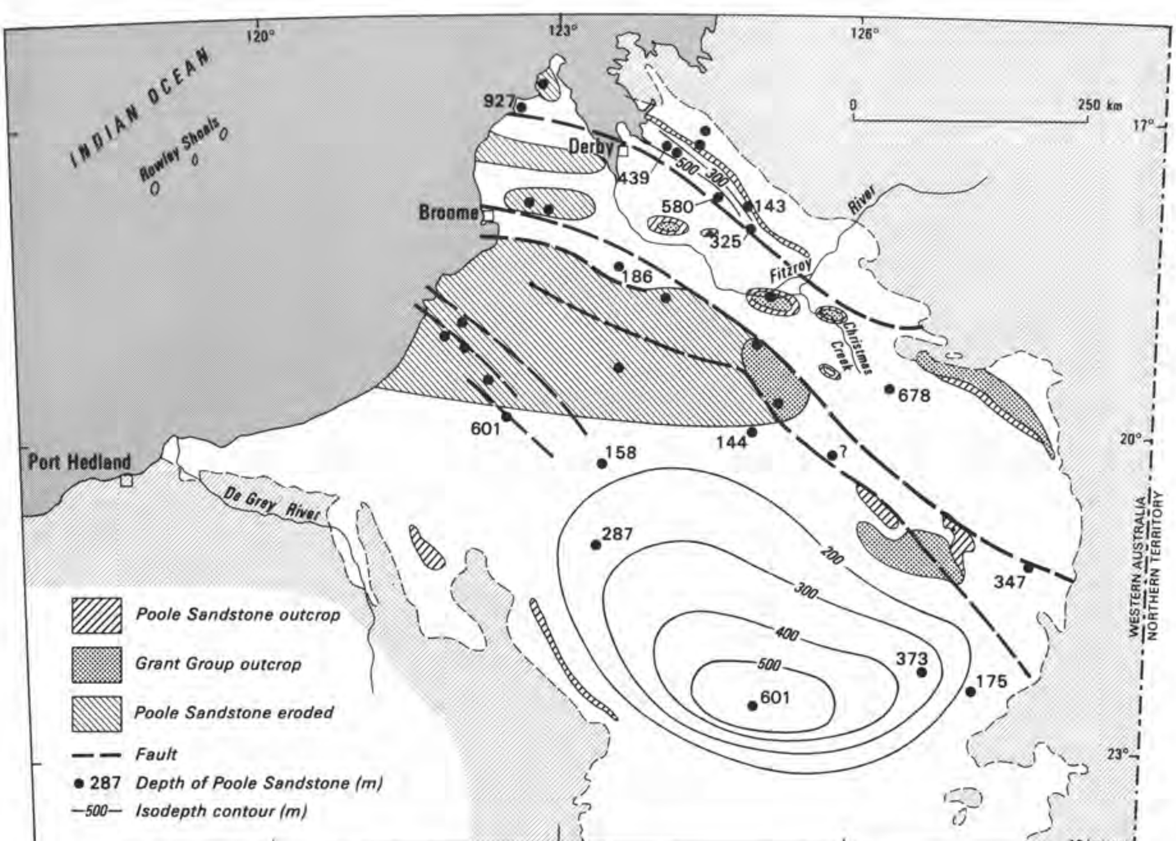

Figure 9. Depths of the Poole Sandstone in the surveyed wells.

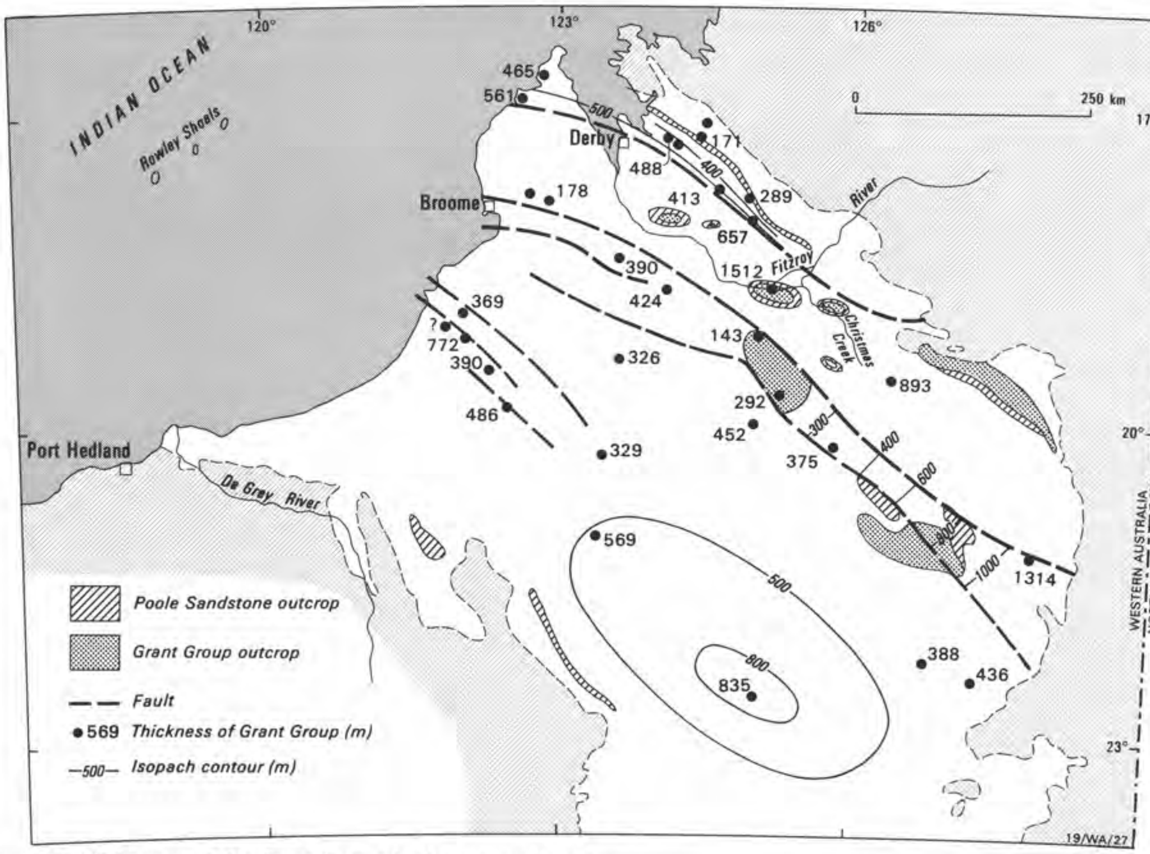

Figure 10. Thicknesses of the Grant Group in the surveyed wells.

