HYDROGEOLOGY
OF AUSTRALIA

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227

J E LAU D P COMMANDER & G JACOBSON

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BULLETIN 227

Hydrogeology of Australia

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FOREWORD

About 80 per cent of Australia is totally dependent on groundwater, or uses large quantities of groundwater to supplement inadequate supplies of surface water. Without groundwater, much of Australia's livestock industry, a significant portion of its agriculture, and many of its mines would not be viable. Therefore groundwater is one of our most vital commodities. Despite its importance, information on the nation's groundwater resources is inadequate in many areas, and there is a need to greatly enhance our hydrogeological knowledge and understanding as a prelude to both fully assessing our national water resources and alleviating salinity problems such as those of the Murray Basin.

The hydrogeological map of Australia at 1:5 000 000 scale has been prepared as a contribution to the understanding of the nation's larger groundwater systems, and as a guide to regional groundwater resources assessment. The map and accompanying notes summarise the results of many years of hydrogeological studies by State geological and water agencies, and BMR. The project has involved the collaboration of 25 hydrogeologists from these agencies with the BMR Division of Continental Geology acting as the co-ordinating body. This collaboration was fostered by a working group of the Groundwater Committee of the Australian Water Resources Council, and the project was undertaken in parallel with the Council's 'Review of Australia's water resources and water use 1985'. Compilation of the map was funded, in part, by the Department of Resources and Energy under the Federal Water Resources Assistance Program.

The map has been compiled in the style of the UNESCO international legend for hydrogeological maps, and is believed to be the first map in this style to be published in Australia. It was produced by computer-assisted cartography, and is the most complete Earth-science map yet to be produced by BMR with this technology. The map represents a milestone in the understanding, assessment, and management of Australia's groundwater resources.

(Peter J. Cook)
Chief, Division of Continental Geology

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ABSTRACT

The hydrogeological map of Australia has been compiled at a scale of 1:5 000 000 according to the guidelines of the international legend for hydrogeological maps adapted for the unique conditions of the Australian continent. The map shows aquifer type, lithology, salinity, potentiometry, and groundwater flow directions, and major groundwater abstraction sites.

The hydrogeology of the Australian continent is described in terms of principal aquifers, defined as those producing the best-quality water at highest yield from the shallowest depth. Aquifers are defined as porous or fissured, and subdivided in terms of their extent and productivity; these aspects are shown in solid colour on the map. Subsidiary aquifers are indicated for certain layered systems in major sedimentary basins. Groundwater salinity is indicated by a line representing 1500 mg L^{-1} total dissolved solids, the Australian limit for drinking water. Further subdivision of saline waters is shown on an inset map. The potentiometric surface, general directions of groundwater flow, and groundwater discharge features are shown where information is available. Some important man-made features are also shown, including abstraction sites and locations of the emerging problems of groundwater pollution and salinisation. Inset maps show elements of the Australian hydrogeological environment: topography, annual rainfall deficit, and drainage and runoff.

Major hydrogeological divisions of the continent are the large sedimentary basins, fractured-rock provinces, and the overlying surficial aquifers. Large unexploited groundwater resources are held in some of the sedimentary basins and surficial aquifers.

INTRODUCTION

The map 'Hydrogeology of Australia' at a scale of 1:5 000 000, published in 1987, is the first hydrogeological map of the continent.

The map project was conceived in 1983 following the stimulus of a United Nations workshop in Bandung, Indonesia, on hydrogeological mapping in Asia and the Pacific region (Bestow, 1985; Jacobson, 1985). The project was discussed in Sydney in December 1983 at a meeting of the Working Group on Hydrogeological Mapping of the Australian Water Resources Council Groundwater Committee. It was subsequently endorsed by the Groundwater Committee, and the Bureau of Mineral Resources undertook to compile the map from State contributions. A guide for the preparation of the State contributions, based on the UNESCO (1983) international legend for hydrogeological maps, was developed and circulated by the Geological Survey of Western Australia. The State contributions were completed in mid-1985, and some problems of compatibility and difficulties with the legend were discussed by the Working Group at a second meeting held in Canberra in May 1985.

The map has been produced concurrently with the 'Review of Australia's water resources and water use 1985' (Australian Water Resources Council, in press).

Map compilation

Hydrogeology was compiled by hand at final scale on five separate sheets, showing: principal aquifers; subsidiary aquifers; groundwater quality and temperature; groundwater movement; and man-made features and alterations of the groundwater regime. The main sources of information were published groundwater resource maps for three states (Laycock & Wecker, 1971; Shepherd, 1982; Nahm, 1982); the unpublished State contributions to the project; and other relevant publications. Compilation was begun in December 1984, and drafting was complete by April 1986.

The map was drafted on a computer graphics system which allowed enlargement and interactive map editing on a screen at a graphics workstation. Map features were digitised, and proof plots compared with the original compilation. Coloured penplots were checked by the State contributors, and final drafting corrections were made in October 1986.

Concepts and definitions

The map has an adapted version of the international legend for hydrogeological maps (UNESCO, 1983). The adaptation was necessary to match the level of detail on the Australian source maps, the small scale of the final map, and the complete lack of data in many parts of Australia.

Solid colour represents aquifers — their type, distribution, and productivity (Fig. 1). This is a significant departure from previous groundwater resources maps of Australia in which solid colour represents water quality (Australian Water Resources Council, 1975).

Where aquifers are superimposed, the aquifer represented is the principal aquifer, defined as the aquifer which produces the best-quality water at highest yield from the shallowest depth.

Aquifer type has been designated on the assumption that, in general, aquifers in sedimentary basins have intergranular porosity (blue) and those in fractured-rock provinces have fractured or fissured porosity (green). In detail, it is commonly difficult to classify aquifers in this way: several important Australian aquifers are both intergranular and fissured, and the relative importance of porosity and fissuring may change spatially within one aquifer.

Aquifer productivity is defined by tones of the primary colour (Fig. 1). Highly productive aquifers (dark blue or dark green) are classified as those with an average bore yield of more than 5 L s^{-1}. This figure matches current European usage (Egorov & Nikolaev, 1979; Egorov & others, 1982) and proposed Australian usage. It approximates the figure used on the Queensland groundwater resources map (Laycock & Wecker, 1971), but is considerably lower than figures used on the Victorian (Nahm, 1982) and South Australian (Shepherd, 1982) groundwater resources maps.

Aquifer distribution is described as extensive or local, as in the international legend. Extensive aquifers (shown in blue or green) indicate that groundwater is widely available. Local aquifers (in brown) indicate that groundwater occurrence is localised, and that bores may require specific siting for success.

Aquifer lithology is shown by pattern symbol, and aquifer age by letter symbols, based on generalised information from the geological map of Australia at 1:5 000 000 scale (D'Addario & others, 1982). Only granites and plateau basalts have been differentiated from other igneous and medium-high-grade metamorphic rocks. For the Tertiary and Quaternary aquifers, boundaries have been added from the published State maps and unpublished contributions.

One of the main shortcomings of single-sheet hydrogeological mapping is the representation of multiaquifer systems. Most Australian sedimentary basins have a number of superimposed aquifers. On the map a green boundary line has been used in some major sedimentary basins to indicate the extent of a significant subsidiary aquifer. The age and position of such an aquifer relative to a principal aquifer is indicated by a letter symbol and a bar. The cross-section on the face of the map, and ancillary information in this map commentary, should also help to overcome some of the limitations of single-sheet presentation.

Aquifer distribution	Aquifer productivity	Aquifer type	
		Intergranular	Fissured or fractured
Extensive *(most bores yield more than 0.5 Ls^{-1}*	High *(most bores yield more than 5 Ls^{-1}*	Dark blue	Dark green
	Low-medium	Light blue	Light green
Local	Low	Brown	

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Fig. 1. Correlation of aquifer type, productivity, and distribution with solid colour on the hydrogeological map.

Hydrodynamic features have been depicted in violet. These features, which include generalised contours on the potentiometric surface, have been shown for major sedimentary basins. In multiaquifer systems the potentiometric contours relate to the basal aquifer, and, in the Great Artesian Basin, potentiometric contours are corrected for temperature. The direction of groundwater flow has been indicated by violet arrows. Other features such as groundwater divides, the limits of confining beds, and the limits of artesian flow have been shown with violet symbols similar to those of the international legend. Groundwater divides shown for parts of western and central Australia are based on sparse topographic and potentiometric information.

In order to represent significant discharge zones of major groundwater systems, groups of springs have been depicted with violet symbols. A violet-striped groundwater seepage symbol has been used to indicate playas and other features which are the discharge zones of many groundwater systems in the Australian interior. Very old groundwaters have been identified in arid and semi-arid Australia (Airey & others, 1983; Calf, 1978; Drury & others, 1984), and a symbol for the radiometric age of such water has been introduced.

Representation of groundwater quality and temperature is in orange. On the map, the boundary between fresh and brackish groundwater is defined as 1500 mg L^{-1} total dissolved solids, which coincides with the World Health Organisation's maximum desirable limit for drinking-water quality. Further subdivision of the brackish and saline groundwater has been attempted on an inset map at scale 1:15 000 000, on which the limiting value of 5000 mg L^{-1} coincides with that of the concurrent 'Review of Australia's water resources and water use 1985' (Australian Water Resources Council, in press). In many fractured-rock provinces the salinity pattern is complex, and simplifications have been made on the map. Groundwater of up to 14 000 mg L^{-1} is used in Australia for stock water supplies, and groundwater of up to 180 000 mg L^{-1} is used for industrial and mining purposes.

Ambient water-table temperature, which varies by only about 1°C annually, ranges from 13°C in Tasmania to 31° in the northwest of Western Australia. In the absence of systematic maps of the parameter, only temperatures of 30°C and higher are plotted to represent abnormally warm groundwaters. In multiaquifer systems, borehole temperatures are generally for wellhead flow rather than downhole measurement, and are for the basal aquifer.

Surface hydrology is shown in blue. Distinctions between perennial and intermittent streams, and discharge data, are based on information supplied by the Division of National Mapping. Perennial streams are defined as those which have gauged flow for at least nine years out of ten.

Man-made groundwater abstraction features, and alterations of the groundwater regime, are shown in red. Symbols have been introduced for the more important cases of regional groundwater pollution, and salinisation due to rising water-tables.

Inset maps at 1:30 000 000 scale depict important components of the hydrogeological environment of the Australian continent — topography, climate, and surface hydrology — and also the principal hydrogeological divisions of the continent. Topography has been generalised from the Division of National Mapping (1978) 1:5 000 000 'General reference map' of Australia. The parameter mapped on the climatic map — 'Annual rainfall deficit' — is defined as mean annual precipitation minus mean annual pan evaporation, and is derived from information published by Brown (1983). The annual rainfall deficit is an indicator of aridity, which relates to the need for groundwater use. On the third inset map — 'Drainage and runoff' — surface drainage basins have been categorised as external, internal, or unco-ordinated (D'Addario & others, 1979), and mean annual surface runoff is based on data collected by Brown (1983). The principal hydrogeological divisions are shown on the fourth inset map as sedimentary basins or fractured-rock provinces with boundaries based on an unpublished BMR map of the major structural domains of Australia; at this scale, surficial aquifers cannot be shown as hydrogeological divisions, despite their great importance for groundwater abstraction.

The cross-section is shown at a vertical exaggeration of ×100, to illustrate the three-dimensional nature of some of the major groundwater systems.

AUSTRALIA — THE HYDROGEOLOGICAL ENVIRONMENT

Geological evolution

The geological evolution of the Australian continent can be traced back 3500 million years, the oldest rocks being the Archaean greenstones of the Pilbara region in Western Australia. The long history of Archaean and Proterozoic sedimentary, igneous, and metamorphic events led to the development of several stable platforms consisting of complexes of deformed igneous and metamorphic rocks. Platform covers, consisting of sequences of relatively undeformed sedimentary basins, accumulated in broad downwarps on the platforms. Successive sedimentary basins were superimposed in the Palaeozoic and Mesozoic (Fig. 2).

Much of Australia has been land since Cretaceous times. From the Cretaceous onwards, the continent drifted northwards after its separation from Antarctica. Significant features of the continent's geology and geomorphology developed in the Cainozoic era, including several large sedimentary basins and part of the present drainage pattern (Fig. 3).

Deep weathering with associated duricrusts affected much of the land area in the earlier parts of the Tertiary. The western and central Australian palaeodrainages were active and integrated river systems in the early Tertiary, but by the Middle Miocene significant flow of water in these drainage systems had ceased (van de Graaff & others, 1977) owing to climatic change.

Since the Late Pliocene, the Australian climate has probably fluctuated through many cycles. In the most recent cycle, Late Pleistocene to Holocene, a wetter period with expanded lakes has been dated in southeast Australia at between 50 000 and 30 000 years old (Bowler, 1982). This was followed by a period of aridity, which reached its maximum about 18 000 years ago, when cold windy conditions contributed to the deposition of sand dunes throughout much of the Australian continent and glaciation in the southeast highlands.

Topography; rainfall deficit; drainage and runoff

The continent has generally low relief. The western half is a plateau edged in places by a coastal plain. Over a large part of this plateau, drainage is unco-ordinated or internal. The eastern highlands, which extend the length of the east coast and have a maximum elevation of 2228 m (Mount Kosciusko), are a drainage divide from which streams flow inland to the largest drainage basin, the Murray–Darling

Basin. Lake Eyre, which is below sea level, is the focus of a large internal drainage basin with low runoff.

The highest rainfall occurs in the eastern highlands in eastern and southern Australia, and in the monsoonal and cyclonic areas of northern Australia. A large part of western and central Australia is arid, having mean annual rainfall below 250 mm, although even the most arid regions are vegetated. The seasonal distribution of rainfall over the continent generally varies from winter-dominant in the south to summer-dominant in the north. Evaporation generally increases from south to north across the continent, and also inland from the coast. Annual values of pan evaporation exceed 4000 mm in parts of western and central Australia. For most of the continent, annual potential evaporation is many times the mean annual rainfall.

The total surface runoff from the Australian continent is only about 440 000 000 m^3 y^{-1} (Brown, 1983), of which a large proportion flows in streams to the Gulf of Carpentaria and in Tasmania. About one-third of Australia, including the western plateau, has unco-ordinated drainage with no significant runoff. Runoff from Australia is low compared with other parts of the world, and shows pronounced seasonal and annual variations.

