GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 12

PROFESSIONAL PAPERS FOR 1982

DEPARTMENT OF MINES
WESTERN AUSTRALIA

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PROFESSIONAL PAPERS FOR 1982

GOVERNMENT PRINTING OFFICE
PERTH 1984

25336—1

THE HONOURABLE PETER DOWDING LL.B., M.L.C.
MINISTER FOR MINES

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National Library of Australia Card Number and ISBN 0 7244 8745X

ISSN 0508—4741
ISSN 0812—8952

CONTENTS

REVISED LATE JURASSIC AND EARLY CRETACEOUS STRATIGRAPHY IN THE PERTH BASIN

by John Backhouse

ABSTRACT

The name, Parmelia Formation, is proposed for a widespread unit of sandstone, siltstone, and shale that was formerly included in the Yarragadee Formation. The type section is in Peel 1 between 1625 m and 3551 m. Palynological evidence indicates a Tithonian to Berriasian age range for the formation. The Otorowiri Member at the base and the Carnac Member are extensive siltstone-shale units within the formation and represent extended periods of lacustrine or, in the case of the Otorowiri Member, possibly restricted marine deposition. The remainder of the formation is predominantly a fluviatile deposit with thin lacustrine beds. The formation was deposited in a rapidly subsiding rift-valley system immediately prior to the separation of southwest Australia from the Indian plate.

INTRODUCTION

Detailed palynological study of boreholes in the Vlaming Sub-basin and Dandaragan Trough of the Perth Basin (Fig. 1) has facilitated a re-assessment of the sediments assigned to the Cretaceous part of the Yarragadee Formation by Cockbain and Playford (1973) and Playford and others (1976).

Between 1968 and 1981 a number of oil-exploration wells were drilled in the offshore Vlaming Sub-basin, principally by West Australian Petroleum (Wapet). All these wells encountered a sequence of interbedded shale, siltstone, and sandstone conformably overlying the predominantly sandstone, Jurassic Yarragadee Formation and unconformably overlain by the Early Cretaceous Warnbro Group. The type section of the Yarragadee Formation cannot be firmly dated, but mapping and palynological evidence from nearby boreholes suggest that it is significantly older than the siltstone, shale, and sandstone section in the Vlaming Sub-basin. A shale unit at the base of this sequence was informally named the "Quinns Shale" (Bozanic, 1969). A thick sequence of (predominantly) siltstone and shale, some distance above the "Quinns Shale", was referred to in unpublished Wapet reports as the "Carnac Formation" (D. C. Lowry, pers. comm.). Cockbain and Playford (1973) and Playford and others (1976) included in the Yarragadee Formation all the sequence between the top of the Middle Jurassic Cadda Formation and the base of the Warnbro Group (Fig. 2). They recognized two members, the "Quinns Shale Member" in the Vlaming Sub-basin, and the "Otorowiri Siltstone Member" in the Dandaragan Trough. From their similar stratigraphic position, Backhouse (1975; 1978) concluded that the two members are the same unit, and used the earlier name "Otorowiri Siltstone Member".

Drilling by the Western Australian Mines Department in the central Dandaragan Trough between 1967 and 1977 revealed a thick succession of siltstone, shale, and minor sandstone overlying Jurassic sandstones. This section correlates with the section in the Vlaming Sub-basin above the "Otorowiri Siltstone Member" and is lithologically comparable with the "Carnac Formation" of Wapet.

It is proposed to refer all the sediments between the base of the Otorowiri Member and the base of the Warnbro Group to a new unit, the Parmelia Formation. The Yarragadee Formation is restricted to the section between the Cadda Formation and the base of the Otorowiri Member. A new member, the Carnac Member, is proposed for the Parmelia Formation. The Otorowiri Member is placed at the base of the Parmelia Formation, and the term siltstone is dropped from the name because shale is as common as siltstone in the unit.

YARRAGADEE FORMATION

The type section (Fairbridge, 1953), and the two surface reference sections (McWhae and others, 1958) for the Yarragadee Formation are stratigraphically below the Otorowiri Member. The subsurface reference section in Gingin 1, suggested by Playford and others (1976) is amended from 188 m-3 315 m to 356 m-3 315 m. The definition and description of the Yarragadee Formation as stated by Playford, Wilmott, and McKellar in McWhae and others (1958), and reiterated by Playford and others (1976) is retained, except that it now excludes the section above the base of the Otorowiri Member. No members are now recognized in the Yarragadee Formation.

The Yarragadee Formation of this report is a predominantly fluviatile deposit of discontinuous

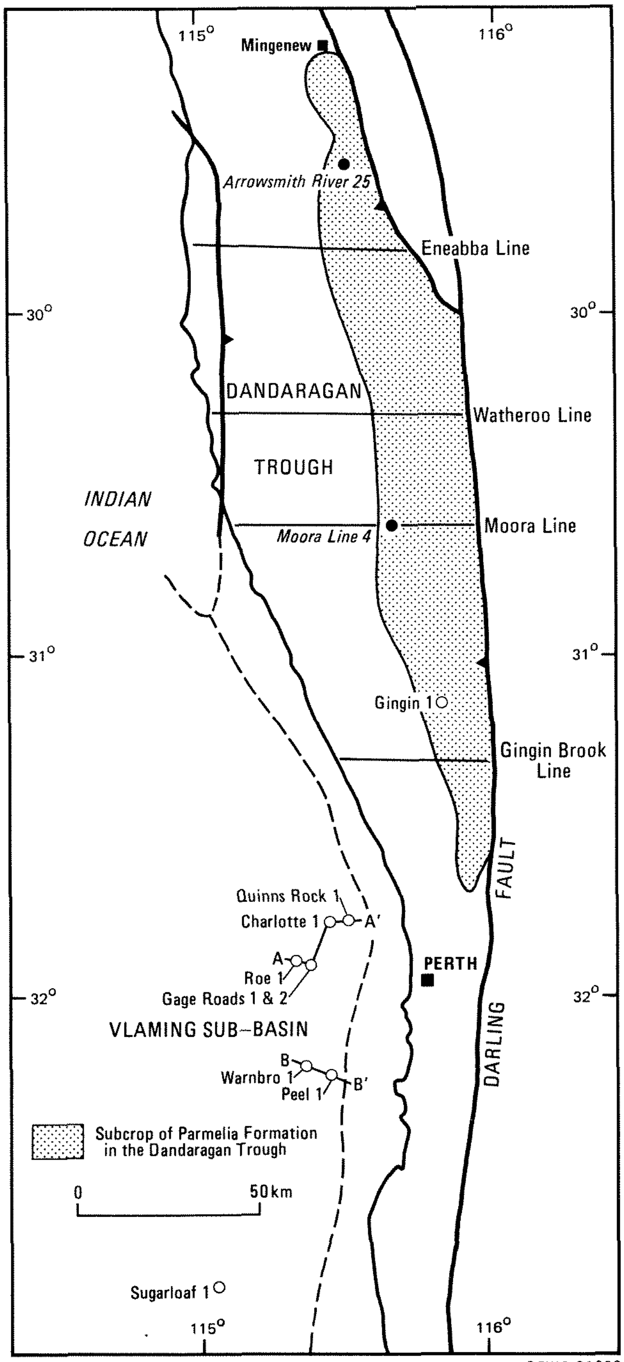

Figure 1 Location map showing boreholes and sections mentioned in text.

sandstone units and thin shale beds. The sandstone is predominantly medium grey to white, fine to coarse grained and poorly sorted. Carbonaceous stringers are common.