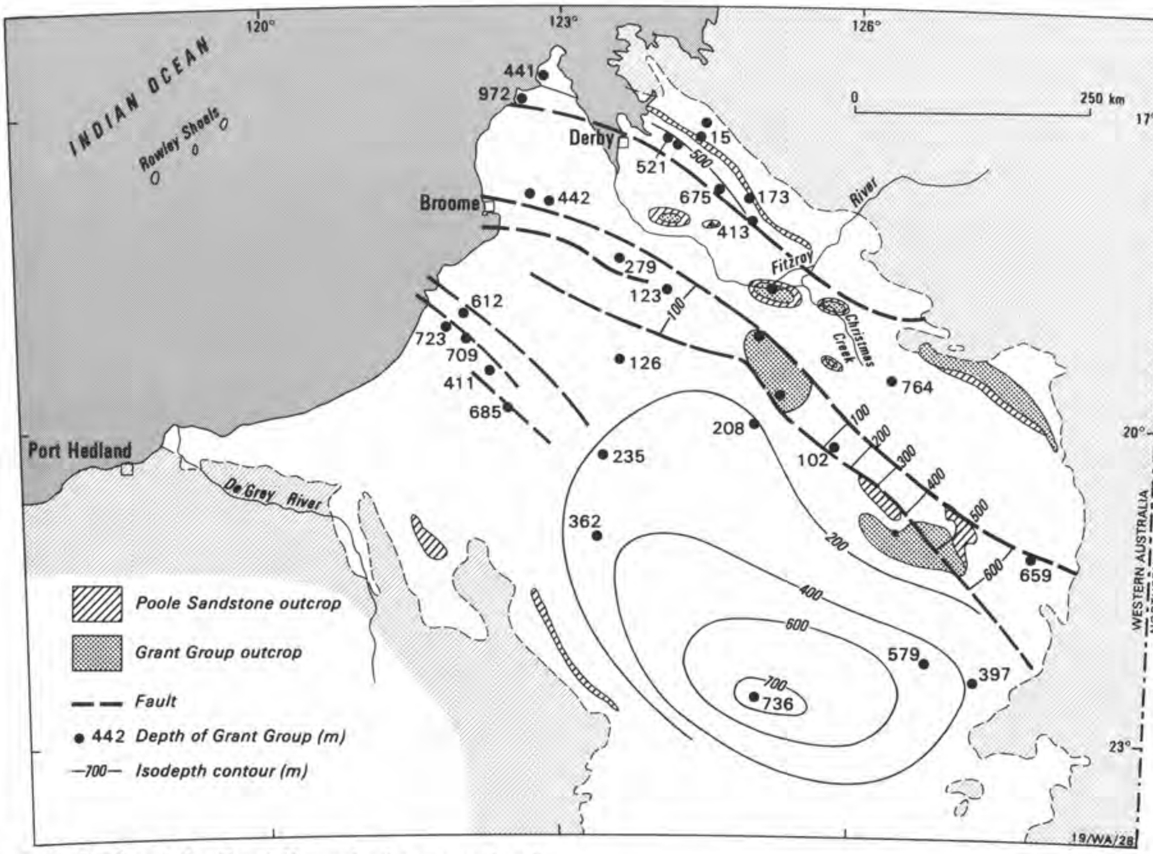

Figure 11. Depths of the Grant Group in the surveyed wells.