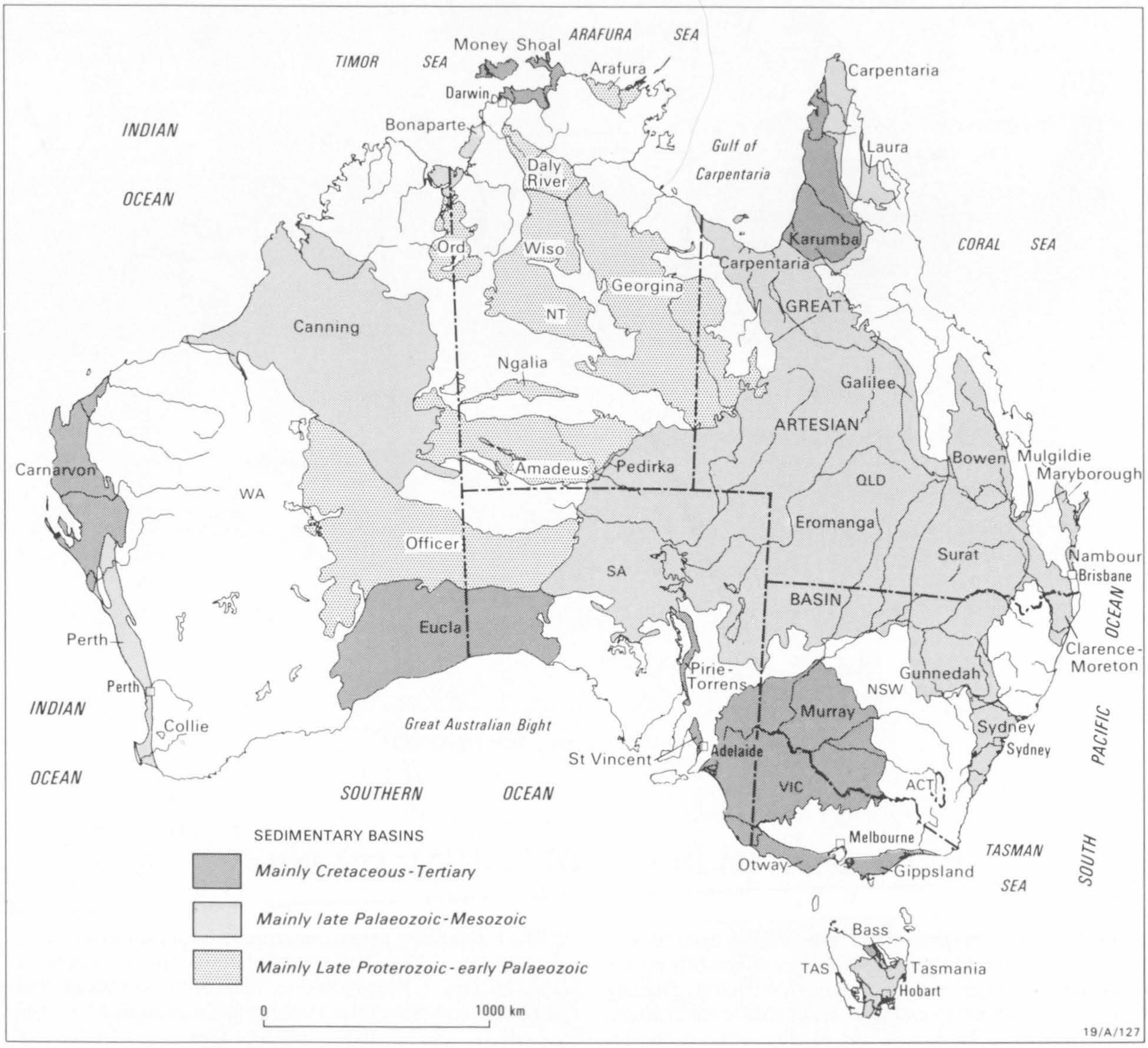

Fig. 2. Sedimentary basin groundwater provinces.

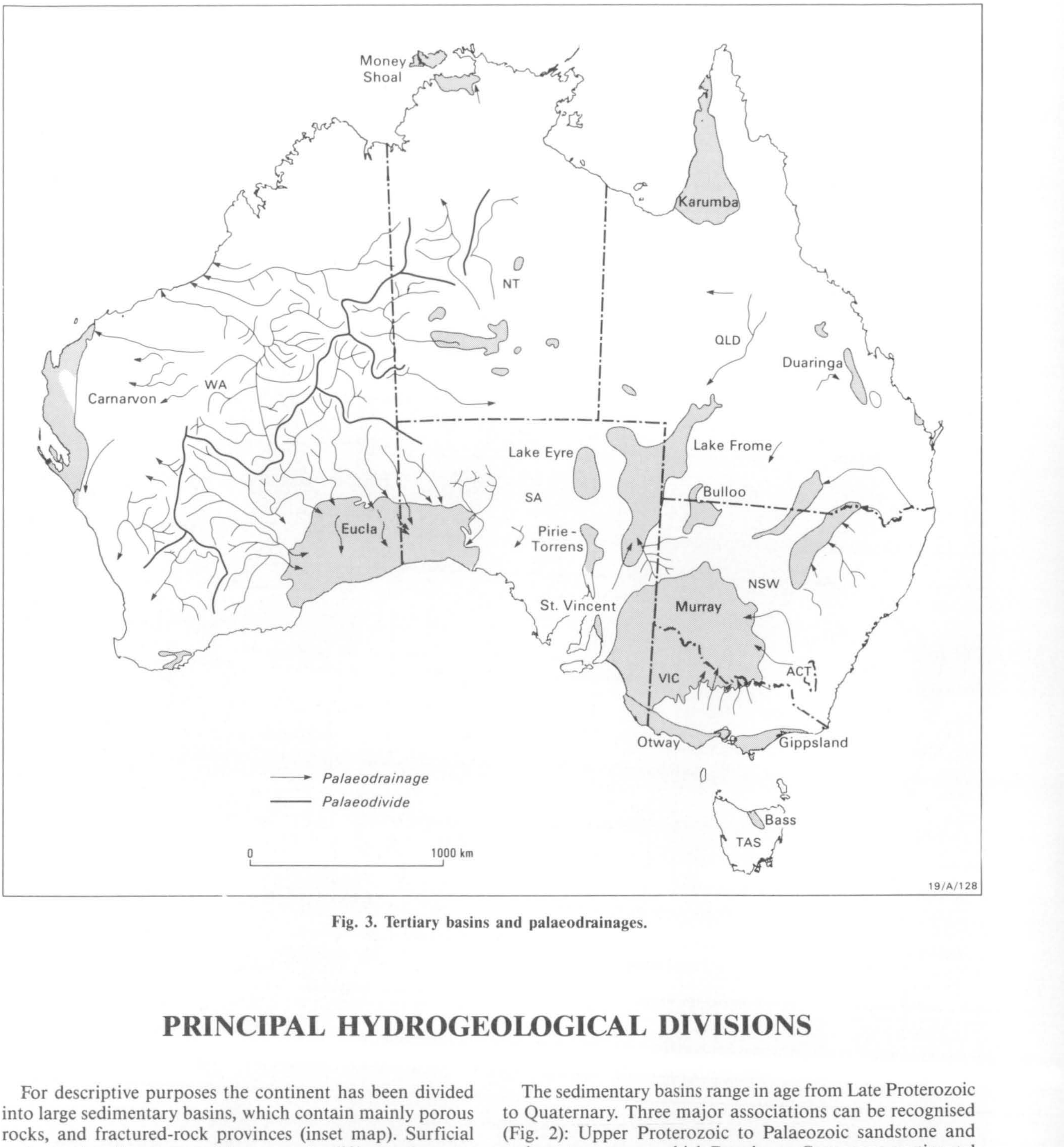

Fig. 3. Tertiary basins and palaeodrainages.

PRINCIPAL HYDROGEOLOGICAL DIVISIONS

For descriptive purposes the continent has been divided into large sedimentary basins, which contain mainly porous rocks, and fractured-rock provinces (inset map). Surficial rocks, both sedimentary and igneous, of a different character are considered to be part of the hydrogeological division which they overlie. The sedimentary basins so defined are relatively undeformed and unmetamorphosed, and contain extensive permeable sediments thousands of metres deep in all but a few of the basins. In many of the basins, aquifers are confined, and artesian conditions apply in low-lying coastal areas or inland areas of groundwater discharge. The fractured-rock provinces are usually structurally complex and contain igneous, metamorphic, and older sedimentary rocks lacking porosity. Water-bearing fractures occur in a variety of rock types, and generally do not extend below a few hundred metres. In the fractured-rock provinces, groundwater is essentially unconfined, and flow systems relate to topography.

The sedimentary basins range in age from Late Proterozoic to Quaternary. Three major associations can be recognised (Fig. 2): Upper Proterozoic to Palaeozoic sandstone and carbonate sequences; thick Permian to Cretaceous continental sandstone and coal sequences; and Cretaceous to Tertiary carbonate and thin sandstone sequences.

The fractured-rock provinces have been grouped into four geographic provinces (Fig. 4). The western province includes Archaean granite and greenstone, and Proterozoic metamorphic and sedimentary rocks. The northern province consists mainly of Proterozoic sedimentary rocks. The central province includes Archaean and Proterozoic metamorphic complexes, and Proterozoic sedimentary rocks. The eastern province comprises mainly Palaeozoic sedimentary and volcanic rocks and granite.

Surficial rocks include Cambrian volcanics in northern Australia, Jurassic dolerite in Tasmania, and Cainozoic basalt

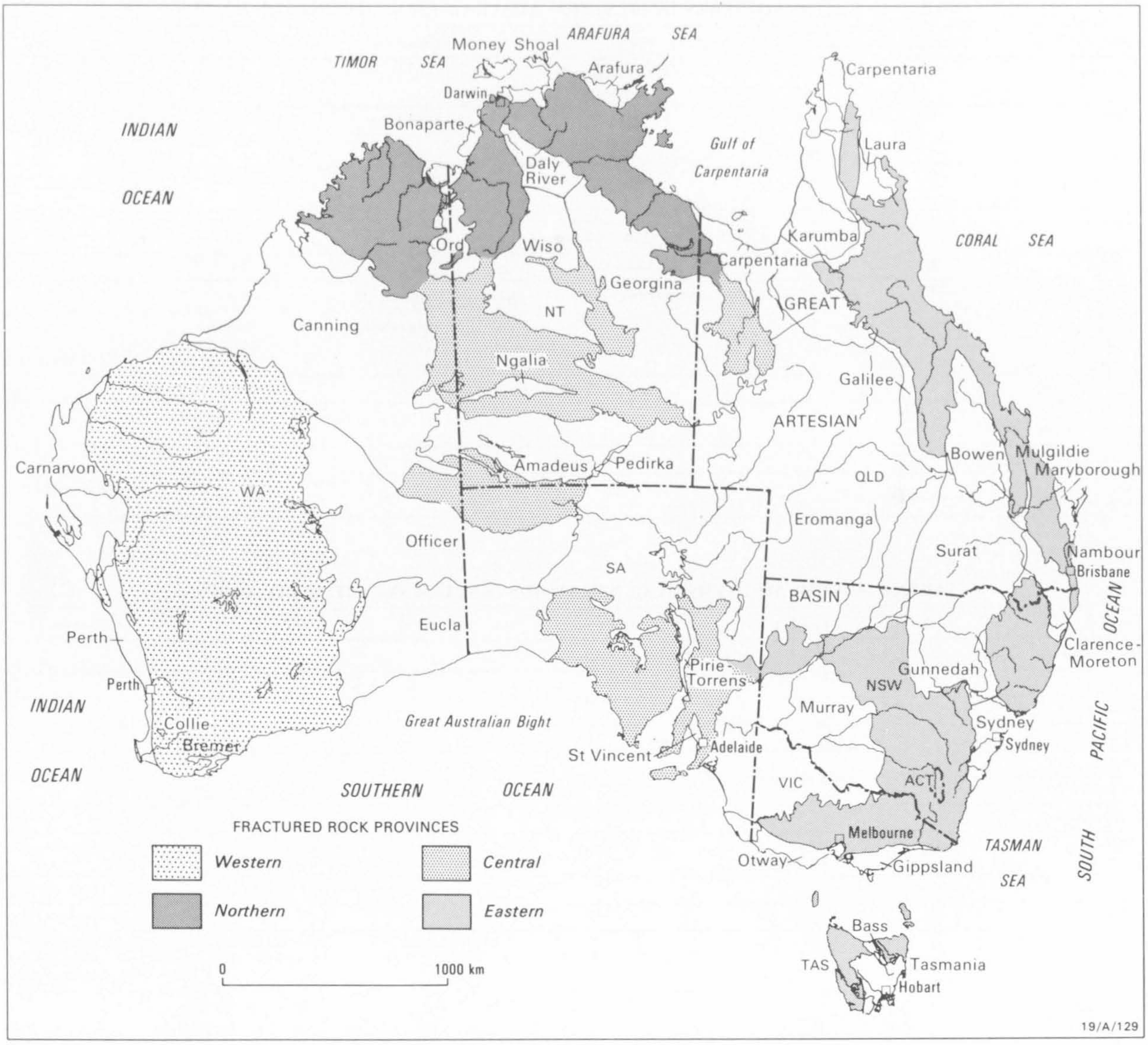

Fig. 4. Fractured-rock groundwater provinces.

and sediments. Surficial Tertiary sediments in palaeodrainages in central and western Australia and in deep leads in eastern Australia, and Quaternary sediments in active drainages and on the coastal plains, are of great importance for water supply because they contain easily exploitable shallow water.

A brief description of each hydrogeological division follows.

LARGE SEDIMENTARY BASINS AND SURFICIAL COVER

The major aquifers in Australian sedimentary basins are listed in Tables 1, 2, and 3.

Proterozoic–early Palaeozoic basins

The *Amadeus Basin*, in central Australia, is a complex region of folded and faulted rocks of Late Proterozoic to Carboniferous age, overlain in places by Cainozoic cover up to 300 m thick. Many of the water-bearing sandstones are both fractured and porous.

In the southern half of the basin, shallow aquifers in the Cainozoic sequence overlie the older, fractured rocks to form a two-component system (Fig. 5). This two-layer system discharges to a chain of playa lakes 500 km long that includes Lake Amadeus; these playas contain highly saline (200 000 mg L^{-1}) brines and are actively precipitating gypsum (Jacobson, 1987). The Yulara tourist resort is supplied from the Cainozoic aquifers, after desalination from 1500 to 400 mg L^{-1} total dissolved solids. Calcrete of Quaternary age provides the best-quality water (1000–1500 mg L^{-1}) in this region. Recharge is of the order of 1 mm y^{-1} over the catchment area, and occurs directly to rock outcrops and by infiltration through stream beds after occasional flooding.