Biostratigraphy

Palynomorphs are the only frequently recorded fossils in the formation. Filatoff (1975) provided a palynological zonation for the Jurassic of the Perth Basin. In terms of this zonation, the Yarragadee formation ranges from the *Dictyotosporites complex* Oppel-zone up to, and including, the *Murospora florida* Microflora. Backhouse (1978) zoned the upper part of the Jurassic in the Dandaragan Trough. The *Retitriletes watherooensis*, and *Aequitriradites acusus* Zones of this zonation are in the Yarragadee Formation.

Age

The Yarragadee Formation ranges in age from Middle Jurassic (Bathonian) to Late Jurassic (Tithonian).

PARMELIA FORMATION

The name, Parmelia Formation, is proposed for the sediments between the top of the Yarragadee Formation, as redefined above, and the unconformity at the base of the Warnbro Group. It represents the last period of sedimentation in the Perth Basin before extensive block faulting of Jurassic and older sediments. This period of faulting was associated with the separation of southwestern Australia from the Indian plate. It was followed by rapid erosion of the freshly deposited sediments and by a marine transgression in the Valanginian which led to deposition of the Warnbro Group.

The type section of the Parmelia Formation is between 1 625 m and 3 551 m in Peel 1 (Lat. 32°15′47.8″S, Long. 115°26′43.0″E). Two members are recognized, the Otorowiri Member (formerly the "Otorowiri Siltstone Member" of the Yarragadee Formation), and the Carnac Member.

The Parmelia Formation is a sequence of sandstone, shale, and siltstone. The sandstone is light grey to white, fine to very coarse grained, moderately

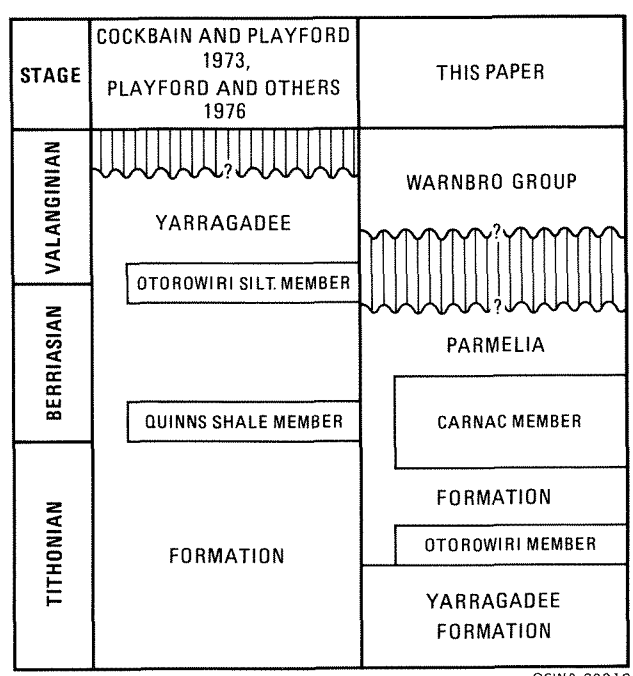

Figure 2 Revised nomenclature and age of the units.

to poorly sorted and contains subrounded to subangular grains in a kaolinitic or siliceous cement. Fragments of coal are incorporated in the sediments at some horizons. The shale is light grey, dark grey, or brownish grey, micaceous, carbonaceous, silty, and subfissile. The light-grey siltstone is usually present as thin laminae in the shale, but occasionally forms thicker beds.

The frequency of shale and siltstone beds varies vertically and horizontally. The Otorowiri Member at the base, and the Carnac Member in the middle of the formation are composed predominantly of siltstone and shale. The Parmelia Formation above the Otorowiri Member and below the Carnac Member contains silty shale beds from a few centimetres to several metres thickness, and is often similar in gross lithology to the Yarragadee Formation. Only two sections of the Parmelia Formation above the Carnac Member have been drilled: one is in Peel 1 (see below), and the other, in Charlotte 1 between 1 593 m and 2 164 m. Shale intervals in this section are infrequent, and usually thin.

A description of the type section of the Parmelia Formation in Peel 1 based partly on the unpublished well-completion report by Phillips Australian Oil Company is given below.

* * * * *

	Thickness
Warnbro Group 859-1 625 m	
Parmelia Formation 1 625-3 551 m	**1 926**
1 625-2 409 m Predominantly sandstone with a few thin shale beds. The sandstone is quartzose, white, light grey, or tan, poorly sorted, fine to very coarse grained and contains occasional pebbles. The grains are subangular to subrounded, and the cement is kaolinitic or siliceous. The shale is firm, dark grey, black, or brownish grey, micaceous, carbonaceous, and silty. Rare, thin coal seams are recorded	895
2 409-3 064 m (Carnac Member). Sandstone, siltstone, and shale continuously interbedded. The sandstone is white, light grey, or tan, fine to medium grained, and often well sorted. Individual grains are subangular to subrounded, and the cement is kaolinitic or siliceous. The siltstone and shale are medium grey, or brownish grey, firm, micaceous, carbonaceous, and sub-fissile. The siltstone forms lighter coloured laminae, or intergrades with the shale.	655.
3 064-3 505 m Predominantly sandstone with frequent thin to moderately thick (up to 5 m) siltstone and shale beds. The sandstone is white, light grey, or tan, fine to coarse grained, and poorly sorted. The grains are subangular to subrounded; the cement is kaolinitic, siliceous or, rarely, carbonaceous. The siltstone and shale are medium grey, black, or brownish grey, micaceous, carbonaceous, and occasionally pyritic..	441
3 505-3 551 m (Otorowiri Member) Shale with minor siltstone and fine-grained sandstone. The shale is medium grey or brownish grey, micaceous, carbonaceous, and often silty. Siltstone and fine-grained sandstone laminae are evident at some horizons................................	46
Yarragadee Formation 3 551-3 714 m	

* * * * *

The section in Moora Line 4 hydrogeological borehole between 0 and 484 m is suggested as a reference section for the Parmelia Formation in the Dandaragan Trough. A description of this section based partly on the unpublished borehole completion report is given below.