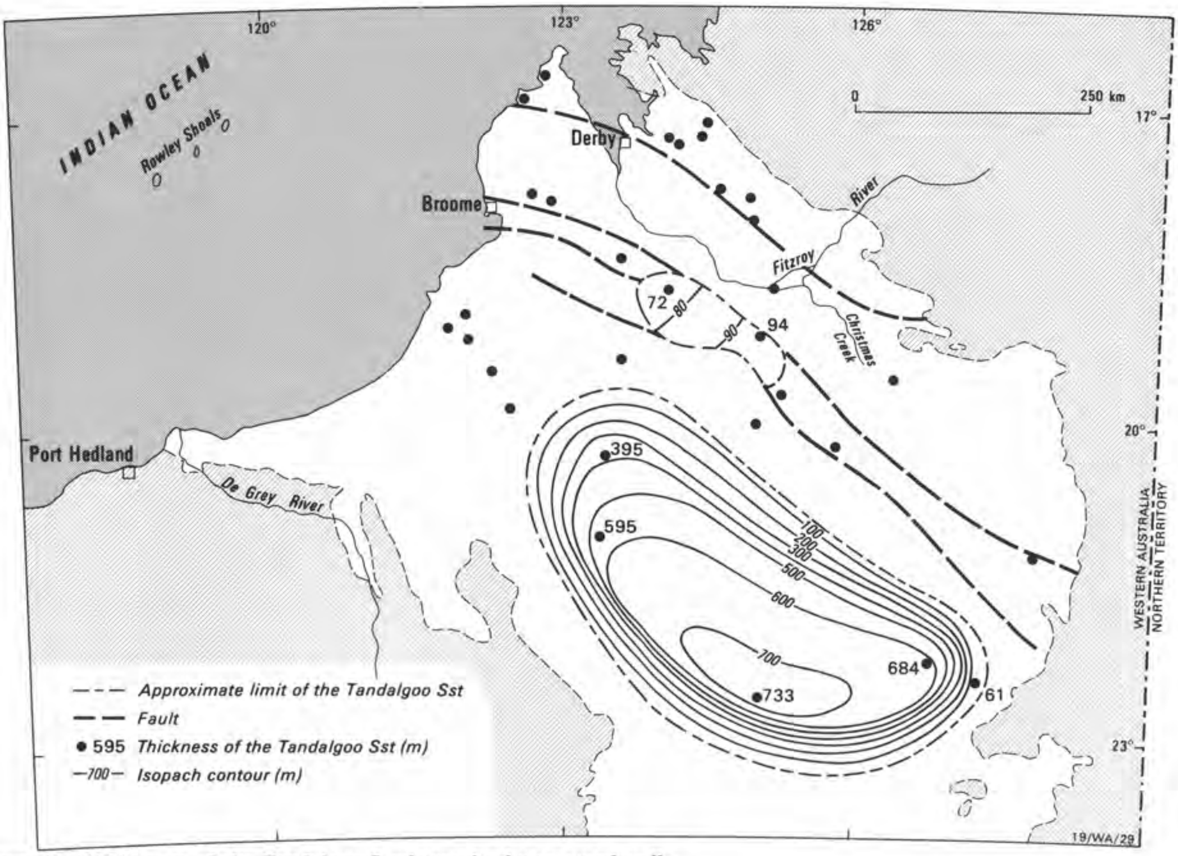

Figure 12. Thicknesses of the Tandalgoo Sandstone in the surveyed wells.

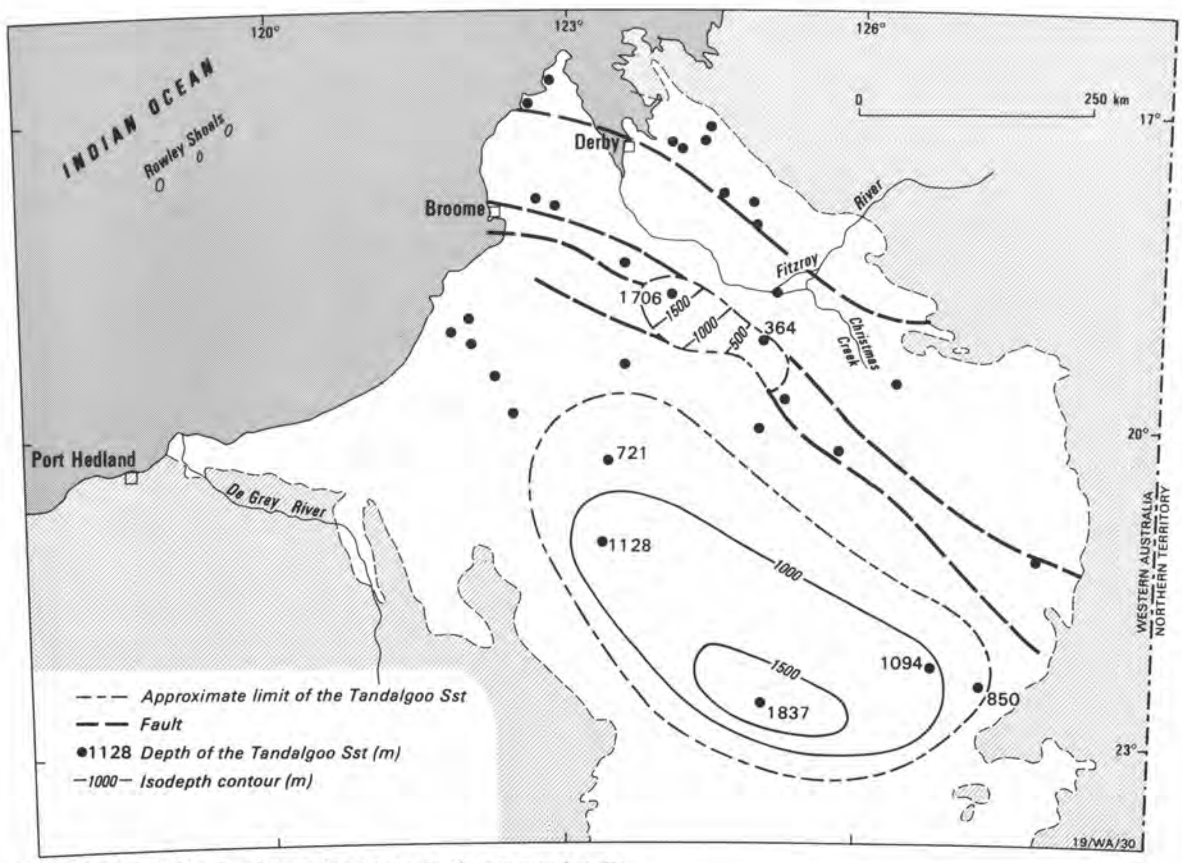

Figure 13. Depths of the Tandalgoo Sandstone in the surveyed wells.

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) EDFD[1] ($lb\ gal^{-1}$)	(4) Geostatic ratio ($Psi\ ft^{-1}$) (3) × 0.052	(5) Fluid pressure (Psi) (2) × (4)	(6) Elevation head (ft) −(2)	(7) Pressure head EFW[2] (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

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

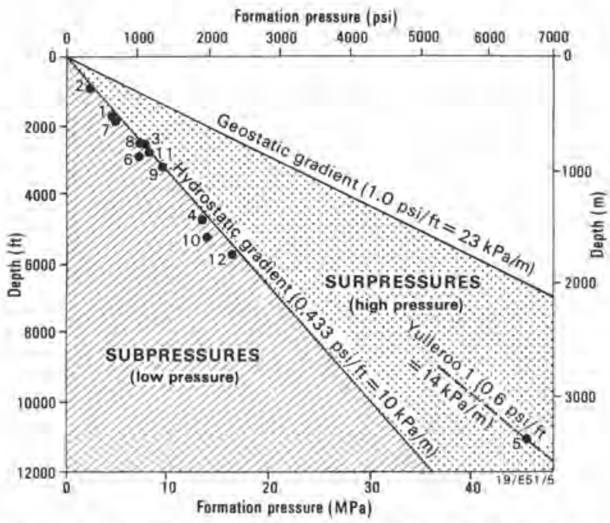

Figure 14. Measured formation pressures in drill stem tests *v.* depths (see Table 4).