TABLE 1. MAJOR AQUIFERS IN WESTERN AUSTRALIAN SEDIMENTARY BASINS

Age	*Symbol*	*Eucla*	*Perth*	*Carnarvon*	*Canning*	*Officer*
Quaternary	Q		Superficial formations			
Tertiary	T	Abrakurrie Lst Wilson Bluff Lst Hampton Sst		Tulki Lst		
Cretaceous	K	Madura Fm Loongana Sst	Leederville Fm	Birdrong Sst	Broome Sst	Samuel Fm
Jurassic	J		Yarragadee Fm Cockleshell Gully Fm		Alexander Fm Wallal Sst	
Triassic	Ꞧ		Lesueur Sst		Erskine Sst	
Permian	P		High Cliff Sst	Cundlego Fm Mallens Sst Moogooloo Sst	Triwhite Sst Liveringa Gp Poole Sst Grant Gp Paterson Fm	Paterson Fm
Carboniferous	C				Conglomerate	
Devonian	D				Limestone and sandstone	
Silurian	S		Tumblagooda Sst	Tumblagooda Sst		
Palaeozoic undifferentiated	Pz					Lennis Sst

TABLE 2. MAJOR AQUIFERS IN CENTRAL AUSTRALIAN SEDIMENTARY BASINS

Age	*Symbol*	*Amadeus*	*Ngalia*	*Daly River*	*Wiso*	*Georgina*
Quaternary	Q	Calcrete				
Tertiary	T		Sand			
Cretaceous	K					
Jurassic	J					
Triassic	Ꞧ					
Permian	P					
Carboniferous	C		Mt Eclipse Sst			
Devonian	D	Hermannsburg Sst Mereenie Sst	Kerridy Sst			Dulcie Sst
Silurian	S					
Ordovician	O	Pacoota Sst		Oolloo Lst		Ninmaroo Fm
Cambrian	Є			Tindall Lst	Point Wakefield beds Montejinni Lst	Meeta beds Camooweal Dol Steamboat Sst
Palaeozoic undifferentiated	Pz				Lake Surprise Sst	

TABLE 3. MAJOR AQUIFERS IN EASTERN AUSTRALIAN SEDIMENTARY BASINS

Age	*Symbol*	*Karumba*	*Gippsland*	*Bowen*	*Great Artesian*	*Murray*	*Otway*
Quaternary	Q						Newer Volcanics
Tertiary	T	Wyaaba Fm Bulimba Fm	Boisdale Fm Older Volcanics Latrobe Valley Coal Measures	Springsure Basalt		Pliocene sand Murray Gp Renmark Gp	Gambier-Portland Lst Wangerrip Gp
Cretaceous	K				Winton Fm Mackunda Fm		
Jurassic	J				Hooray Sst Hutton Sst Precipice Sst Gilbert River Fm		
Triassic	Ꞧ			Clematis Sst			
Permian	P			Aldebaran Sst			

The northern half of the basin contains continuous sandstone units which form a multiaquifer system with groundwater flow from west to east along the axes of major synclines. The principal aquifers are the Devonian–Carboniferous Mereenie and Hermannsburg Sandstones (DC on face of map), and several sandstone and limestone units in the Proterozoic–Ordovician (ꝐO) sequence (Macqueen & Knott, 1982). Hydraulic continuity between some of these units occurs in places as a result of faulting, erosion, and facies changes. The Mereenie Sandstone supplies the town of Alice Springs with 10 000 000 m^3 y^{-1} of good-quality water. Radioisotope dating of the borefield waters indicates that most recharge took place in pulses at 1400 and 5500 years BP (Calf, 1978).

The *Ngalia Basin*, also in central Australia, has a complex structural and sedimentary history similar to that of the

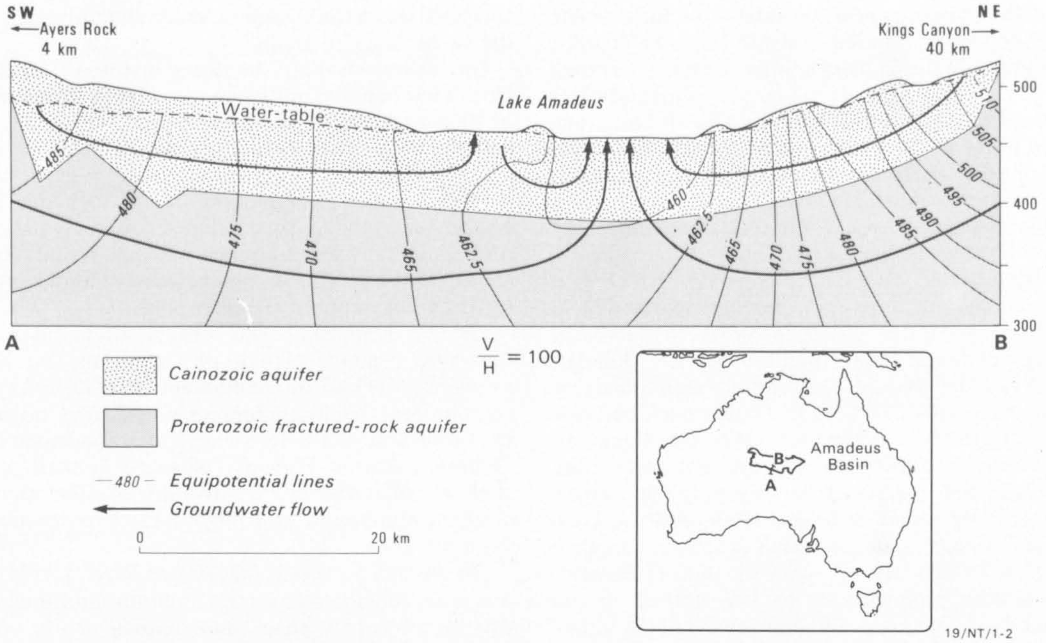

Fig. 5. Hydrogeological cross-section through Lake Amadeus, southern Amadeus Basin.

Amadeus Basin. The best-known aquifer is a fractured Devonian sandstone, the Kerridy Sandstone (DC) which supplies Yuendumu settlement. The overlying Devonian-Carboniferous Mount Eclipse Sandstone (DC) also has aquifer potential (Wells & Moss, 1983). Tertiary sediments 300 m deep overlying the southern Ngalia Basin have indicated high yields of low-salinity water.

The *Officer Basin* lies between the western and central fractured-rock provinces, and is adjacent to the Canning and Eucla Basins. The Proterozoic to lower Palaeozoic rocks are overlain by Permian strata, and a thin, mostly unsaturated Cretaceous cover in the west (Fig. 6).

The Paterson Formation (P) is an aquifer overlying the western part of the basin. Limited information indicates that the water-table is fairly flat and below the level of the Tertiary drainages (T), and may therefore be 100 m deep in places. Groundwater salinity in the few bores tested ranges from 1000 to 3000 mg L^{-1}.

The eastern part of the basin is occupied by the Lennis Sandstone (Pz), in which fresh water has been encountered in Lennis No.1 and Birksgate No. 1 petroleum exploration wells. In the Birksgate well, water of less than 1500 mg L^{-1} extends to at least 170 m. In the Proterozoic sequence below the Lennis Sandstone, groundwater salinity rises from 10 000 to over 100 000 mg L^{-1}.

The Officer Basin is occupied by the Gibson and Great Victoria Deserts and is consequently undeveloped.

The *Daly River Basin*, in the Northern Territory, contains gently warped Middle Cambrian to Lower Ordovician carbonate rocks up to 700 m thick (Fig. 7). The principal aquifers are the Ordovician Oolloo Limestone (O) and the Cambrian Tindall Limestone (ЄO), which consist of dolomite

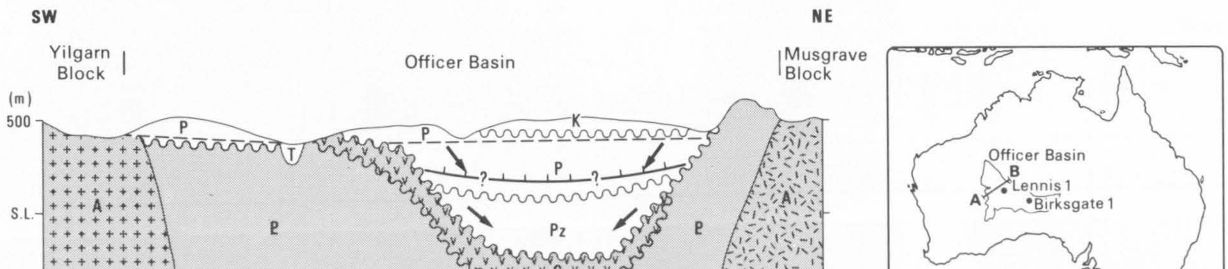

Fig. 6. Hydrogeological cross-section, Officer Basin.

with both solution cavities near the water-table and porosity after dolomite recrystallisation at depth (Lau, 1976; Jolly, 1984). The groundwater in these aquifers contains less than 500 mg L^{-1} total dissolved solids. Groundwater temperatures are as high as 49°C in the Tindall Limestone 600 m deep in the centre of the basin, and fluoride values are up to 6 mg L^{-1} in the deepest part. The potentiometric surface on the basal aquifer, the Tindall Limestone, is shown on the hydrogeological map. Groundwater discharges by springs to the perennial Daly River and its tributaries.

In the *Wiso Basin*, also in the Northern Territory, a northwest-trending fractured-rock province (Kennewell & Huleatt, 1980) separates an open northern sub-basin containing groundwater of less than 1500 mg L^{-1} (Randal, 1973) from a closed, more arid, southern sub-basin containing groundwater of less than 1500 mg L^{-1} only on its southeast margin (Fig. 7). The most widespread aquifer is the Cambrian Montejinni Limestone (€O). Major porous aquifers are the Point Wakefield beds (€), which partly supply the town of Tennant Creek (Verhoeven & Knott, 1980), and the Lake Surprise Sandstone (Pz) on the basin's southern margin; a small overlying Tertiary basin (T) once supplied all Tennant Creek. Cretaceous sediments up to 100 m thick in the northern sub-basin are generally above the regional water-table, but may allow recharge to the underlying Montejinni Limestone (Fig. 7).

The *Georgina Basin* extends across the Queensland-Northern Territory border. It contains mainly Cambrian-Ordovician dolomite and limestone aquifers (€O), and some sandstone aquifers around the southern margin. Tertiary aquifers occur in small overlying basins, but are not shown on the map because they are generally more saline.

A regional confined aquifer system is maintained by recharge along the basin margins (Randal, 1978). Groundwater flow is partly northwest to an internal drainage basin centred on Brunette Downs, which has a restricted connection with the adjoining Wiso Basin, and partly southeast down the Georgina Valley and ultimately beneath the Great Artesian Basin.

Groundwater salinity increases in these flow directions from a few hundred milligrams per litre to maximum values of 7000 mg L^{-1} total dissolved solids. The internal drainage basin is characterised by higher salinity and also by relatively high fluoride values. Large groundwater reserves have been indicated in the Georgina Basin, although the shallower aquifers are only lightly developed for stock and domestic supplies, and the deeper aquifers have not been explored. The Dulcie Sandstone (D) on the southwest margin has potential for irrigation supplies (Woolley, 1965).

The *Ord Basin*, comprising separate sub-basins in northern Australia, contains 600 m of Cambrian and Devonian sedimentary rocks. Like the adjacent Wiso Basin the principal aquifers are Cambrian limestones (€) and an overlying sandstone unit — the Devonian Elder Sandstone (D). The Cambrian Antrim Plateau Volcanics, at their maximum thickness in northwestern Australia of 1000 m, link the overlying sub-basins, and provide stock water around the basin margins.

The onshore portion of the *Arafura Basin*, also in northern Australia, contains two thick Cambrian sandstone units (€) separated by thick shale, and dipping gently northward beneath the Arafura Sea. Aquifer potential is untested.

Late Palaeozoic-Mesozoic basins

The *Sydney Basin*, in southeastern Australia, has as its most extensive aquifer the Hawkesbury Sandstone (Ʀ in part), which contains fresh groundwater but has low aquifer productivity. In the Hunter Valley, the main Permian aquifers (P) — coal measures with connate saline water (Kellett & others, in press) — discharge saline base-flows to rivers. The productive aquifers are in the overlying fluvial alluvium of the Hunter River and its tributaries (Q) and in coastal sand deposits at Botany Bay and Tomago (Q). The unconfined

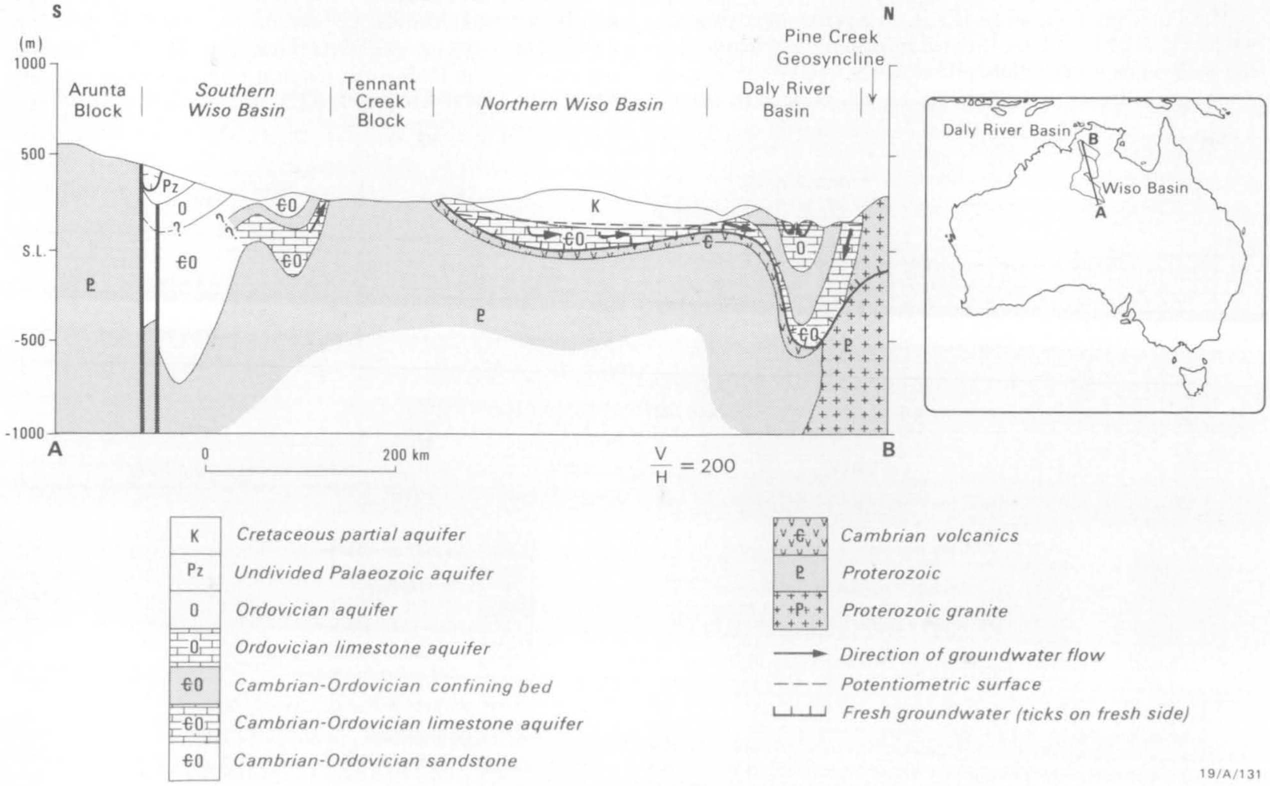

Fig. 7. Hydrogeological cross-section, Daly River and Wiso Basins.