* * * * *

	Thickness
Top of formation removed	
Parmelia Formation 0-484 m	**484**
0-9 Lateritic clay, brown, yellow, and white	9
9-364 m (Carnac Member) Claystone and shale, medium-grey to brownish-grey, micaceous, carbonaceous, and silty, with thin beds of siltstone and fine grained sandstone.......................	355
364-428 m. As above, but with more sandstone. Sandstone fine- to coarse-grained, with clear and frosted quartz grains, and rare pyrite.	64
428-484 m (Otorowiri Member) Shale with minor siltstone. The shale is light grey or brownish grey, micaceous, carbonaceous, and sub-fissile. The siltstone is light grey or tan, and is present as fine laminae in the shale...................	56
Yarragadee Formation 484-732 m	

* * * * *

Otorowiri Member

The Otorowiri Member was originally defined as the Otorowiri Siltstone Member of the Yarragadee Formation by Ingram (1967b). The type section is in Arrowsmith River 25 (Lat. 29°33′25″S, Long. 115°32′00″E) between 253 and 277 m. As mentioned above, Backhouse (1975; 1978) considered it to be the same unit as the "Quinns Shale" of the Vlaming Sub-basin. Subsequent work has reinforced this view. The type section erected for the Quinns Shale in Quinns Rock 1 between 1 590 m and 1 647 m (Bozanic, 1969) is suggested as a reference section for the Otorowiri Member in the Vlaming Sub-basin.

The Otorowiri Member is a silty shale unit, locally with a substantial siltstone component. The shale is light grey, dark grey, or brownish grey, carbonaceous, sub-fissile, and usually very micaceous. Thin fine-grained sandstone laminae are sometimes present.

The outcrop of the Otorowiri Member can be traced between the Arrowsmith River boreholes and the Moore River (Commander, 1978; A.D. Allen, pers. comm.). Some of this outcrop may include part of the Carnac Member, which in this part of the basin almost immediately overlies the Otorowiri Member. In the Vlaming Sub-basin, the top of the Otorowiri Member is an important seismic horizon (Playford and others, 1976).

Carnac Member

The name "Carnac Formation" has been used extensively in unpublished Wapet reports to refer to a thick siltstone and shale unit encountered in offshore wells in the Vlaming Sub-basin. The Carnac Member of this report is defined as the section in Peel 1 between 2408 m and 3064 m. The lithology of this section in Peel 1 is described above. Elsewhere the Carnac Member is similar to the type section, where light-grey, medium-grey, or brownish-grey silty shale is the dominant lithology. Sandstone units within the Carnac Member are thinner than in the rest of the formation, and the sandstone is moderately well sorted. Shale beds are often pyritic. Siltstone and fine grained sandstone form numerous thin laminae in some sections. The thickest (1 262 m) drilled section is an incomplete section in Roe 1 between 872 m and 2 134 m.

Biostratigraphy

Spores, pollen, acritarchs, and dinoflagellate cysts are recorded in great abundance from sections now referred to the Parmelia Formation (Ingram, 1967a,b; Backhouse, 1974, 1975; 1978; and unpublished Wapet and GSWA reports). A change in the microflora occurs in all sections at the base of the Parmelia Formation with the first appearance in the Perth Basin of species of the schizaeaceous spore genus *Cicatricosisporites*, and a number of other spore species. This is the base of the *Biretisporites eneabbensis* Zone of Backhouse (1978). In terms of Balme's (1957, 1964) broad subdivision, the Parmelia Formation lies within the lower part of the *Microcachryidites* Assemblage. Over ninety species of spores and pollen are known from the Parmelia Formation as well as a small number of acritarch and dinoflagellate cyst species. The acritarchs are principally forms of *Schizosporis* Cookson and Dettman and *Schizophacus* Pierce. The dinoflagellate cysts include a species of *Fusiformacysta* Morgan. The only described species of *Fuziformacysta*, *F. salasii* Morgan from the Great Australian Basin, was regarded by Morgan (1975) as a non-marine cyst. The other dinoflagellate cysts are undescribed forms, some of which are abundant in parts of the formation. Marine dinoflagellate cysts of similar age, such as those present in the Barrow Formation in the Carnarvon Basin, are almost entirely absent. The only examples are a number of specimens in the Otorowiri Member, which may be recycled from late Jurassic deposits in the Carnarvon Basin. Abundant recycled palynomorphs of Devonian, Permian, Triassic, and Jurassic age have been reported from the Otorowiri Member (Ingram, 1967b). Early Permian, and Early Triassic forms are common in the remainder of the Parmelia Formation, but Late Permian, Late Triassic and Jurassic forms are rare. Devonian forms are only recorded from the Otorowiri Member in the Dandaragan Trough north of Eneabba.

Age

On palynological evidence, the age of the Parmelia Formation ranges from Late Jurassic (mid or late Tithonian) to Early Cretaceous (Berriasian). A considerable thickness of sediment was removed from horst blocks in the Vlaming Sub-basin before deposition of the Warnbro group commenced, probably no later than mid Valanginian. Deposition of the Parmelia Formation probably ceased no later than late Berriasian, and probably by the mid Berriasian. Using the time scales of van Hinte (1976a,b), the time interval available for deposition is no more than 8 m.y. and may be as brief as 5 m.y. These time intervals give an average rate of deposition for the type section of approximately 0.2 and 0.4 mm/year respectively. An average rate of deposition four times these rates is indicated for the area west of Roe 1, where on seismic evidence the formation is over 8 000 m thick.

Distribution

The Parmelia Formation is encountered in all the offshore oil-exploration wells drilled to date between Sugarloaf 1 in the south and Quinns Rock 1 in the north. It is thickest towards the continental slope west of Roe 1. Geological cross-sections of this area by Jones and Pearson (1972) and Playford and others (1976), based on unpublished seismic evidence, indicate over 8 000 m of section for the Parmelia Formation (indicated on these cross-sections as Lower Cretaceous and Early Neocomian respectively).

Cross-sections between Roe 1 and Quinns Rock 1 (Fig. 3B) and between Warnbro 1 and Peel 1 (Fig. 3C) illustrate the distribution of the Parmelia Formation in oil-exploration wells in the Vlaming Sub-basin.