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.

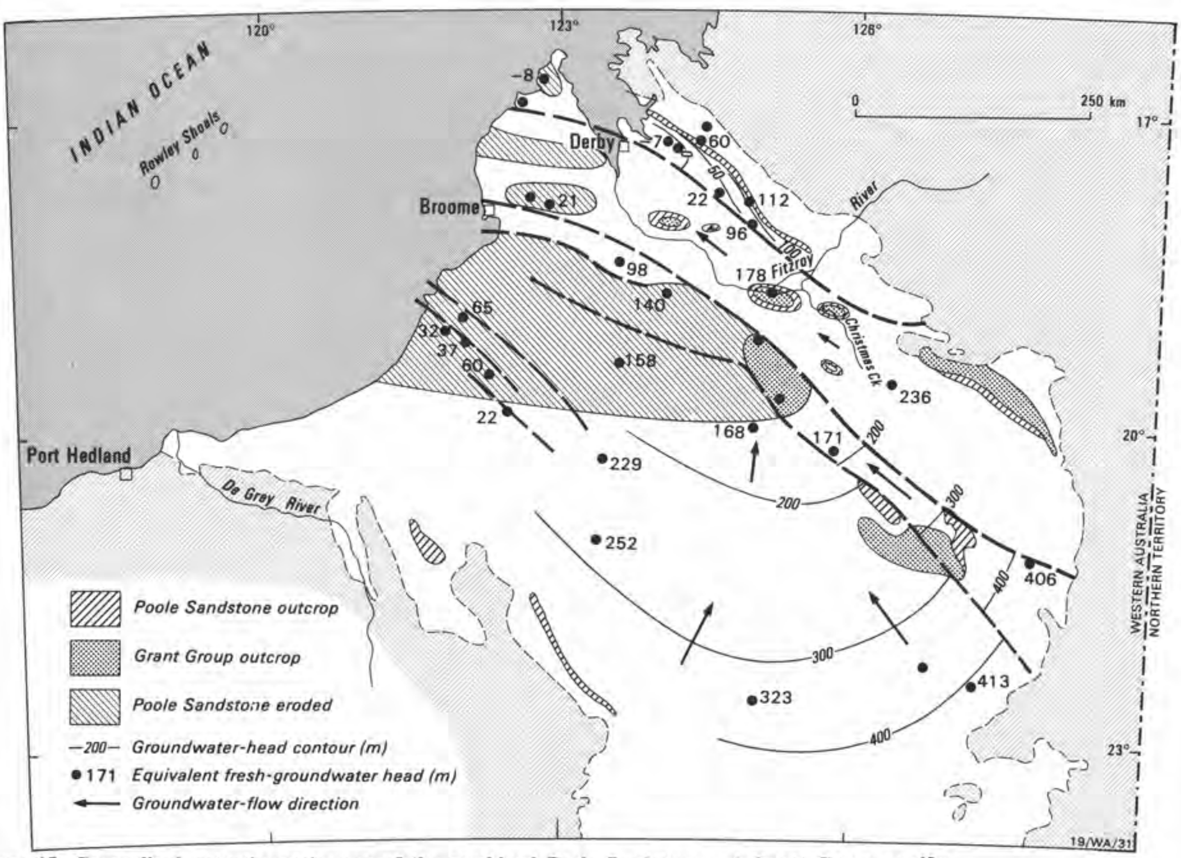

Figure 15. Generalised potentiometric map of the combined Poole Sandstone and Grant Group aquifer.