Tomago sand aquifer supplies 25 per cent of the water supply for the city of Newcastle. The aquifer is 15-20 m thick, and is tapped by about 300 water extraction points with yields ranging from 3 to 7 L s^{-1}.

The *Gunnedah Basin* links the Sydney and the subsurface Bowen Basins, and also contains coal measures.

The western side of the *Bowen Basin* contains Permian continental sandstones (P). The Aldebaran Sandstone is 650 m thick and contains fresh water in outcrop areas, where it has been used to augment the Springsure town water supply (Hair & Draper, 1985). At depth in the Denison Trough, this aquifer is being tested for production of sodium bicarbonate brines. On the eastern side of the basin, Permian rocks are predominantly volcanogenic and folded, and their hydrogeology is similar to that of the adjoining coastal fractured-rock province (Pz). Coal measures are widespread throughout the Permian sequence.

The Triassic Clematis Sandstone (Ʀ) occurs in isolated synclinal structures in the north of the basin, where it is largely untested. In the Taroom Trough in the south, and in the contiguous *Galilee Basin* to the west, it is effectively the lowermost aquifer in the Great Artesian Basin (see section on hydrogeological map), where — however — it occupies a smaller area than the main Jurassic and Cretaceous aquifers.

Both Permian and Triassic sedimentary rocks are overlain by Tertiary basalts which produce high yields at Springsure. Up to 1300 m of fine-grained sediments in the overlying Tertiary (T) of the Duaringa Basin (Fig. 3) are untested.

In terms of aquifer thickness and extent, the *Carpentaria*, *Eromanga*, and *Surat Basins* make up most of the Great Artesian Basin, a multiaquifer system (Fig. 8) in which aquifers occur in Mesozoic sandstone interbedded with mudstone. The Surat and Eromanga Basins are up to 3000 m thick (Habermehl, 1980), and form a large synclinal structure uplifted and exposed along their eastern marginal zone (see section on hydrogeological map). Recharge is by rainfall, mainly on the eastern margin. Natural discharge occurs from springs, mainly along the southwestern margin. The hydrodynamics of these basins has been modelled in terms of a confined Cretaceous aquifer (K) separated by thick shale from a confined Jurassic-Lower Cretaceous aquifer (J). The potentiometric surface of the lower (J) aquifer (shown on the hydrogeological map) is above ground level in most areas of the basin; the potentiometric surface of the upper (K) aquifer is below the ground surface throughout most of the basin.

About 4000 flowing artesian wells in the Great Artesian Basin have been drilled to depths of up to 2000 m, and individual flows exceeding 100 L s^{-1} have been recorded. The total discharge is about 1 500 000 m^3 day^{-1} from bores; a large proportion of this discharge is wasted by evaporation from open-bore drains. Also, about 20 000 non-flowing artesian bores tap mainly the higher aquifers. The largest single withdrawal from the basin will be the proposed supply of 12 000 000 m^3 y^{-1} to the Olympic Dam mining project. Recharge has increased significantly as a result of groundwater withdrawals.

The best-quality groundwater occurs in the lower (J) aquifer, and generally contains about 500 to 1000 mg L^{-1} total dissolved solids dominated by sodium bicarbonate. The upper (K) aquifer contains stock-quality water only. Temperatures of groundwater range up to 121°C, and the mean geothermal gradient in the basin is 48°C km^{-1} (Polak & Horsfall, 1979). Groundwater ages up to 2 million years have been measured using the chlorine-36 technique (Airey & others, 1983).

Tertiary sediments up to 200 m thick overlie much of the Great Artesian Basin, but are not generally mapped as aquifers because their water quality and yield are thought to be poorer than in the underlying aquifers (J,K). Important aquifers that have been mapped include sediments of the Karumba Basin which overlie the Carpentaria Basin, and

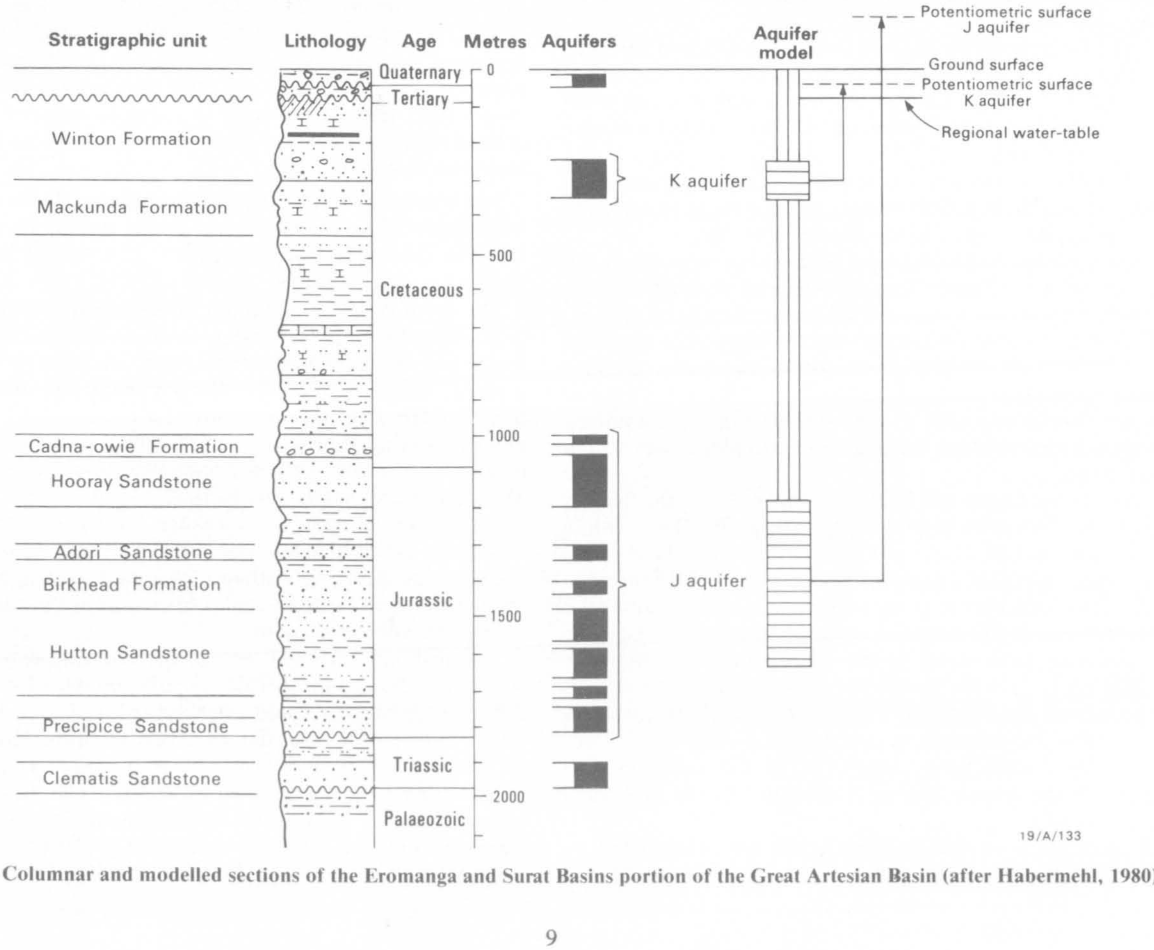

Fig. 8. Columnar and modelled sections of the Eromanga and Surat Basins portion of the Great Artesian Basin (after Habermehl, 1980).

alluvial fans associated with the Gwydir, Namoi, and Macquarie tributaries of the Darling River; the Namoi fan, centred on Narrabri (NSW), produces 175 000 000 m^3 of irrigation water annually. Permian rocks beneath the Great Artesian Basin generally contain saline water, but may have been flushed where they are in hydraulic contact with the Jurassic aquifers (Youngs, 1975).

The *Clarence-Moreton, Nambour,* and *Maryborough Basins,* in eastern Queensland, contain Jurassic sandstones stratigraphically equivalent to those in the Great Artesian Basin. However, most bores penetrate them in outcrop, where they are regarded as low-yielding aquifers in which permeability is limited to fractures. The most important aquifers are in the Cainozoic sediments and basalts that overlie these sedimentary basins. They include fluviatile sandstone of the Tertiary Elliott Formation (T) near Bundaberg, Tertiary sands (T) associated with the Condamine River, and Quaternary alluvium (Q) of Lockyer Creek in the Brisbane River valley.

In the *Laura Basin,* in northeast Queensland, the basal Dalrymple Sandstone and the overlying Gilbert River Formation (J) are artesian aquifers. The two formations are stratigraphic equivalents of the upper part of the Jurassic aquifer of the Great Artesian Basin.

The *Mulgildie Basin,* in southeast Queensland, is a northern offshoot of the Surat Basin. The principal aquifer shown on the map is the Mulgildie Coal Measures (J), in which bores yield generally less than 5 L s^{-1} of water containing more than 1500 mg L^{-1} total dissolved solids. The underlying Precipice Sandstone is also an aquifer, but of unknown water quality.

The *Tasmania Basin* contains Permian coal measures and Triassic sandstone (PR), but their total thickness is only 500 m. The basin is dominated by the dolerite sills of Jurassic age which intrude it.

The *Pedirka Basin,* in central Australia, contains sandstone aquifers in the Crown Point Formation (P), which supplies stock water along part of the western margin of the Great Artesian Basin.

The *Canning Basin* lies between the western and northern fractured-rock provinces. It contains extensive sandstone aquifers of Permian, Jurassic, and Cretaceous ages, and small areas with Triassic, Devonian, and Carboniferous sandstone in the northeast.

The basin comprises a gently folded part, including the Kidson and Willara Sub-basins, and the more structurally complex area of the Fitzroy Trough (Fig. 9).

Information on groundwater is limited to bores along the coast and in the Fitzroy Trough, and to oil exploration wells which suggest that fresh water extends to depths of 1000 m. Recharge to aquifers occurs around the margins of the basin and directly to outcrop areas within the basin. Surface drainage is significant only in the Fitzroy Trough. Groundwater flow is probably to the northwest in most aquifers, which discharge along the coast and into playa lakes within the basin.

The Grant Group and Poole Sandstone (P) are the thickest and most extensive aquifers (Pg in Fig. 9). The Triwhite Sandstone and the Liveringa Group (P) higher in the Permian sequence also contain aquifers. The Jurassic Wallal Sandstone (J), a confined aquifer in the northwest, is artesian along the coast, where it has heads of up to 25 m above the surface; it contains fresh water in the south, but brackish water (2000 mg L^{-1}) in the north. The Broome Sandstone (K), an unconfined aquifer in the northwest of the basin, overlies the Wallal Sandstone, and contains fresh water away from low-lying coastal areas (Leech, 1979). Groundwater also occurs in the Triassic Erskine Sandstone (R) and in Tertiary calcretes (T).

Large tracts of the Canning Basin are uninhabited — especially in the southern and central parts, which are covered by the Great Sandy Desert — so groundwater is a largely untapped resource. Indeed, apart from a few town water supplies and limited pastoral use, groundwater in the Canning Basin is virtually undeveloped. The Canning stock route, surveyed in 1906, crosses the only part of the basin where shallow potable water is available.

The *Perth Basin* extends for 800 km along the west coast of Australia, and ranges from 15 to 90 km wide onshore. The basin contains a sedimentary pile up to 15 km thick in which fresh water extends in places to a depth of 2000 m. The most important aquifers are thick unconsolidated sandstones ranging in age from Triassic to Early Cretaceous, together with superficial sand and calcarenite of Pleistocene age on the coastal plain (Allen, 1976, 1979). The Silurian Tumblagooda Sandstone (S) is an aquifer in the northern part of the basin.

The basin has a structure dominated by north-south faulting, and is bounded on the east by the 15 km throw of the Darling Fault. The structure controls the direction of groundwater flow, which is subparallel to the basin margin throughout much of the basin. Recharge to the aquifers tends to be concentrated in elevated areas in the central parts of the basin, rather than at the eastern faulted margin. Aquifers along the eastern margin of the basin commonly contain saline water.

The most extensive aquifer is the Upper Jurassic Yarragadee Formation (J), which has two flow systems: a northern one in the Dandaragan Trough, and a southern one in the Bunbury Trough (Fig. 10). Fresh water extends to depths of around 2000 m in both systems.

The Lower Cretaceous Leederville Formation (K) is preserved in the central and southern part of the basin, and ranges up to 400 m thick. It consists of interbedded sandstone and shale, and is generally confined by Upper Cretaceous siltstone or overlain by superficial deposits. It is the most commonly used artesian aquifer, but the water often has a high iron content.

Superficial formations (Q), consisting of sand, clay, and limestone, on the coastal plain contain up to 60 m of fresh water recharged directly by rainfall. The groundwater salinity ranges from fresh in the sand to saline in areas of poorly drained clay. Shallow water often requires treatment for iron and organic coloration.

Sandstones of Permian (P) and Triassic age (R) are of local importance where they crop out at the surface or directly underlie the Leederville Formation. The salinity in these aquifers is quite variable.

The Perth Basin is the largest developed source of water in Western Australia, supplying much of the population in Perth and other coastal towns, and also supplying, by pipeline, towns east of the Darling Fault. In the Perth metropolitan area, 60 000 homes have a private bore for garden watering. Increasing use is made of groundwater for irrigation of market gardens, vineyards, and fodder crops. The superficial sands are subject to contamination by industrial waste and effluent leakage, but tight control over land use is exercised in areas of public water supply (Fig. 11).

The *Collie Basin,* in southwest Western Australia, contains up to 1500 m of Permian coal measures, and sandstone (P) with some aquifer potential.