The Parmelia Formation has been removed from the north-trending positive area which separates the Vlaming Sub-basin and the Dandaragan Trough. It subcrops on the eastern side of the Dandaragan Trough between Mingenew and the Upper Swan area northeast of Perth (Fig. 1), and is encountered in the Eneabba Line boreholes (Commander, 1978),

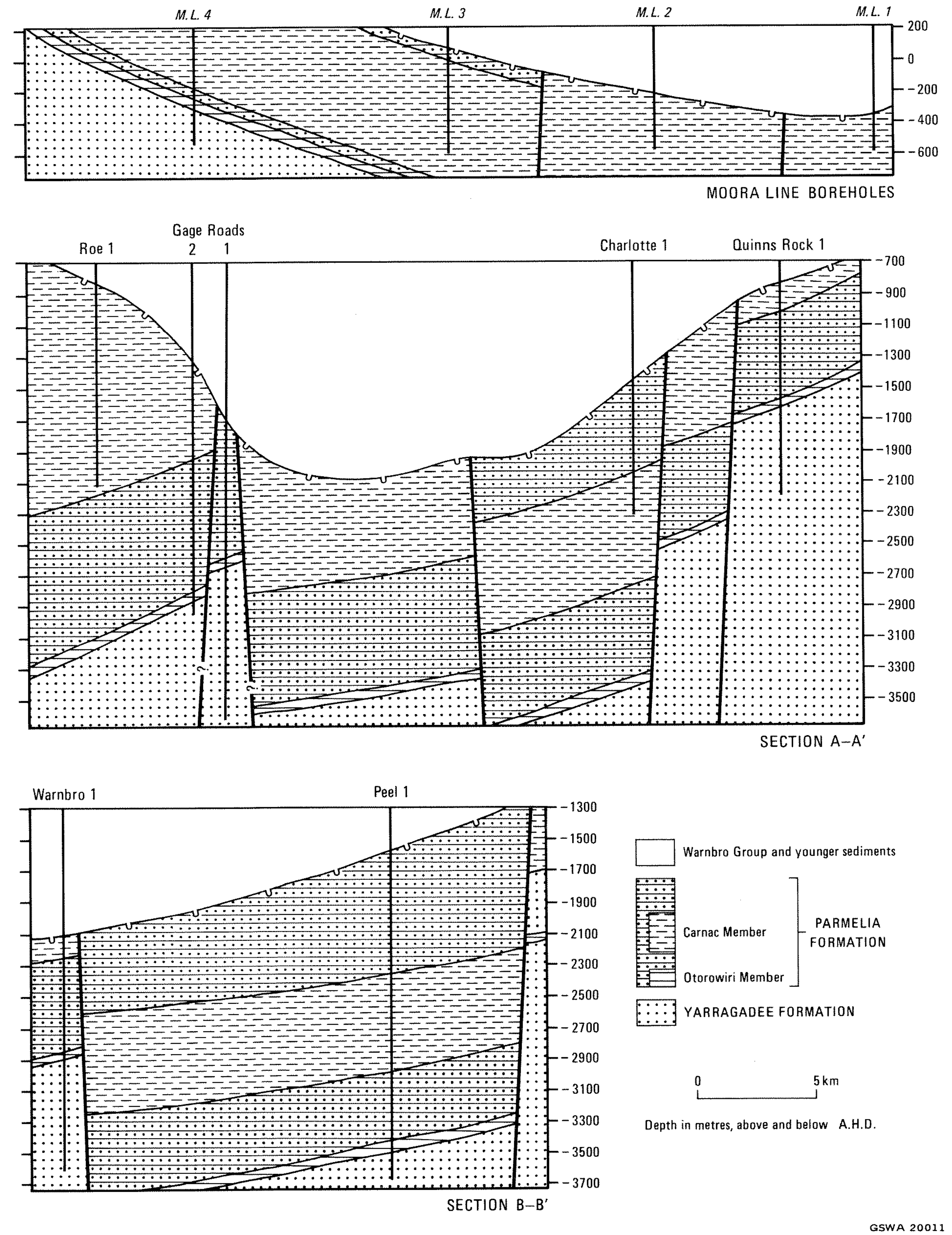

Figure 3 Geological cross-sections
A—Moora line boreholes B—Section A-B (*see* Figure 1 for location) C—Section C-D (*see* Figure 1 for location)

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the Watheroo Line boreholes (Harley, 1975), the Moora Line boreholes (Briese, 1979), and the Gingin Brook boreholes (Sanders, 1967). The maximum thickness in the Dandaragan Trough of approximately 900 m is attained in the vicinity of the Moora and Watheroo Line boreholes. A cross-section through the boreholes at the eastern end of the Moora Line illustrates the revised nomenclature in the Dandaragan Trough (Fig. 3A).

Environment of deposition

Jurassic sedimentation in the Perth Basin took place in a rapidly subsiding rift-valley system. Movement along the Darling Fault and associated smaller faults controlled the rate of subsidence on the eastern side of the rift valley; the western side, on the Indian plate, is no longer available for study.

The Yarragadee Formation was deposited as a mainly sandstone fluviatile deposit in the rift valley, with sediment input from a number of directions. The Otorowiri Member, at the base of the Parmelia Formation, represents a change to shale and siltstone deposition over most of the Vlaming Sub-basin and Dandaragan Trough. This took place in a large lake or marine embayment, possibly with a narrow northward connection to the sea.

In the Vlaming Sub-basin deposition of the Otorowiri Member was followed by a return to fluviatile sedimentation interspersed with intervals of local lacustrine deposition, and then by extensive lacustrine sedimentation with deposition of the Carnac Member. Evidence for the non-marine nature of these deposits is provided by the abundant non-marine dinoflagellate cysts. The upper part of the Parmelia Formation, above the Carnac Member, is a rapidly deposited fluviatile sandstone. Thin shale beds rich in non-marine dinoflagellate cysts represent brief periods of lacustrine deposition. This lithofacies is encountered in only two sections where the upper part of the Parmelia Formation has been preserved by faulting; its original extent is unknown.

In the Dandaragan Trough south of the Eneabba Line, lacustrine conditions continued after deposition of the Otorowiri Member. The lacustrine lithofacies represented by the Carnac Member immediately, or almost immediately, overlies the Otorowiri Member. In the Eneabba Line and in the Arrowsmith River boreholes alternating beds of sandstone and silty shale of fluvio-deltaic origin succeed the Otorowiri Member, suggesting a major sediment source to the north in the Dandaragan Trough.