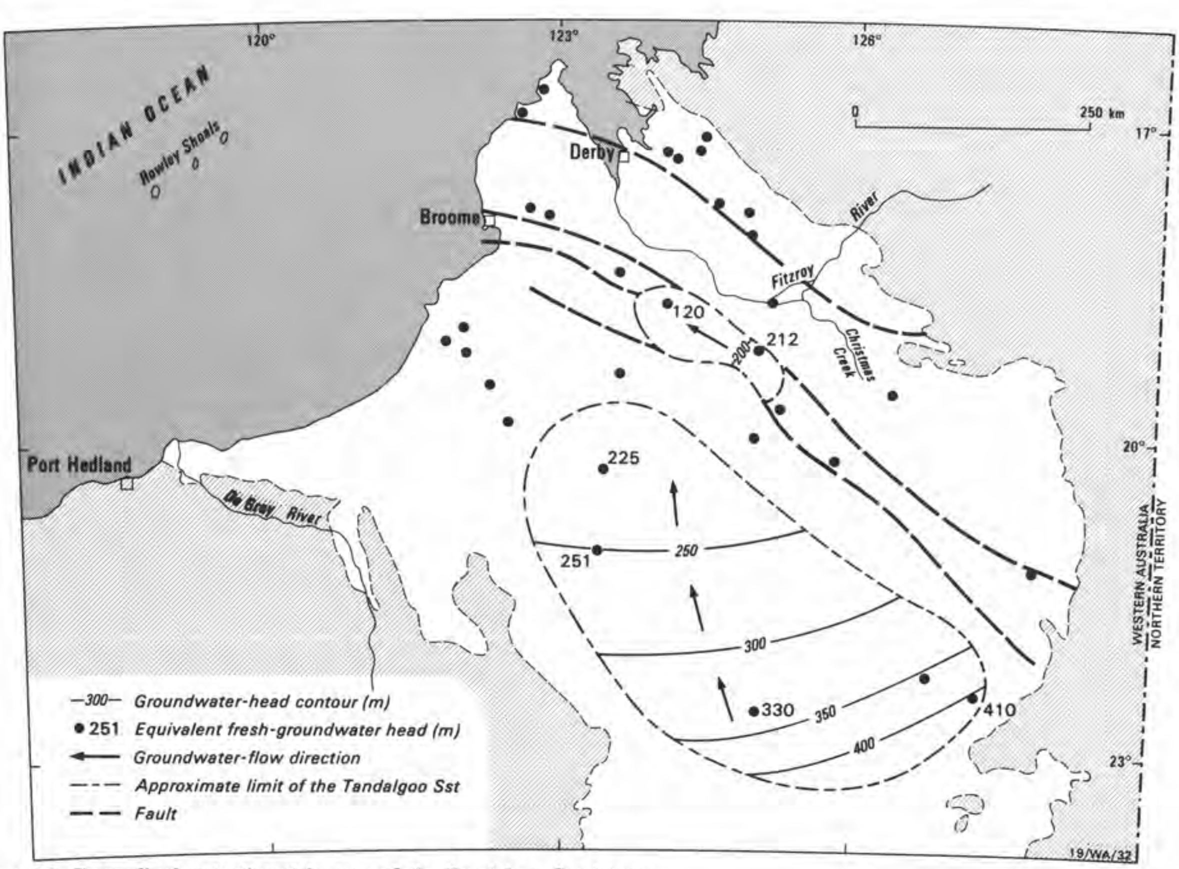

Figure 16. Generalised potentiometric map of the Tandalgoo Sandstone.

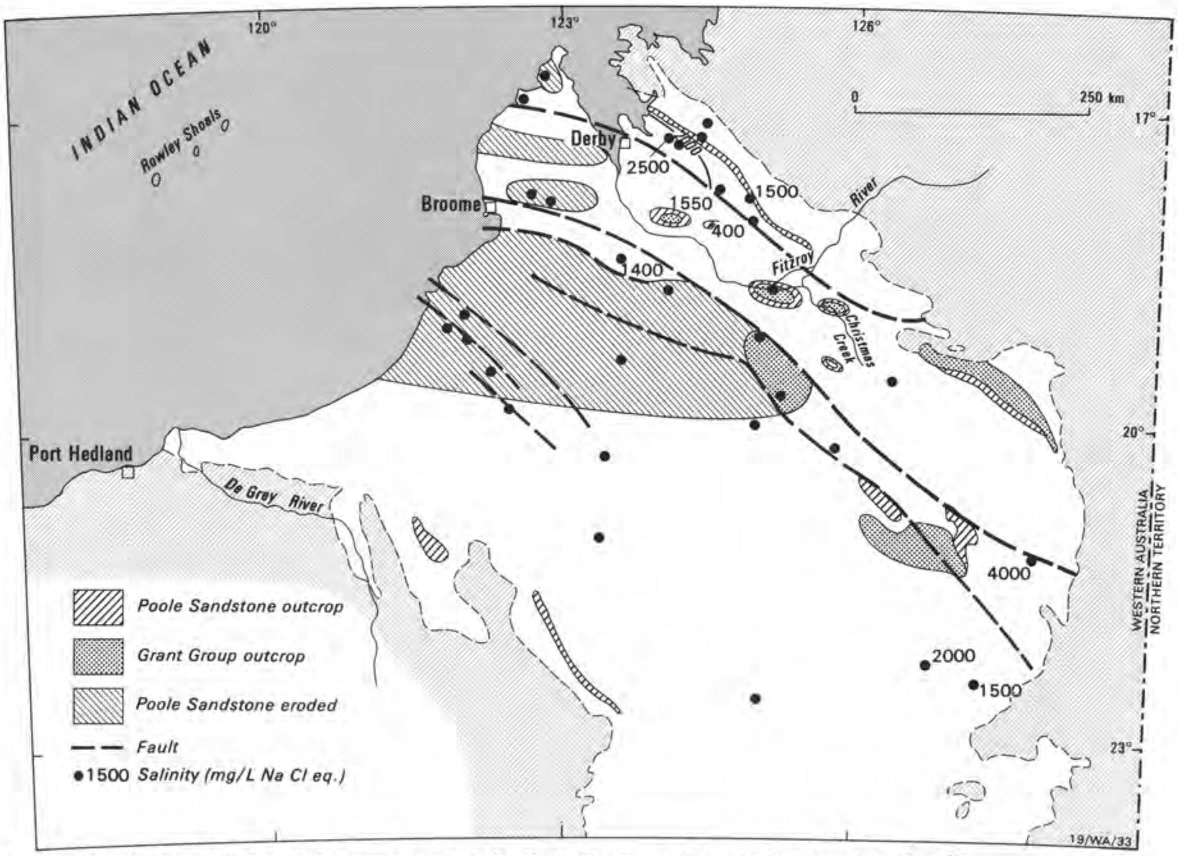

Figure 17. Groundwater salinity of the upper part of the Poole Sandstone for a limited number of wells.