The onshore portion of the *Bonaparte Basin,* in northern Australia, contains gently folded Carboniferous-Triassic (C, PR) sedimentary rocks overlying a block-faulted Cambrian-Devonian (€, D) sequence. In Spirit Hill No. 1 oil exploration well in the south of the basin, fresh groundwater with a salinity of 330 mg L^{-1} flowed from an unconformity in the Carboniferous sequence at a depth of 260 m. Devonian (D) limestones at mining prospects on the southern margin have yielded large quantities of low-salinity

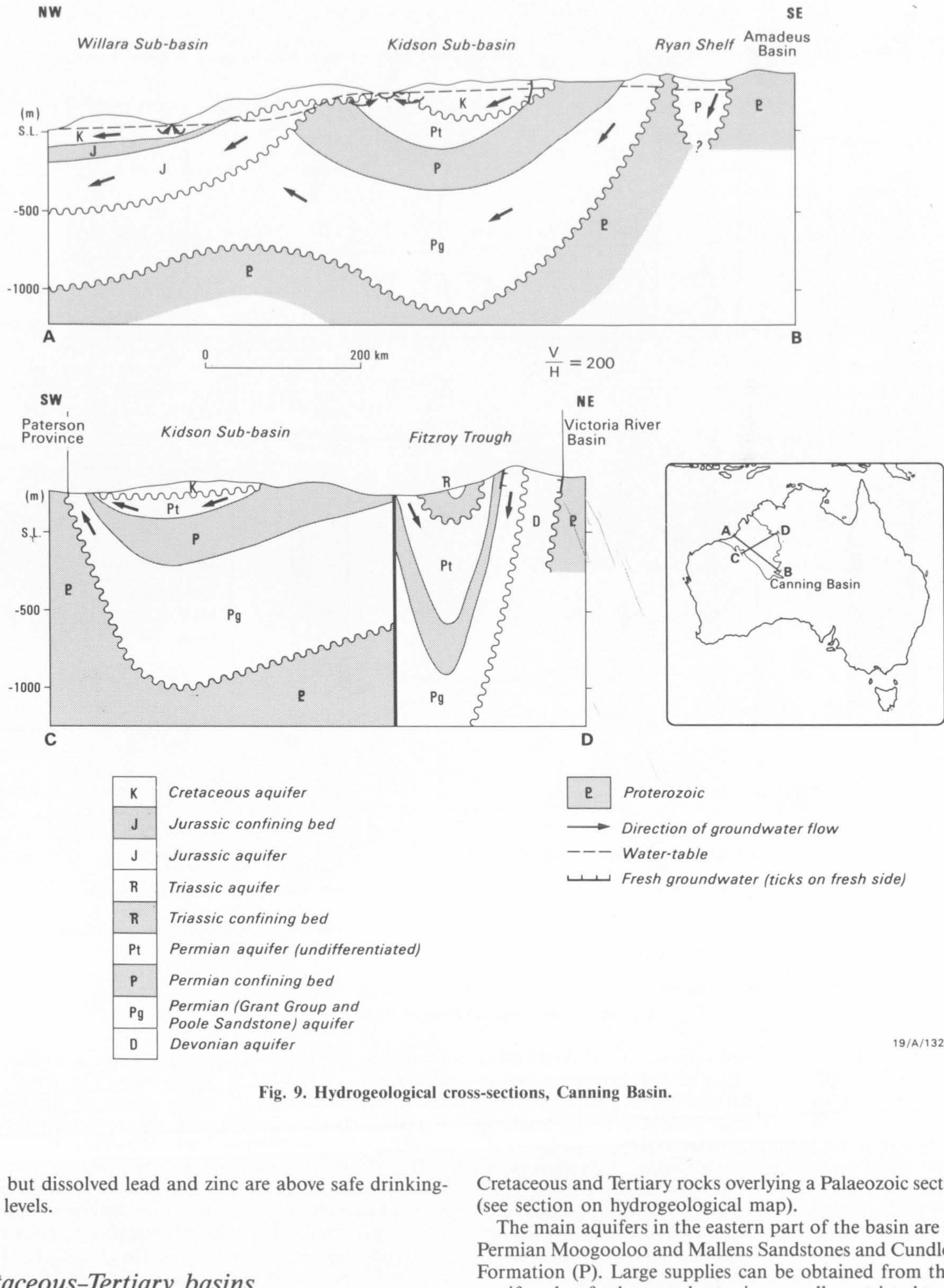

Fig. 9. Hydrogeological cross-sections, Canning Basin.

water, but dissolved lead and zinc are above safe drinking-water levels.

Cretaceous–Tertiary basins

The *Carnarvon Basin* extends for 800 km along the northwest coast of Australia, and is up to 200 km wide. It contains mainly impermeable rocks, and thin sandstone units of Permian and Cretaceous ages. The groundwater is characterised by high salinity, and is suitable only for stock throughout much of the basin. This results both from the lack of suitable aquifers and outcrop areas, and also from the low rainfall.

The basin can be divided structurally into an eastern part containing steeply dipping upper Palaeozoic sedimentary rocks, and a western part with gently westerly dipping Cretaceous and Tertiary rocks overlying a Palaeozoic section (see section on hydrogeological map).

The main aquifers in the eastern part of the basin are the Permian Moogooloo and Mallens Sandstones and Cundlego Formation (P). Large supplies can be obtained from these aquifers, but fresh groundwater is generally restricted to the outcrop areas.

The Birdrong Sandstone (K), which is up to 35 m thick, underlies the western part of the basin. The aquifer is artesian over much of the coastal plain; water temperature ranges up to 60°C, and salinity is generally 3000–10 000 mg L^{-1} but exceeds 14 000 mg L^{-1} in the south. Some bores also produce water from Silurian and Devonian sandstones underlying the Birdrong Sandstone.

In the south of the basin, groundwater occurs in the Silurian Tumblagooda Sandstone (S). Tertiary limestone (T) containing a thin layer of fresh groundwater overlying saline

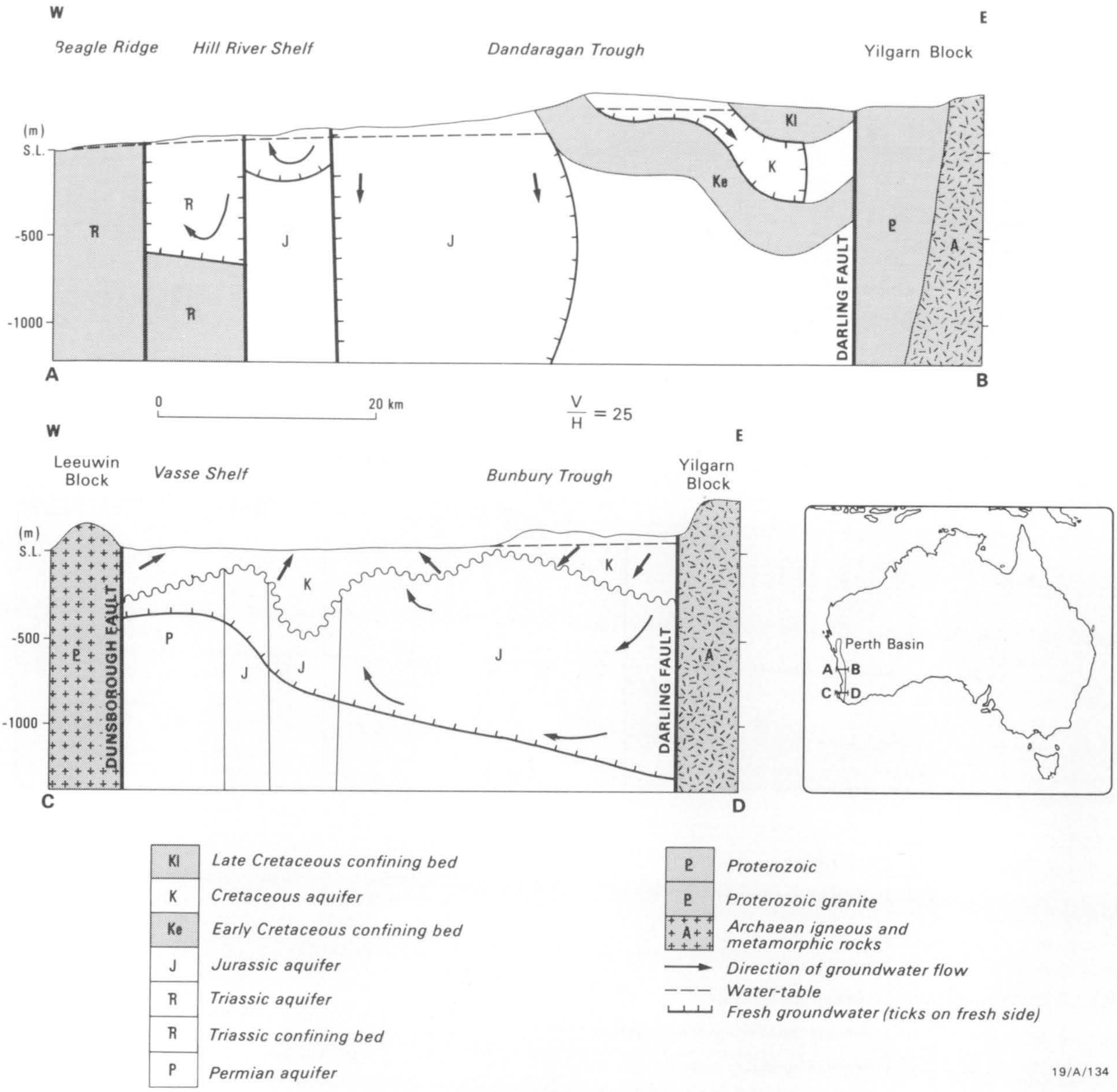

Fig. 10. Hydrogeological cross-sections, Perth Basin.

groundwater is an unconfined karst aquifer at North West Cape. Small supplies of high-salinity shallow groundwater can be obtained from the thin alluvial cover throughout the basin. Large supplies of fresh groundwater are available locally in river bed sands and gravels (Q) of the major rivers.

The major groundwater development, for irrigation at Carnarvon, is in river bed sand of the Gascoyne River. Stock water is obtained from all aquifers, and saline groundwater from the Birdrong Sandstone (K) is desalinated for town supply at Denham and Useless Loop. Shallow brine is extracted for salt production at Lake Macleod.

The *Eucla Basin* lies at the head of the Great Australian Bight, and extends for up to 300 km inland, where it is adjacent to the Officer Basin. It contains up to 600 m of Cretaceous to Tertiary rocks (Lowry, 1970), and is characterised by very high groundwater salinity.

The rocks are undeformed, and dip gently towards the coast (Fig. 12). The surface of the basin is flat and formed by Tertiary limestone in which drainage is underground. Annual rainfall averages about 200 mm, and is usually low intensity.

The basal Cretaceous sandstone (K), the Loongana Sandstone together with sandstone in the overlying Madura Formation, is a confined aquifer from which artesian flows discharge on to Roe Plains. The salinity of the water ranges from 3000–5000 mg L^{-1} in the centre of the basin, to 10 000–50 000 mg L^{-1} around the eastern and western margins, where recharge is from saline runoff.

The Hampton Sandstone and the Wilson Bluff and Abrakurrie Limestones (T) constitute an unconfined aquifer. Karst phenomena are common in the limestone, where the water-table is up to 100 m deep; underground lakes several kilometres long occur in some caves. The groundwater is fresh only in a small area in the northwest of the basin; elsewhere it is brackish or saline.

Because of the high salinity, pastoral development is limited to areas of stock-quality groundwater.

The *Money Shoal Basin*, in the Northern Territory, contains a thin Cretaceous to Tertiary sequence onshore and on Bathurst and Melville Islands. The Van Diemen Sandstone (T) provides high bore yields, and maintains perennial flow in many streams on Bathurst and Melville Islands. The Bathurst Island Formation (K) is generally low-yielding except in the more sandy facies on Coburg Peninsula (Hughes, 1978) and in basal gravel (overlying Precambrian dolomite), which in part supplies Darwin. Thick sands of possible Tertiary (T)

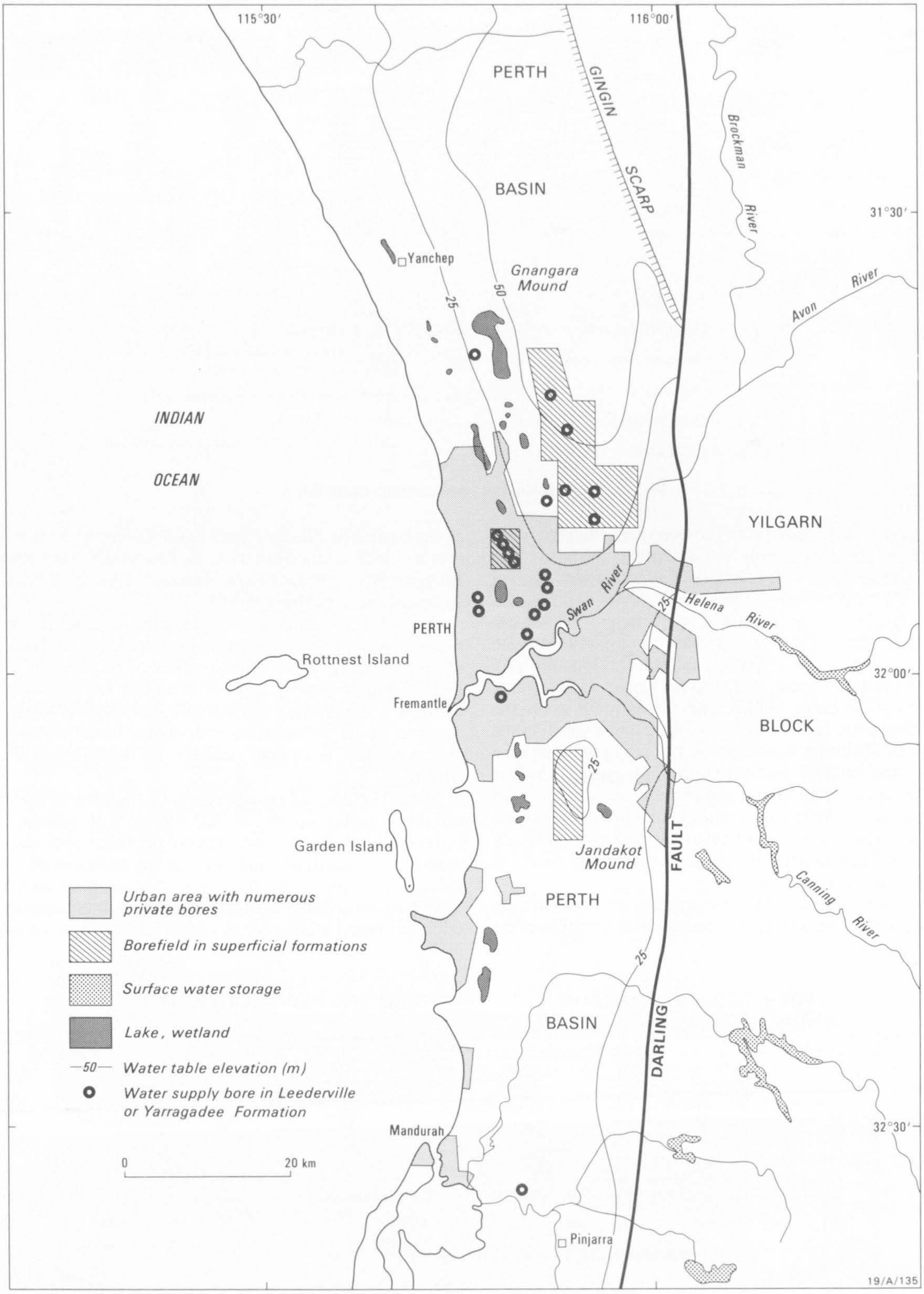

Fig. 11. Hydrological features of the southern Perth Basin.

age underlie laterite watersheds of the major rivers (Stuart-Smith, 1977).