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THE WAGGON CREEK FORMATION—AN EARLY CARBONIFEROUS SUBMARINE FAN DEPOSIT IN THE BONAPARTE GULF BASIN

by G. M. Beere

ABSTRACT

The Waggon Creek Formation is a submarine fan deposit in which two facies associations are recognized and related to deposition in separate areas of the fan. The lower coarse-grained association (40 m thick) consists of conglomerate, pebbly sandstone, and sandstone, deposited in an upper fan channel environment; and the upper fine-grained association (80 m thick) consists of sandstone and shale, deposited in the suprafan lobe area of the mid fan. The valley in which the formation now occurs may be an exhumed submarine erosion channel associated with the fan. Turbidity currents deposited most sediments. However, coarser deposits lack Bouma sequences and their texture, fabric and internal structures reflect differing sites of deposition within the channel. Minor depositional processes include debris flows in the coarse-grained facies association, and modification of turbidites by fluidization in the fine-grained facies association. Distinctive conglomerate clasts include Cambrian sandstone and dolomite transported several kilometres and laminated dolomite locally derived from the underlying Cockatoo Formation.

INTRODUCTION

In the southern Bonapart Gulf Basin, Veevers and Roberts (1966; 1968) mapped a unit of pebbly sandstone and conglomerate, which they named the Waggon Creek Breccia. They considered the unit to be unconformably overlain by sandstone tentatively correlated with the Point Spring Sandstone. Mapping in 1980 and 1981 by the Geological Survey of Western Australia has suggested that the lower conglomeratic unit and the upper sandstone unit are part of the same formation, here renamed the Waggon Creek Formation.

STRATIGRAPHY

The Waggon Creek Formation is a unit of conglomerate, pebbly sandstone, sandstone and shale occurring in the valley between the Ningbing Range and the Pretlove Hills (Fig 1). The type section of the Waggon Creek Formation (Section C) is 86 m thick, the lower 40 m of which corresponds with Veevers and Roberts (1966) type section for the Waggon Creek Breccia (their thickness is stated as 56 m). Section B (120 m) thick is here designated as a reference section (Fig. 1).

The formation consists of a lower coarse-grained facies association of conglomerate and pebbly sandstone, which corresponds to Veevers and Roberts' 'Waggon Creek Breccia' and an upper fine-grained facies association of sandstone with minor shale, mapped by them as ?Point Spring Sandstone. The two facies associations are here included in an enlarged Waggon Creek Formation because:

1. there is no field evidence for any discontinuity between them;
2. there is lithological unity throughout the formation; and
3. the fine-grained facies association bears little resemblance to the typical Point Spring Sandstone, which outcrops 20 km to the east.

The Waggon Creek Formation is at least 120 m thick. It unconformably overlies sandstone with very thick dolomite beds of the Hargreaves Member of the Cockatoo Formation. The top of the unit is nowhere exposed.

Part of the formation occupies a channel cut into the Hargreaves Member. In the westernmost exposure (Fig. 1) the channel is about 150 m wide and a few tens of metres deep; 2 km to the east it widens to about 700 m, but the base is not exposed.

Brachipods and bivalves in the formation suggest a mid-Visean (Veevers and Roberts, 1966) to late-Visean (Veevers and Roberts, 1968) age. Early Carboniferous shale (Jones, 1958) is present in boreholes in the valley (Fig. 1), but its precise stratigraphic relationship with the Waggon Creek Formation is not known. The shale may correlate with mid-Visean shale (A. J. Mory pers. comm. 1982) beneath Burvill Beds 14 km to the northeast, and with the Milligans Beds in the eastern part of the basin. Consequently, the Waggon Creek Formation may correlate wth part of the Milligans Beds (Fig. 2).

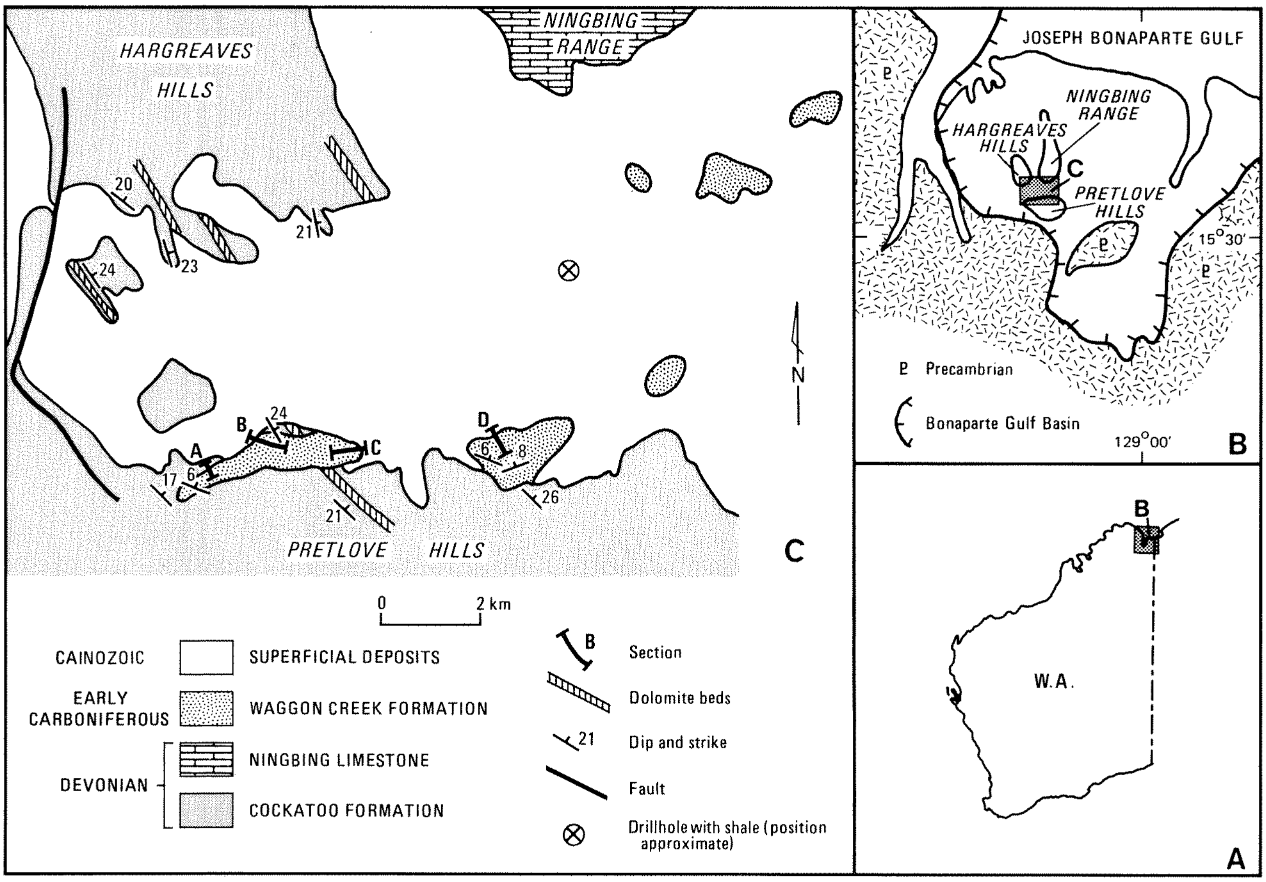

Figure 1. Location of the Bonaparte Gulf Basin (A, B) and geological map of the Waggon Creek area (C). Sections A, B, and C are in the "Waggon Creek Breccia", and section D the "mid-Tournaisian breccia" (Veevers and Roberts, 1968). Most other outcrops of the Waggon Creek Formation were originally mapped as Point Spring Sandstone.