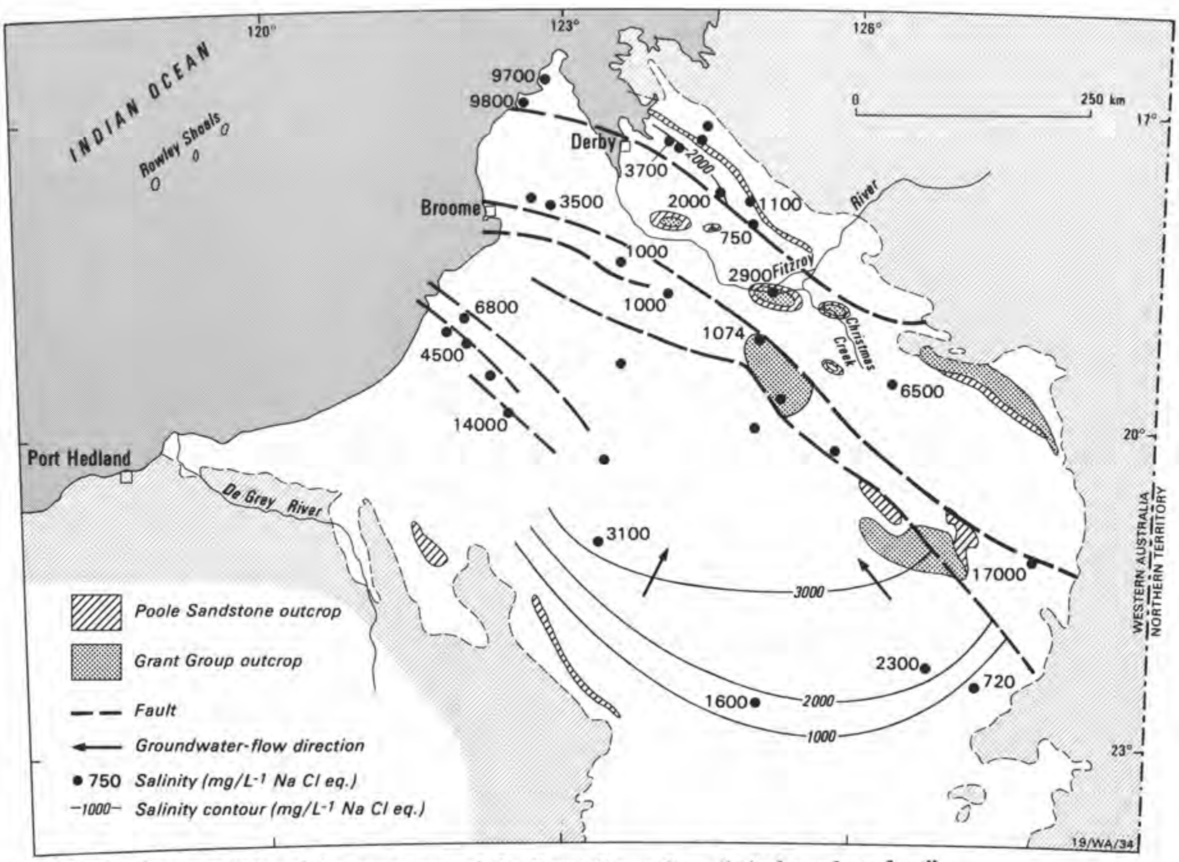

Figure 18. Groundwater salinity of the upper part of the Grant Group for a limited number of wells.

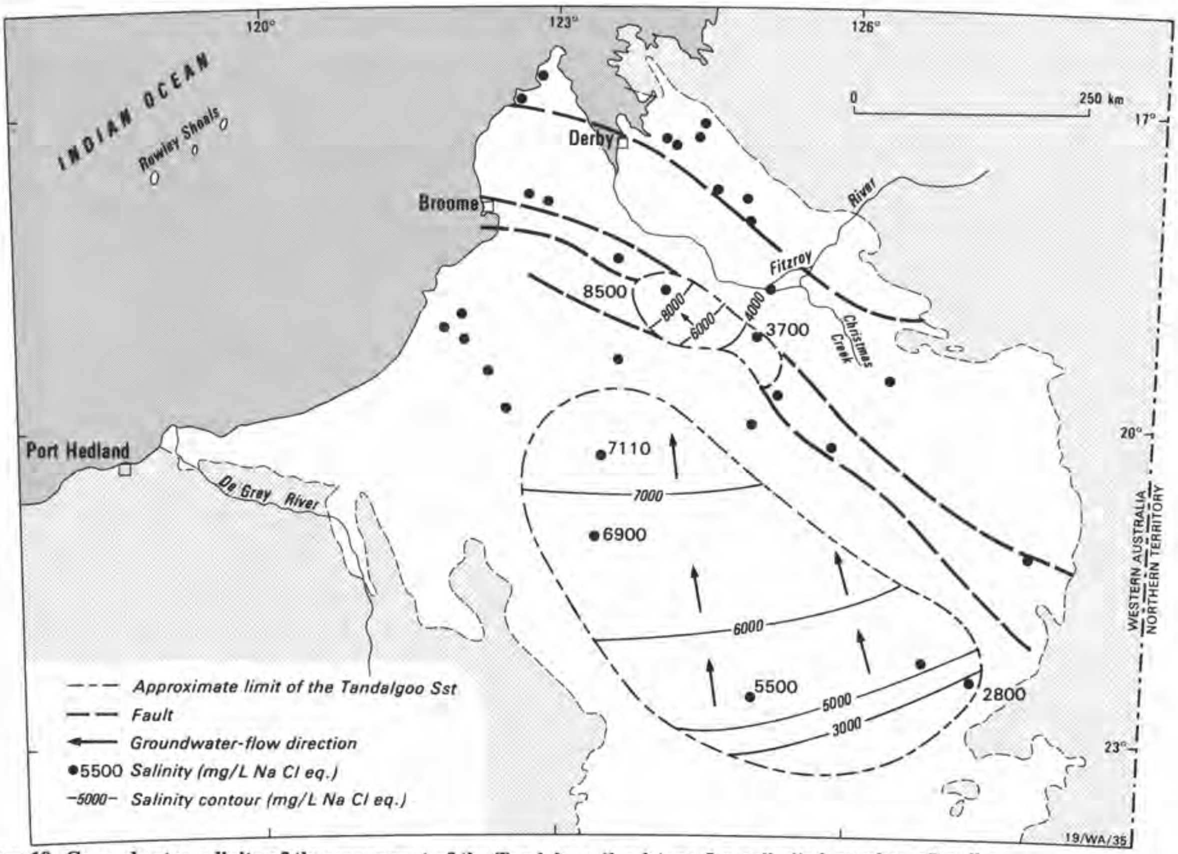

Figure 19. Groundwater salinity of the upper part of the Tandalgoo Sandstone for a limited number of wells.