The Cainozoic *Karumba Basin*, in northeast Australia, contains the principal regional aquifers for the western part of Cape York Peninsula because water from the underlying Carpentaria Basin is too high in fluoride for domestic use (Smart & others, 1980). The Karumba Basin provides domestic water and part of the processing water used at the Weipa bauxite mine; individual bores have yielded up to 15 L s^{-1}.

The *Murray Basin*, in southeast Australia, is a multiaquifer system in flat-lying Tertiary sediments (Fig. 13; Evans, 1986). The basal Renmark Group aquifer (Te) comprises lower Tertiary fluvial silt, sand, clay, and minor gravel; it is used

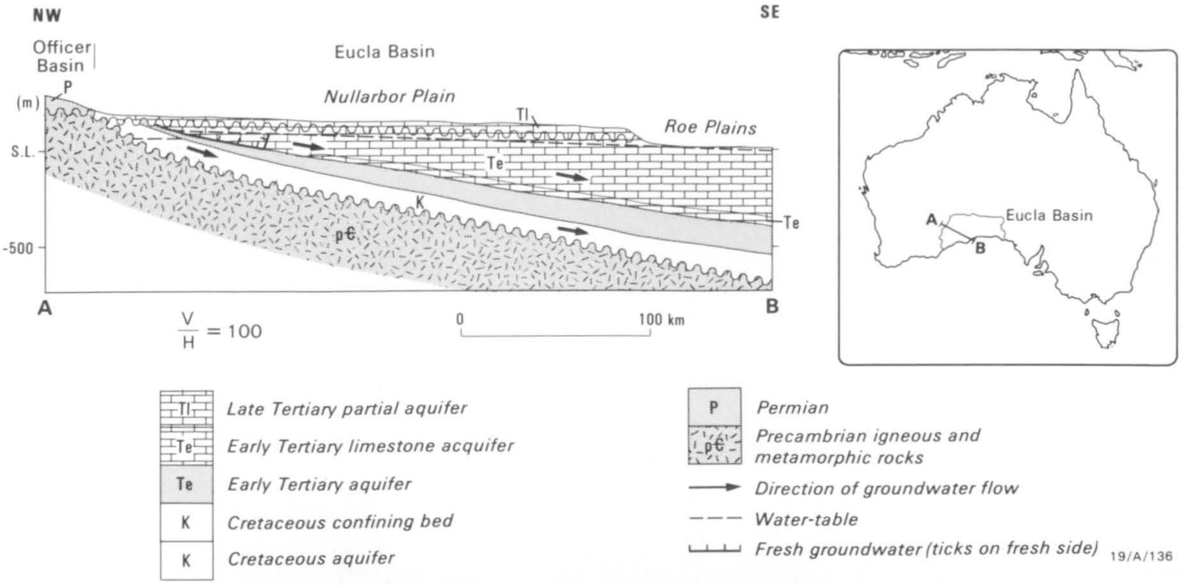

Fig. 12. Hydrogeological cross-section, Eucla Basin.

for irrigation in the east (with the overlying Pliocene sand aquifer) and for stock supply in the centre of the basin. The Murray Group aquifer (T1) comprises mainly upper Tertiary marine limestone in the west and south of the basin, and is extensively used for agriculture. The Pliocene sand aquifer (Tl), which blankets most of the basin, consists of marine sand and silt in the west, and fluvial gravel, sand, silt, and clay in the east and south; it is used for irrigation in the east and south of the basin, but becomes too salty for use in the west of the basin. In the east and in the tributary valleys the Pliocene sand aquifer is overlain by Pliocene to Quaternary clay, silt, and sand of the Shepparton Formation, which is an aquifer of local importance as a groundwater resource (but not depicted on the map) because it underlies the eastern irrigation areas and contains rising regional water-tables. In the west the Pliocene sand aquifer is blanketed and confined by Quaternary aeolian material.

In most of the basin, the three aquifers are separated by confining beds (Fig. 14). In the eastern and northern parts of the basin, the Pliocene sand aquifer directly overlies and is in hydraulic connection with the Renmark Group aquifer. Bore yields of 300 L s^{-1} are obtained in these alluvial-fan sediments near Griffith (NSW).

Groundwater recharge generally occurs near the basin margin, particularly where the major rivers cross it. Discharge is either directly to the lower reaches of the Murray River and its tributaries or by direct evaporation. Leakage between aquifers is a dominant process and can contribute significantly to aquifer recharge. Most discharge from the Renmark Group aquifer is through leakage to the Murray Group aquifer.

Natural salinity of groundwaters in the Murray Basin is variable, ranging up to 300 000 mg L^{-1}. In general, the better-quality water is found around the basin margins, and salinity increases down-flow towards the basin centre. Man-induced changes to the hydrologic regime have increased salinity by remobilising existing salt stores or by concentrating salt in the near-surface zone by evaporation. This has resulted

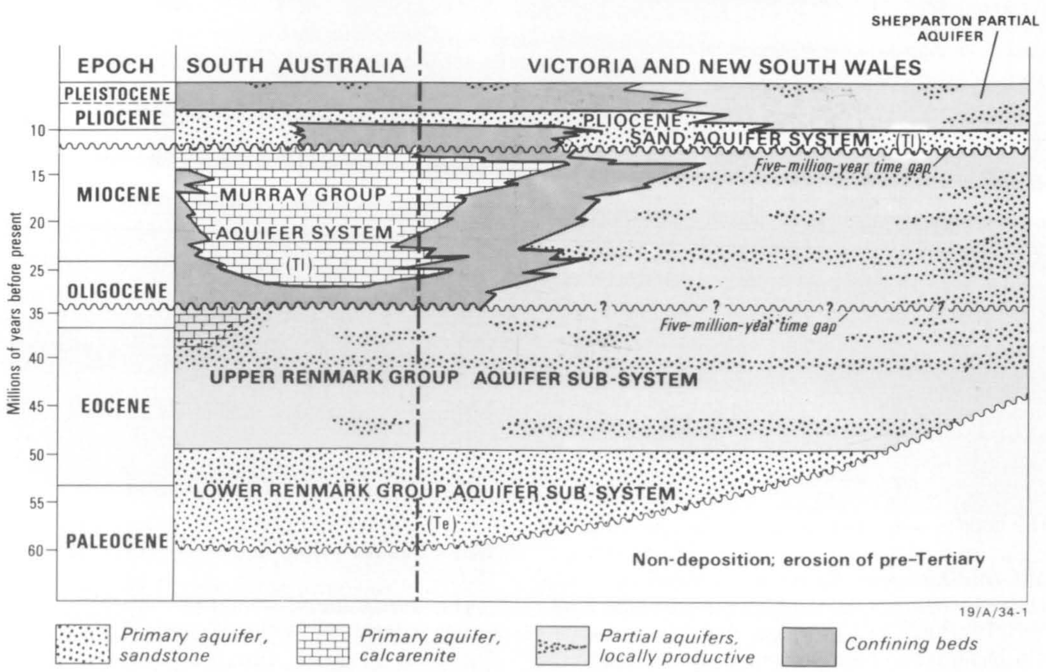

Fig. 13. Regional aquifers, Murray Basin (after Perry, 1983).

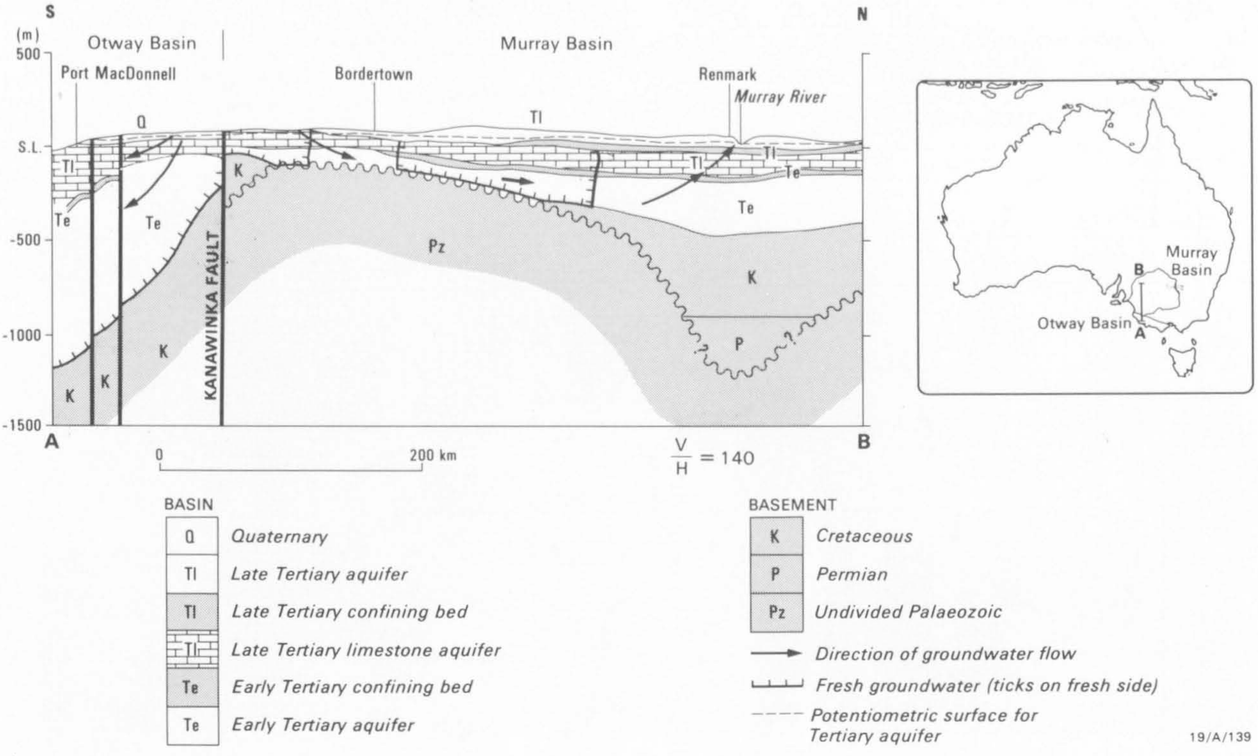

Fig. 14. Hydrogeological cross-section, Murray and Otway Basins (after Shepherd, 1983).

in an increase in both the incidence of soil salinisation and the salinity of the Murray River, Australia's largest river and the main source of water for Adelaide and southern South Australia.

The *Gippsland Basin*, on the south coast of Victoria, contains two high-yielding sedimentary aquifers. One of these, the Boisdale Formation (Tl), provides the water supply for the city of Sale. The other, the Latrobe Valley Coal Measures of Late Cretaceous-Eocene age (Te), contains Victoria's principal energy sources of onshore brown coal and offshore oil and gas. In this formation two sand units are dewatered by 28 000 000 m^3 annually to ensure pit stability at the Morwell open-cut coal mine. Groundwater salinity is low (900 mg L^{-1} total dissolved solids) and temperatures high (up to 70°C at Morwell). A freshwater wedge extends up to 40 km offshore (Kuttan & others, 1986), and onshore recharge drives recovery in the Bass Strait oil and gas fields (Fig. 15). In contrast to the Murray and Otway Basins, upper Tertiary limestones in the Gippsland Basin sequence are generally low-yielding marls. To the west, the relatively small Westernport Sub-basin yields more than 10 000 000 m^3 annually for irrigation and town supply from confined aquifers in the lower Tertiary Westernport Group (T). Pumping is now regulated to prevent sea-water intrusion into the aquifers.

The *Otway Basin*, straddling the Victoria-South Australian border, contains two major sedimentary aquifers, each with groundwater salinities less than 1000 mg L^{-1}. The confined aquifer of the Wangerrip Group (Te) yields up to 125 L s^{-1} to bores, and supplies towns including Geelong. The overlying Gambier-Portland Limestone (Tl) aquifer is unconfined, and is polluted in places by nitrate derived from factory wastes. To the east, in the Port Philip Sub-basin, the main groundwater supplies are derived from the confined Fyansford Formation-Brighton Group aquifer (Tl), which generally yields less than 5 L s^{-1}. The Otway and Murray Basins are hydraulically connected (Fig. 14).

The *St Vincent Basin* is a graben downfaulted on its eastern margin with sediments thickening eastward and southward (Fig. 16). The Adelaide Plains Sub-basin, a water-quality rather than a structural subdivision, contains fresh groundwater in the upper two of three confined aquifers. The aquifers range in age from Early Eocene to Late Pliocene. The upper aquifers are hydraulically connected in places, and are probably recharged from bedrock via deeply buried thick clastic deposits along the Eden Fault (Gerges, 1987). Carbon-dating indicates water ages of 5000 years near this fault, and 13 000 years farther down the flow path. Pumping, for irrigation and in drought years for supplementary urban supply for Adelaide, is now regulated to control saline intrusion from adjacent (T) and overlying (Q) aquifers.

The onshore portion of the *Bass Basin* in the Tamar Valley of northern Tasmania contains 800 m of Tertiary sediments. Confined sand and gravel aquifers in the explored upper 150 m yield more than 5 L s^{-1} of groundwater with marginally less than 1500 mg L^{-1} total dissolved solids (Matthews, 1983).

The *Pirie-Torrens Basin* contains a confined Tertiary sand aquifer up to 40 m thick which yields irrigation water near Port Pirie (Shepherd,1983).