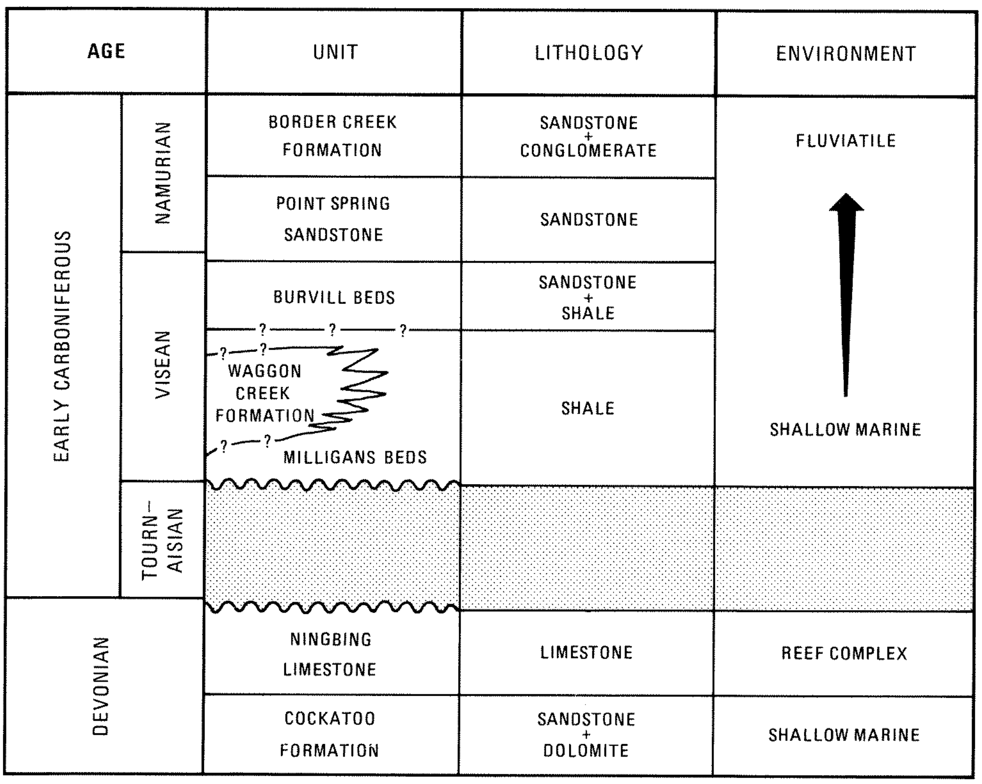

Figure 2. Stratigraphy, lithology and environmental interpretation of the sequence in the Waggon Creek area (modified from Veevers and Roberts, 1968).

A mid-Tournaisian age (Veevers and Roberts, 1966) has been ascribed to exposures on the southern side of the outcrop area (Fig. 1). These rocks are lithologically similar to the Waggon Creek Formation and are here tentatively assigned to that formation. The older age may be due to a reworked fauna, but if so, it is not clear why a Tournaisian fauna has not been recovered from other outcrops.

Preliminary interpretation of field data suggests the Early Carboniferous sequence above the Milligans Beds is a shallowing sequence, probably associated with delta progradation. The clay mineralogy in Milligans Beds suggests it was deposited in a nearshore environment (Veevers and Roberts, 1968, p. 136).

FACIES DESCRIPTION

Four sections were examined in the two main outcrops (Fig. 3). One complete section (B) was examined through the central part of the western outcrop. Section C is located near the original type section of the "Waggon Creek Breccia". Because exposure consists mainly of tumbled blocks up to several metres in diameter, with rare *in-situ* exposure, only diagrammatic facies are shown in the sections in Figure 3. Weathered shale horizons are believed to control the nature of outcrop, and a qualitative estimate of the shale content was made according to the "rubbliness". Facies thicknesses were estimated by plotting keypoints identified on aerial photographs onto the 1:100 000 Carlton topographic sheet. Two major facies associations containing seven facies are recognised (Table 1).

Coarse-grained facies association

This facies association is at least 40 m thick and is characterized by pebbly sandstone and conglomerate with shale fragments and locally abundant dolomite clasts. Erosive bases are common and shale horizons may be a minor part of the corase-grained facies association. Dolomite cementation occurs in coarser parts of the unit. Facies include bedded conglomerate (both matrix supported and clast supported), massive and normally graded pebbly sandstone, and interbedded conglomerate and sandstone with interbeds both well-defined and gradational (Table 1.). Thin- and thick-bedded sandstone, and massive sandstones are present but are more typical of the fine-grained facies association. Individual facies within the association do not have consistent vertical sequences or thicknesses between sections, a factor which indicates lensoidal distribution (Fig. 3). Abraded dolomite cobbles and boulders up to 0.7 m in diameter include stromatolitic, oolitic, laminated, massive and sandy types, and a single cobble of the coral *Syringopora*. Large boulders up to 15 m diameter of laminated dolomite occur in the lower parts of sections B and C. A block of sandstone with trilobites occurs near the base of section C.

Fine-grained association

The fine-grained facies association is up to 80 m thick and characterized by medium- to fine-grained massive and bedded sandstone showing sole markings. Shale horizons form an important part of this association. Individual facies within this association include massive sandstone, thin and thick bedded structured sandstone, and shale (Table 1). Thick bedded structured sandstone, only occurs at the base of section D in the coarse-grained facies association.

DOLOMITE CLAST PROVENANCE

The provenance of dolomite clasts in the Waggon Creek Formation yields important clues to transport and depositional processes. Pre-Early Carboniferous dolomites in the Bonaparte Gulf Basin are common at several levels in the Devonian Hargreaves Member of the Cockatoo Formation, and also within the Cambrian Skewthorpe Formation.

Hargreaves Member dolomites include laminated dolomite and intra-clast breccia dolomite. Oncolitic and brachiopod dolomites are uncommon. Stromatolitic dolomite is rare and occurs mainly as gently convex laminae. Venvers and Roberts (1966) also report oolitic dolomite.