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

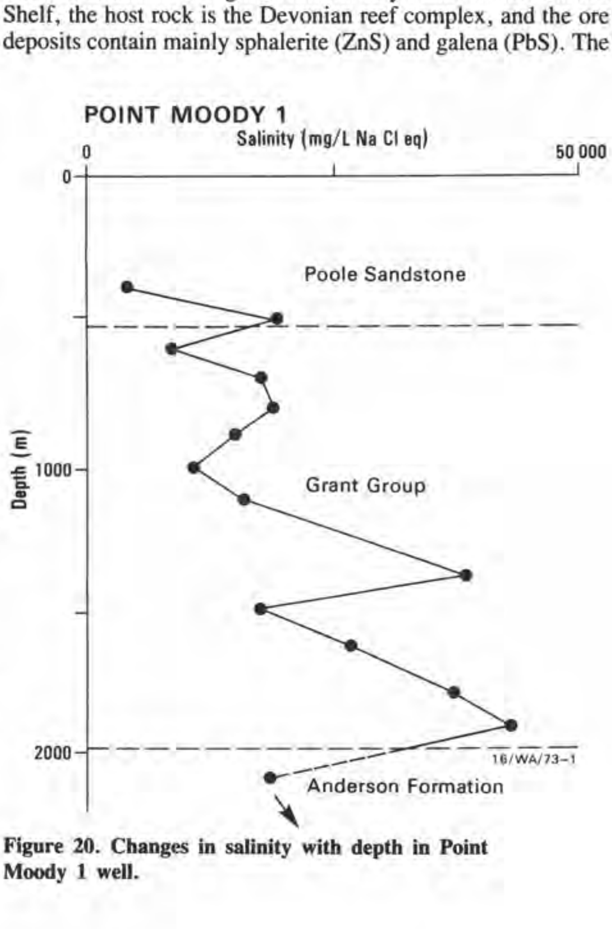

Figure 20. Changes in salinity with depth in Point Moody 1 well.

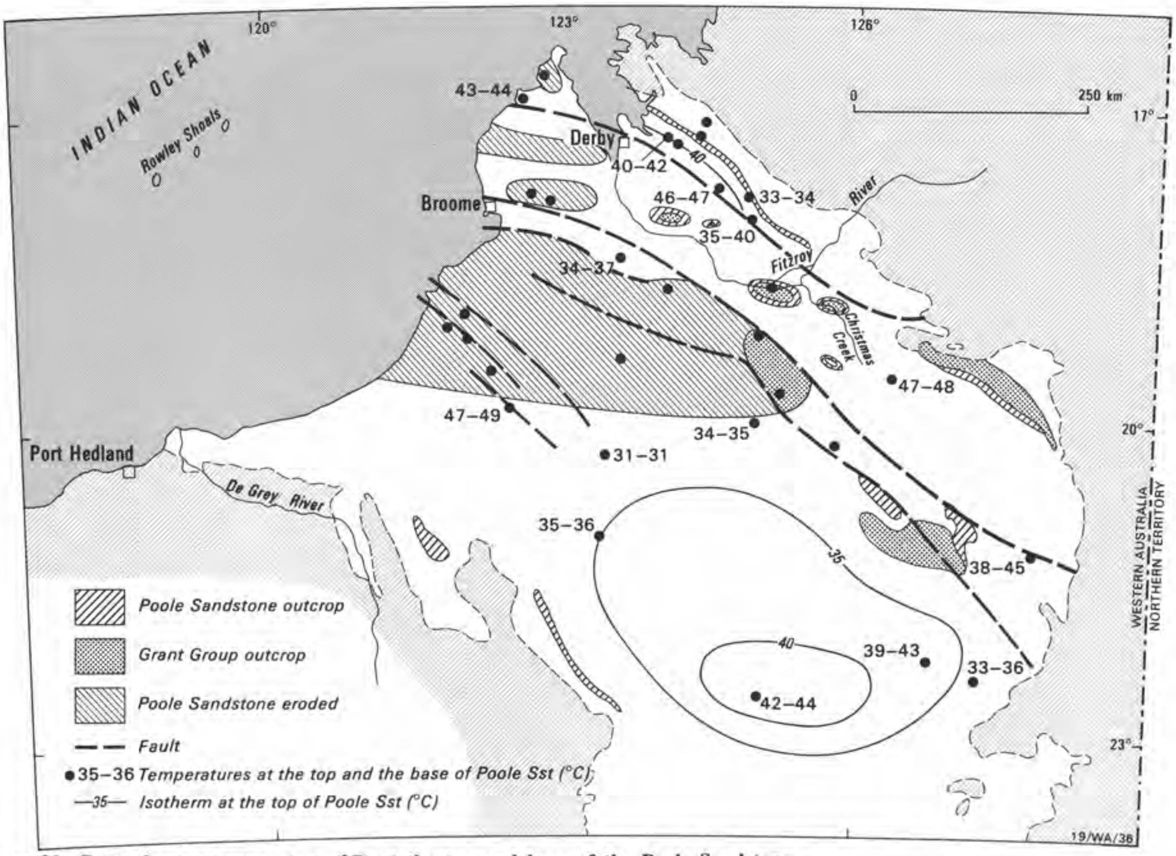

Figure 21. Groundwater temperature (°C) at the top and base of the Poole Sandstone.