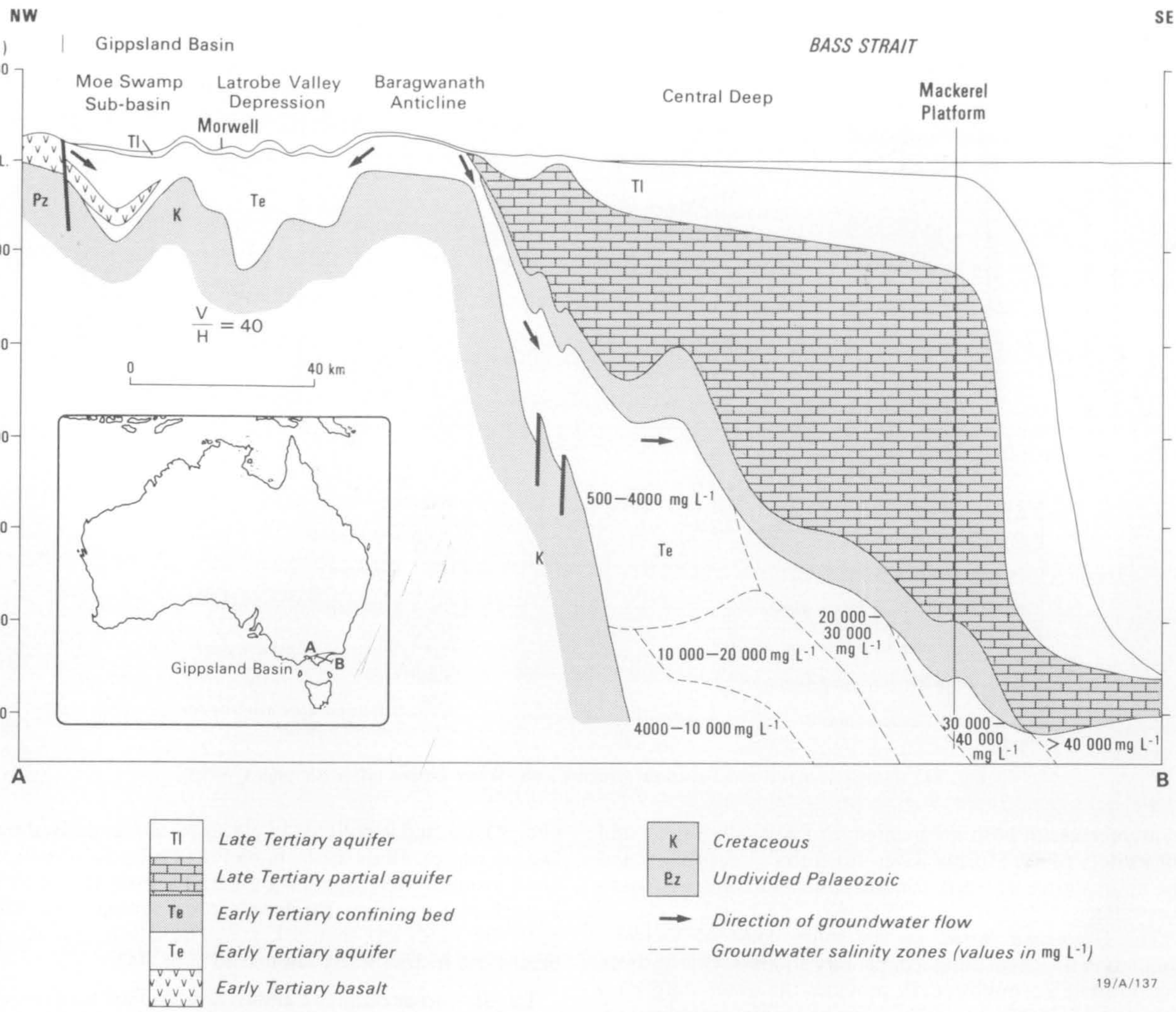

Fig. 15. Hydrogeological cross-section, Gippsland Basin (including information from Kuttan & others, 1986).

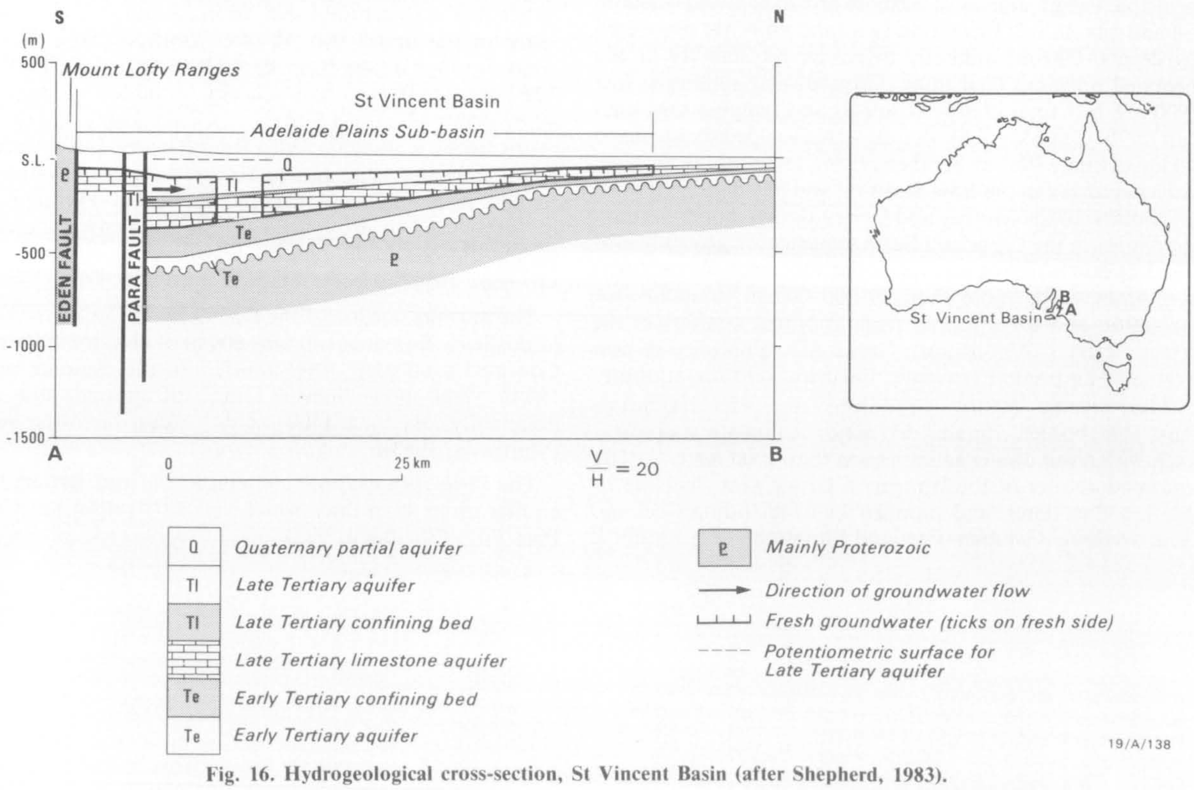

Fig. 16. Hydrogeological cross-section, St Vincent Basin (after Shepherd, 1983).

FRACTURED-ROCK PROVINCES AND SURFICIAL COVER

Western province

The western fractured-rock province (Fig. 4) includes Archaean granite-greenstone terrane (A) and Proterozoic metamorphic belts and sedimentary basins (Ᵽ). These rocks have a thin cover of superficial deposits and weathering products. Cainozoic alluvial sediments occur in the palaeodrainages, and have been dissected by the active rivers of the northwest.

The topography varies from low plateaux and plains of subdued relief over the granites, to ranges and dissected plateaux in the greenstone belts and Proterozoic basins. The climate changes from one of regular winter rainfall in the south, with decreasing intensity eastwards, to one of irregular summer rainfall in the north characterised by intense storms resulting from tropical cyclones. Apart from the extreme southwest corner, which has a perennial drainage, the south of the province is occupied by interior salt-lake drainages, and groundwater salinity is consequently high. In the north, which is drained externally, groundwater salinity is much lower.

The major part of the province is underlain by granite. In the south a laterite profile has developed on the granite, which is weathered to depths of 60 m; the best aquifers are at the base of the weathered zone. In the north, where the depth of weathering is less than 10 m, groundwater occurs in fractures. Recharge is a small proportion of annual rainfall (Allen & Davidson, 1982), and occurs through the weathered zone. Groundwater conditions in the greenstone belts and Proterozoic basins are highly variable, and depend on rock type, structure, and topography. Large yields can be obtained locally from chert, iron formation, sandstone, dolomite, shale, volcanic rocks, and metasediments.

The highest-yielding aquifers in the province are alluvial sands and gravels, and calcretes in the Tertiary palaeodrainages. Most of the groundwater in the paleodrainages is saline, but fresh water occurs in the upper parts. Groundwater salinity in the alluvium along the north coast is as low as 200 mg L^{-1}.

The major towns in the northwest are supplied from calcrete (Karratha, Dampier, Tom Price, Newman) or from alluvium (Port Hedland). Environmental considerations have limited production of groundwater from the high-yielding calcrete aquifer at Millstream (Commander, 1983). Fractured-rock aquifers supply some of the smaller towns in the centre and north. In the southwest of the province, fresh groundwater is unavailable, and towns are supplied either from surface storages or from the Perth Basin. In the Kalgoorlie region, saline groundwater for mining is drawn from sands in the palaeodrainages, and water containing up to 180 000 mg L^{-1} is used for ore processing. Stock water is obtained throughout the province from the weathered zone or shallow bedrock, except in the south and southeast where groundwater is too saline.

Clearing for agriculture in the southwest of the province has led to reduced transpiration and increased infiltration. In consequence, water-tables have risen and caused salinisation of previously productive farmland (Fig. 17), and increased the salinities of some streams.

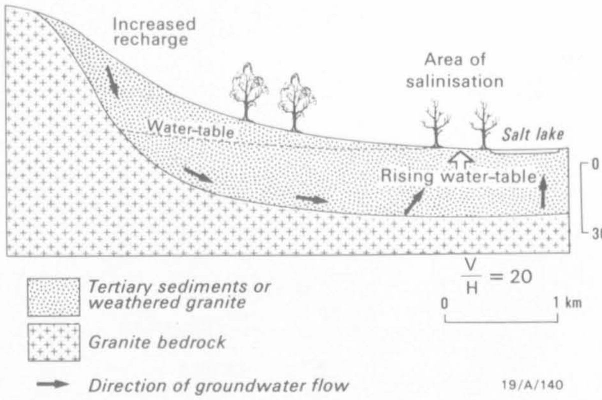

Fig. 17. Diagrammatic section showing the groundwater effects of land-clearing for agriculture in southwest Australia: reduced transpiration, increased recharge, rising water-table, and salinisation.

Northern province

The northern fractured-rock province consists mainly of large Proterozoic sedimentary basins (Ᵽ) in which groundwater occurs in fractures. Proterozoic metamorphic rocks, granite, and dolerite are also included in this province. Overlying units include the Cambrian Antrim Plateau Volcanics, Cambrian sandstone (Ꞓ), Cretaceous (K) and Tertiary (T) sands and gravels, and Quaternary sediments (Q) of the major rivers and coastal plains.

Annual rainfall ranges from 400 mm in the headwaters of the Victoria River to 1200 mm at Nhulunbuy and is intensely summer seasonal. Annual pan evaporation ranges from 2400 to 3600 mm. Drainage is external via five major rivers, one of which contains Australia's largest surface water storage — Lake Argyle. Topography varies from ranges and dissected plateaux over the Proterozoic sedimentary basins to low plateaux and plains, deeply weathered and laterite-capped in places, over the remainder.

The Proterozoic Coomalie Dolomite and overlying Cretaceous sediments contain high-yielding bores which augment Darwin's surface water supply (Verma & Qureshi, 1982). Proterozoic schist provides high yields for pipeline supply to the Jabiru regional centre, and Proterozoic sandstone supplies the iron ore mining communities of King Sound.

The Cambrian Antrim Plateau Volcanics underlie cattle-grazing lands of the Victoria River district. Aquifers in them include vesicular zones as well as interbedded sandstones. The Cambrian Bukalara Sandstone (Ꞓ) of the McArthur River area is up to 300 m thick. Cretaceous aquifers (K) supply the mining township of Nhulunbuy (Macqueen, 1979), and have potential for supplying good-quality water to the town of Katherine (Yin Foo, 1985). The Tertiary and Quaternary aquifers of the Alligator Rivers region are important because they maintain perennial billabongs in the lowlands. Quaternary alluvial aquifers (Q) on the lower reaches of the Ord River provide town water supply for the regional centre of Kununurra.

Central province

The central province comprises mainly Archaean and Proterozoic metamorphic terrane and Proterozoic sedimentary basins (Ᵽ). Overlying Cainozoic alluvial sediments occur in palaeodrainages in the north, and Quaternary aeolianites are common on the south coast. Overlying Tertiary basins are described separately.

Relief is generally less than 500 m, except in the central Australian ranges and the Flinders-Mount Lofty Ranges of southeast South Australia. Both these ranges have significantly modified the annual rainfall contours. In southern South Australia the annual rainfall is greater than 250 mm and winter seasonal. Drainage is unco-ordinated or internal, towards Lake Eyre and Lake Frome, except in the wetter southeast.

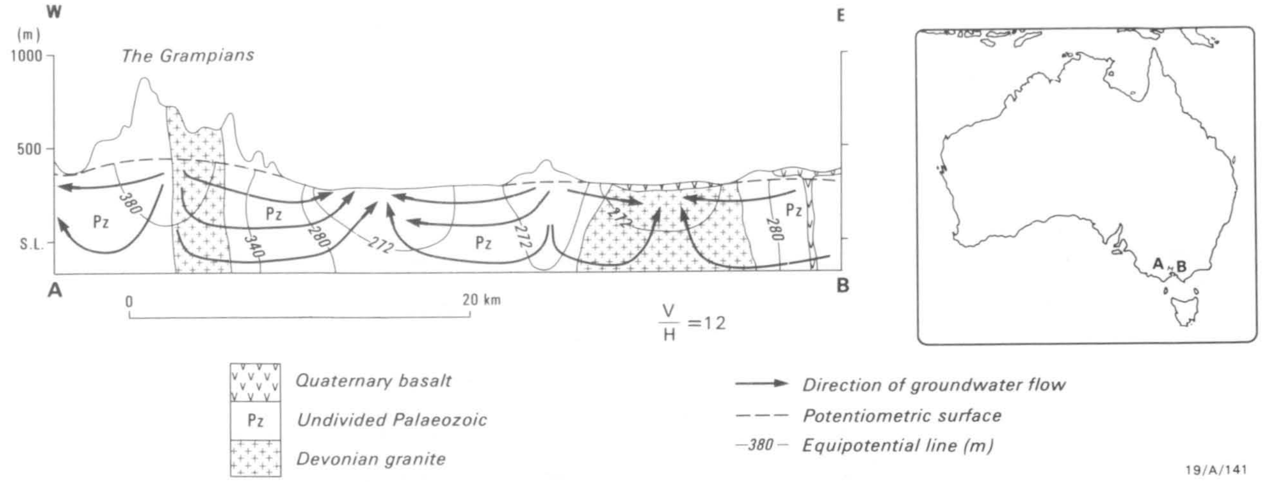

Fig. 18. Hydrogeological cross-section through fractured rocks, Ballarat, Victoria (after Australian Groundwater Consultants, 1986).