Laminated dolomite clasts in the Waggon Creek Formation are similar to dolomites in the Hargreaves Member. The large boulders of laminated dolomite occur near outcrops of the underlying Hargreaves Member and are probably locally derived.

The Cambrian Skewthorpe Formation includes oolitic dolomite and dolomite with well-formed columnar stromatolites similar to those found in the Waggon Creek Formation. Additionally, the boulder of sandstone with trilobite fragments in section C is similar to the Cambrian Clarke Sandstone. Cambrian rocks outcrop in a belt to the west and south, and the Cambrian boulders in the Waggon Creek Formation are at least 3 km from a possible source.

DEPOSITIONAL PROCESSES

Most facies in the Waggon Creek Formation lack traction-developed structures (cross-stratification, plane bedding) and a mechanism is needed to account both for this and the transportation of large clasts over a distance of several kilometres. The presence of some Bouma sequences and sole marks

TABLE 1:
FACIES DIVISION AND CHARACTERISTICS IN THE WAGGON CREEK FORMATION

Facies Association	COARSE-GRAINED			FINE-GRAINED			
Facies	CONGLOMERATE	INTERBEDDED CONGLOMERATE AND SANDSTONE	PEBBLY SANDSTONE	MASSIVE SANDSTONE	THICK STRUCTURED SANDSTONES	THIN STRUCTERED SANDSTONES	SHALE
Thickness	<15 m	<10 m	<10 m	30 m in F.F.A. 10 m in C.F.A.	10 m in C.F.A.	25 m in F.F.A. 15 m in C.F.A.	—
Bed Thickness	0.2-1.5 m	0.5-1.0 m	0.3-1.5	0.5-1.5 m	1-1.5 m	5-30 cm	—
Texture	Pebble to boulder clast- and matrix-supported Subangular to sub-rounded clasts	*Conglomerate* Clast to sand supported *Sandstone* Coarse to fine	Pebbly, fine to medium sandstone, Moderate to poor sorting	Fine to coarse, Well to poorly sorted	Medium to fine, Moderately sorted	Fine to medium Rare coarse sand and pebbly conglomerate	Sandy
Sedimentary Structures	Layered Moderately sorted, coarse tail, Internally massive, Grading, imbrication absent, Irregular upper and lower contacts, Tabular clasts define parallel stratification, Rare vertical tabular clasts	Well defined or gradational interbedding, *Conglomerate* Erosive base, massive bedded basal unit, minor horizontal stratification, or rare cross-stratified tops. *Sandstone* Stronger lamination with finer grainsize, rare thin cross-bedding, coarse sand to granule lag	Massive, or coarse tail fining upward, grading, Erosive and non-erosive base, Rare parallel laminated to low-angle cross-stratified top, Dolomite cementation	Massive, Minor sole marks (including scours and tool marks), Erosive base, pebble base, Distribution grading, lag conglomerate Rare dish structure, Laminated and interference rippled tops, Poor cross-bedding	Incomplete Bouma sequences: Massive, graded base to diffuse lamination to strong lamination to interference rippled top, shale Sharp non-erosive base, undulating tops	Massive, Sole marks common (flutes and tool marks), Minor normal grading, ripple cross lamination, thin parallel bedding, interference ripples Rare ferruginized shale concretions	Horizons of yellow-brown concretions
Clasts	Local boulders to 15 m, quartzite <15 cm, shale <20 cm, dolomite <70 cm, Q>S>Dol	Quartzite, shale, dolomite, <15 cm	Quartzite <12 cm, shale locally abundant, dolomite rare	Quartzite pebbles and shale cobbles in C.F.A.	Small pebbles of quartzite and shale at base	—	—
Fossils	—	Fragmented	Fragmented	Wood fragments (F.F.A.) brachiopods and crinoids (C.F.A.)	—	Wood fragments in sandstone, fragmented fauna in shale	Brachiopods gastropods fish plates