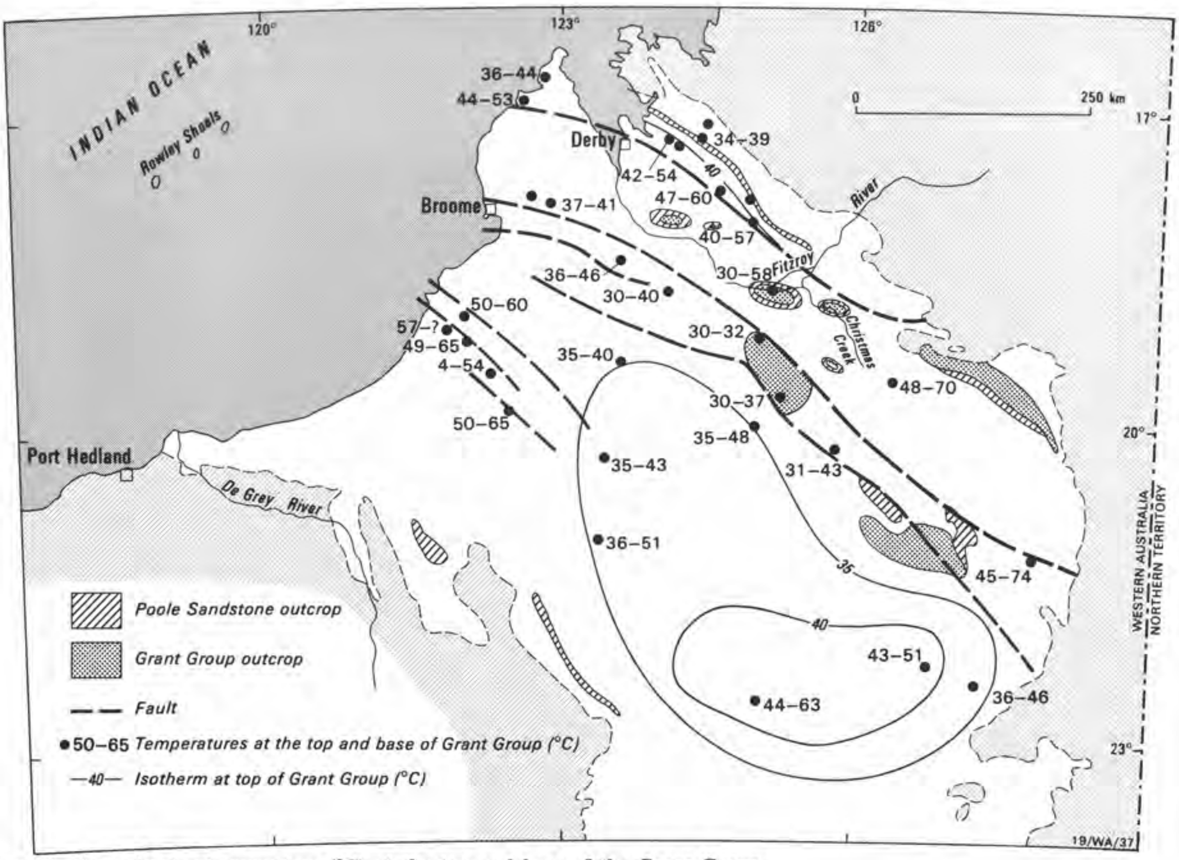

Figure 22. Groundwater temperature (°C) at the top and base of the Grant Group.

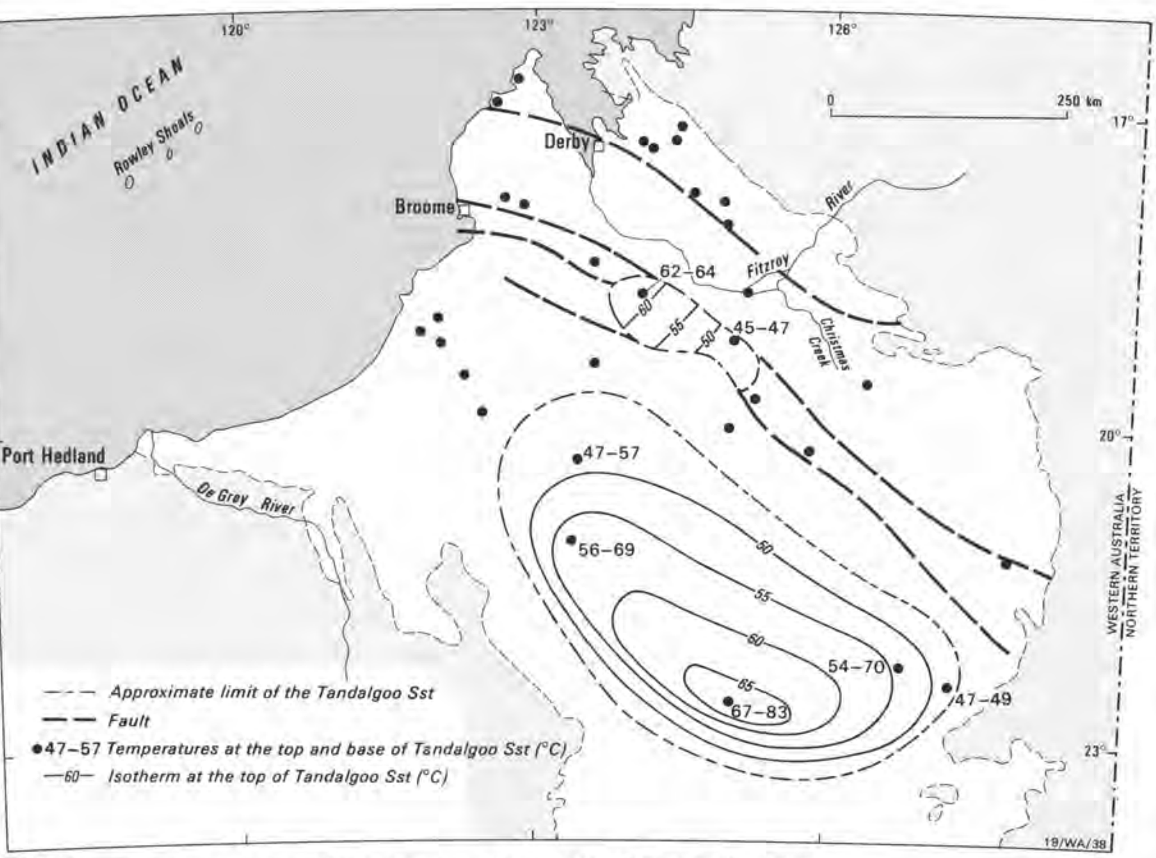

Figure 23. Groundwater temperature (°C) at the top and base of the Tandalgoo Sandstone.

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.