Water quality is a limiting factor to groundwater use in most of this province. Some relatively fresh groundwaters contain high nitrate concentrations (50–150 mg L^{-1}) probably as a result of leaching through the unsaturated zone following nitrogen fixation in the soil by arid-zone vegetation. High nitrate concentrations in groundwater are common in the Arunta Block fractured rocks and overlying Cainozoic aquifers of central Australia (Knott & McDonald, 1983), and in the fractured-rock aquifers of South Australia (Cobb & others, 1982).

The best groundwater prospects are in the high-relief/moderate-rainfall areas: in the Mount Lofty Ranges, east of Adelaide, two sandstone units yield up to 20 L s^{-1} of low-salinity groundwater (Shepherd, 1983); and in the Musgrave Ranges, in northern South Australia, water supplies with less than 1500 mg L^{-1} total dissolved solids have been developed in places for Aboriginal communities (Wharton, 1984).

Two wellfields in fractured and faulted Proterozoic sedimentary rocks in the mining town of Leigh Creek (Waterhouse & Read, 1982) augment surface supplies from a nearby dam. Water is desalinated by a reverse-osmosis plant for domestic supply.

Small Tertiary basins and palaeodrainages (T) contain important sources of fresh water. A small Tertiary basin south of Tennant Creek contains water with 350 mg L^{-1} total dissolved solids in sand, clay, and gravel up to 20 m thick, and was formerly the water supply for Tennant Creek. The Tea Tree basin, 200 km north of Alice Springs, contains water with less than 200 mg L^{-1}, and is the proposed site for large-scale irrigation of vines. At Alice Springs, groundwater in Quaternary fluviatile sand, gravel, silt, and clay associated with the Todd River (Q) was used for town supply until 1964. Other sand aquifers of possible Quaternary age occur as outwash fans around the Flinders and Musgrave Ranges, where low-salinity runoff from the rocky ranges is a source of recharge (Shepherd, 1983).

Thin wind-deposited sandy limestones of the Quaternary Bridgewater Formation (Q) provide fresh groundwater for reticulation to all of Eyre Peninsula. Distinct small basins are defined by the 1500 mg L^{-1} isohaline. Similar Quaternary basins exist on Yorke Peninsula.

Eastern province

The eastern fractured-rock province comprises mainly deformed Palaeozoic sedimentary and low-grade metamorphic rocks (Pz) and granites, but Proterozoic sedimentary rocks (P) and granite occur in places. Overlying elements include small Triassic (R) and Tertiary (T) basins, Cainozoic basalts, and alluvial sediments (Q).

Most of the area is above 200 m, and parts of the eastern highlands and central Tasmania are above 1000 m. Rainfall varies from summer-dominant in the north to winter-dominant in Victoria and Tasmania. Western Tasmania receives about 2400 mm and northern Queensland about 3200 mm annually. Drainage is eastward to the Pacific Ocean or southwest to the Southern Ocean via the Murray–Darling system.

Within this province, groundwater systems are related to topography and geomorphology; in the Australian Capital Territory, for instance, the highest-yielding bores are in valley floors. Groundwaters generally contain less than 1500 mg L^{-1} total dissolved solids, and variations in salinity are due to aquifer geochemistry, dissolution of salts in the unsaturated zone, and residence time of groundwater in the aquifer (Evans, in press). In dry areas such as western New South Wales, low relief and low rainfall are factors in increased salinity of fractured-rock aquifers. A typical groundwater flow system in fractured-rock aquifers of Victoria is shown in Figure 18.

In central Victoria, mineral-water springs occur in fractured Palaeozoic rocks. They commonly contain 2000–4000 mg L^{-1} total dissolved solids, and free carbon dioxide (Malone, 1982).

Tertiary alluvium constitutes the major aquifers in the Macintyre–Dumaresq, Gwydir, Namoi, Lachlan, Loddon, Campaspe, Goulburn, and Murray valleys. Although varying markedly in size and groundwater potential, the valleys of these inland rivers have similar characteristics (Williamson, 1984). In their upper reaches, the alluvial infills are relatively shallow and have good hydraulic connection with the rivers. Downstream the valleys broaden and mature, and contain extensive alluvium — in places more than 100 m thick — providing important groundwater resources (Fig. 19). The alluvial deposits merge downvalley with the fan deposits that form important aquifers in the Murray Basin and overlying the Great Artesian Basin.

Quaternary sediments occur in the coastal river valleys, but their groundwater potential varies considerably. These rivers are relatively short and geologically young, and their thin alluvial infills grade to thicker estuarine, deltaic, and aeolian sediments towards the coast.

The significant alluvial aquifers in the coastal valleys are mostly about 10 m thick in the upper reaches, increasing to about 30 m downstream. The largest of these alluvial deposits, and one of the most intensively developed for groundwater, is in the Hunter Valley (NSW), where bore yields

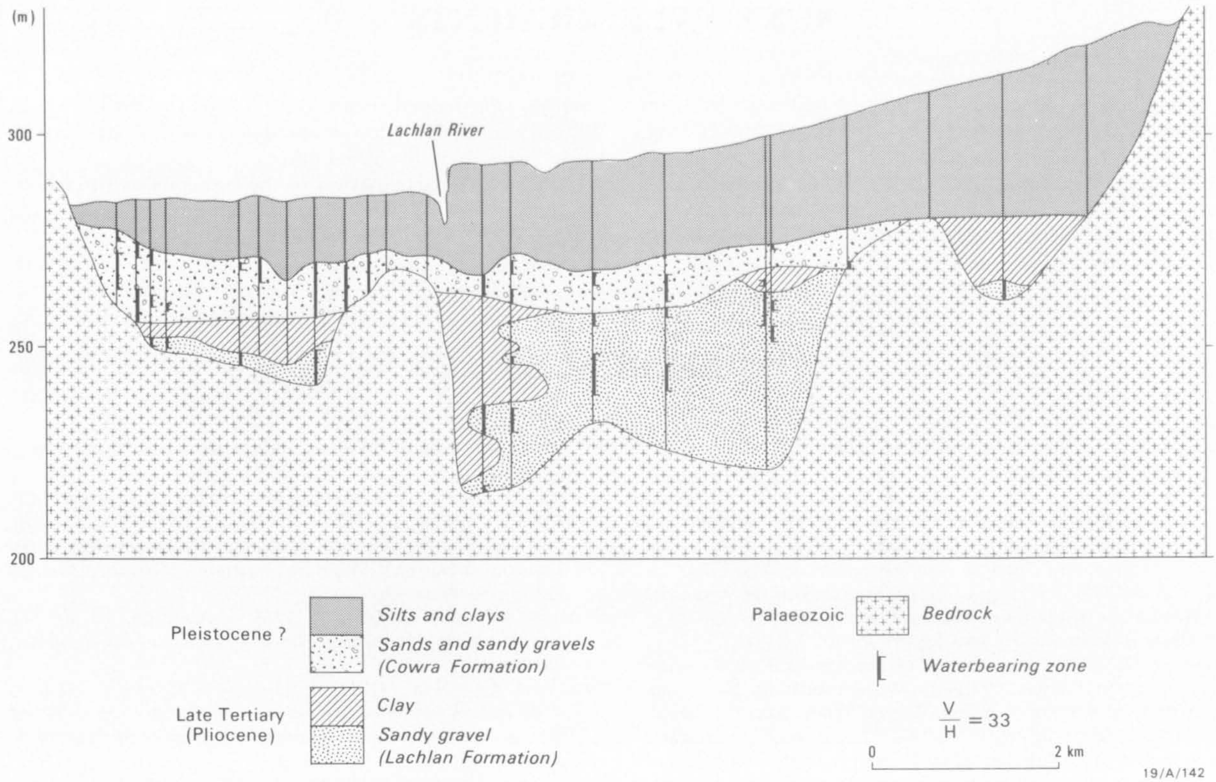

Fig. 19. Hydrogeological cross-section through alluvial aquifers, Lachlan Valley, near Cowra, New South Wales (after Williamson, 1964).

are between 10 and 40 L s^{-1}. Similar high yields are obtained from alluvia of the Burdekin, Pioneer, Burnett, and Brisbane Rivers and Lockyer Creek in Queensland.

Estuarine sediments occupy extensive areas along the east coast of Australia, but groundwater of usable quality is mostly confined to the top few metres, and yields are usually low. The Botany sand beds at Sydney are heavily pumped for industrial use, but the groundwater is acidic and sulphate-rich owing to intercalated peat beds. Saline groundwaters underlie many estuarine deposits owing to Holocene sea-level changes (Arakel & Ridley, 1986); brines are extracted for industrial use in the Fitzroy delta, Queensland.

The Burdekin delta in Queensland is the site of very large groundwater abstraction for irrigation, and the aquifer is sustained by artificial recharge to prevent saline intrusion.

Aeolian sands are important low-salinity aquifers along the coast from Yeppoon to Sydney. The sands are commonly 20 to 30 m thick and are recharged by rainfall, maintaining freshwater wedges overlying denser sea water. Major unexploited groundwater resources are held in the high dunes of Fraser, Moreton, and North and South Stradbroke Islands, in southern Queensland.

GROUNDWATER RESOURCES

The total amount of groundwater used in Australia annually is about 2 460 000 000 m^3, which is about 14 per cent of the total amount of water used (Jacobson & others, 1983). Irrigation use totals 1 640 000 000 m^3; urban and industrial use is 480 000 000 m^3; and 340 000 000 m^3 is used for other, mainly rural purposes, including stock-water supplies. Groundwater is drawn from about 500 000 water-bores. The greatest concentrations of bores are near Perth and Adelaide, and in southeast South Australia, western Victoria, and the central Queensland coast. However, in a large part of the country, groundwater is undeveloped.

Surficial aquifers are generally the groundwater sources most intensively used for irrigation and for urban and industrial water supplies.

The intensive use of groundwater in some areas, especially for irrigation, has led to the overdevelopment of some regional aquifers. This has occurred in at least 13 areas, and is evinced by low water-tables or increased salinity. Most of these areas are now controlled under the relevant State legislation, and the extraction of groundwater is carefully managed. In some of these areas, artificial recharge is used to balance the excessive groundwater extraction; in others, groundwater and surface water are used conjunctively to ameliorate the effects of demand exceeding supply.

Australia's groundwater resources potential has not been fully investigated, and information is not yet available to derive conceptual models for many large groundwater systems. The greatest potential for additional large-scale groundwater development is probably in the surficial aquifers of northern Australia, which are being replenished by present-day groundwater recharge, and in some of the large unexploited sedimentary basins. For Australia as a whole, the total possible annual yield is estimated as about 72 000 000 000 m^3 of fresh groundwater with salinity less than 1000 mg L^{-1} total dissolved solids; brackish and saline groundwater are an additional substantial resource. In comparison, the potential surface water yield is 123 000 000 000 m^3 annually from the total runoff of 440 000 000 000 m^3 (Brown, 1983).

The potential for production of industrial brines from groundwater has not yet been fully investigated, and the hydrogeothermal resources of Australia are little known.

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Principal aquifer; type, distribution and productivity
Porous
Extensive highly productive aquifers
Extensive aquifers of low–moderate productivity
Fractured or fissured
Extensive highly productive aquifers
Extensive aquifers of low–moderate productivity
Local aquifers, generally low productivity
The principal aquifer produces the best quality water at highest yield from shallowest depth
Principal aquifer; lithology
Sedimentary and low-grade metamorphic rocks
Undivided
Limestone
Igneous and medium to high-grade metamorphic rocks
Undivided
Granite
Basalt
Aquifer age and superposition
Age of principal aquifer is shown by black symbol
Age of subsidiary aquifer is shown by green symbol
Principal aquifer overlies subsidiary aquifer
Principal aquifer underlies subsidiary aquifer
Boundary of subsidiary aquifer
Geological features
Geological boundary
Fault, section only
Groundwater quality and temperature
Boundary between fresh and saline groundwater in principal aquifer; 1500 mg/l total dissolved solids isoline, ticks point towards fresh water
Groundwater temperature, degrees Celsius at surface *
Groundwater movement
Contours on the potentiometric surface, metres above sea level *
Direction of groundwater flow *
Limit of main confining bed, ticks point towards confined area *
Limit of artesian flow *
Group of springs, average discharge 0–3 million m³/year
Group of springs, average discharge 3–30 million m³/year
Groundwater seepage
Radiometric age of groundwater, thousands of years *
Groundwater divide *
Man-made features and alterations of the groundwater regime
Borefield, average discharge 1–10 million m³/year
Borefield, average discharge 10–100 million m³/year
Borefield, average discharge >100 million m³/year
Groundwater pipeline
Artificial recharge site
Groundwater desalination plant, feedwater capacity >50 000 m³/year
Pollution of regional aquifer
Rising water table and salinisation
* In multiaquifer systems, these symbols refer to the basal aquifer of the system
Aquifer age
MILLION YEARS
PERIOD
ERA
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
CAINOZOIC
MESOZOIC
PALAEOZOIC
PROTEROZOIC
ARCHAEAN
Surface hydrology
Perennial stream, average discharge >30 m³/second
Perennial stream, average discharge <30 m³/second
Intermittent stream, average discharge >30 m³/second
Intermittent stream, average discharge <30 m³/second
Storages, including lakes so used
Perennial lakes, not used as storages
Ephemeral lakes, not used as storages
It is recommended that this map be referred to as:
Jacobson, G. & Lau, J. E. (compilers) 1987 – Hydrogeology of Australia (1 : 5 000 000 scale map). Bureau of Mineral Resources, Canberra.
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Lau, J. E., Commander, D. P., & Jacobson, G., 1987 – Hydrogeology of Australia. Bureau of Mineral Resources, Australia, Bulletin 227.
TIMOR SEA
ARAFURA SEA
INDIAN OCEAN
SOUTHERN OCEAN
CORAL SEA
SOUTH PACIFIC OCEAN
TASMAN SEA
GREAT AUSTRALIAN BIGHT
GULF OF CARPENTARIA
BASS STRAIT
NORTHERN TERRITORY
WESTERN AUSTRALIA
SOUTH AUSTRALIA
QUEENSLAND
NEW SOUTH WALES
TASMANIA
DARWIN
PORT HEDLAND
PERTH
ADELAIDE
MELBOURNE
GEELONG
CANBERRA
SYDNEY
NEWCASTLE
WOLLONGONG
BRISBANE
GOLD COAST
HOBART
PRINCIPAL HYDROGEOLOGICAL DIVISIONS
TOPOGRAPHY
ANNUAL RAINFALL DEFICIT
DRAINAGE AND RUNOFF
GROUNDWATER SALINITY
Total dissolved solids content of principal aquifer
0–1500 mg/l
1500–5000 mg/l
> 5000 mg/l
Section
A
B
GREAT ARTESIAN BASIN