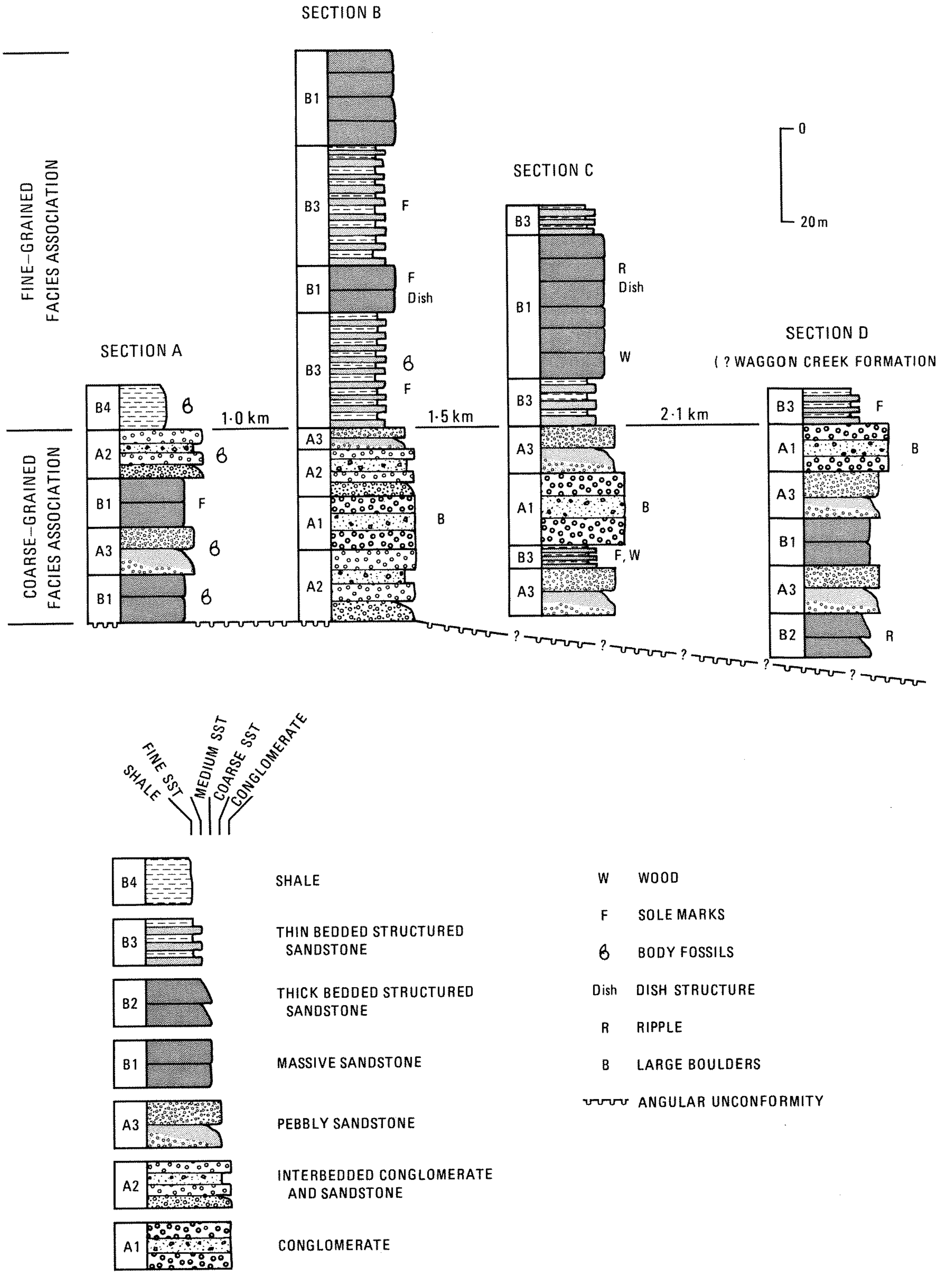

Figure 3. Diagrammatic facies distribution in the Waggon Creek Formation. Facies in the coarse-grained facies association are more lenticular than in the overlying fine-grained facies association. Section D was originally mapped by Veevers and Roberts (1968) as mid-Tournaisian breccia.

suggests turbidity current or other related mass-gravity flows (Middleton and Hampton, 1973). In the following section depositional processes for each facies are interpreted.

Structured Sandstone

The sequence of structures in the thick-bedded structured sandstone includes incomplete Bouma sequences (Rupke, 1978) which were probably deposited by turbidity currents. Most beds in the thin-bedded structured sandstone do not show the Bouma sequence, but have individual features such as sole marks, graded bedding, massive bedding, and ripple cross-lamination suggesting turbidity current deposition.

Massive Sandstone

Scour- and tool-marked bases, a normally graded basal unit and some poorly developed traction current structures at the top of beds, indicate turbidity-current deposition. The lack of internal structures in massive sandstone beds is believed to be due to their degradation by grain collision and a gentle escape of pore fluids in the final phase of deposition (Walker, 1978). Dish structures are thought to be a dewatering feature (Walker, 1978) and those in the Waggon Creek Formation were probably formed by a relatively rapid fluid loss.

Graded pebbly sandstone and interbedded conglomerate and sandstone

Structures in these rocks reflect typical turbidity-current deposition. In a turbidity current, initial rapid deposition from suspension is followed by slower deposition from traction currents (Middleton and Hampton, 1973). Structures in the interbedded conglomerate and sandstone best reflect this sequence of depositional processes, starting with a massive conglomerate at the base, passing up into stratified pebbly sandstone, followed by increasingly fine-grained sandstone with lamination or, rarely, crossbedding, Well defined interbeds of massive conglomerate and structured sandstone suggest either interrupted deposition from different regions of a turbidity current, or the stacking of deposits from turbidity currents of different loads or flow conditions. The presence of lag deposits within some of the sandstone supports the first hypothesis.

Bedded conglomerate

Clast-supported conglomerate lacking internal structure or fabric is similar to Walker's (1978) disorganized bed conglomerates which he believed formed as a lag during rapid deposition on relatively steep slopes. Alternatively a sharp decrease in competence of a current at a marked change in slope may cause rapid deposition of the coarser part of the load, and inhibit the development of structures. Bedding in the Waggon Creek Formation conglomerate is defined by changes in texture and clast composition. Beds defined by a particular clast type have undergone sorting of the coarse fraction. Given a similar provenance, different flow conditions and sorting within a turbidity current will produce such bedding. Matrix-supported conglomerate and massive conglomerate capped by irregular boulder beds are probably debris-flow deposits. These are typically matrix supported, massive (Middleton and Hampton, 1973) and characterized by upward projecting clasts at the top of a bed (Walker, 1978). Debris flows may also account for the formation of the U-shaped channels in pebbly sandstones described by Veevers and Roberts (1966) from the base of section C (not re-located in this study).

DEPOSITIONAL ENVIRONMENT

Turbidity-current and debris-flow deposition are common in submarine fans but are also known from lacustrine environments (Collinson, 1978). The stratigraphic setting of the Waggon Creek Formation within a marine sequence renders a submarine fan environment more probable. Each facies in the formation can be related to the submarine fan model proposed by Walker (1978).

Coarse-grained Facies Association

The coarse-grained facies association is interpreted as a channel deposit on an upper fan. The well-defined channel in the western parts of the outcrop, filled with conglomerate and pebbly sandstone, suggests deposition near the fan head. Bedded conglomerate and massive pebbly sandstone rapidly deposited by turbidity currents, and debris-flow conglomerate were probably deposited in the deepest part of the channel. The coarse-grained facies, representing slower turbidity-current deposition, (interbedded conglomerate and sandstone, graded pebbly sandstone, thick-bedded structured sandstone), were deposited above the channel floor on terraces. Lenses of flaggy sandstone represent overbank turbidity-current deposition on levees flanking the channel. Abundant shale clasts suggest lateral migration of channels with reworking of most overbank shales into the channel deposits. Similarly, some dolomitic sandstone clasts were derived from early-cemented overbank sandstones.

Large laminated dolomite blocks were locally derived from the underlying Cockatoo Formation; however, it is not known how far, if at all, they were transported. The blocks could have been eroded from the floor and sides of the channel, and left as a lag. Alternatively, slides and debris flows (Rupke, 1978) can transport boulders and the large boulders in the Waggon Creek Formation may have been transported by a slide or debris flow from higher up the feeder channel.

Fine-grained facies association

The fine-grained facies association is interpreted as a suprafan lobe deposit in the mid-fan area. Massive sandstone, deposited by a combination of turbidity current and fluidized flow, represents a braided channel deposit. Thin-bedded sandstone was deposited by overbank turbidity currents in interchannel areas. Shales accumulated in areas not affected by clastic input from turbidity currents.

PALAEOGEOGRAPHY

The Waggon Creek Formation occurs near the base of a basin-fill sequence of nearshore shale, shallow marine sand, and fluvial sand. Ancient submarine fans are associated with shallow-water facies in three settings (Rupek, 1978): (a) a prograding delta-front fan in relatively stable tectonic conditions; (b) slope instability at a delta front; and (c) slope instability and local topographic relief produced by basin-margin faulting. Coarse-grained turbidite deposits are found in the last two settings, and conglomerate is associated with basin-margin faulting.

Although the Waggon Creek Formation (and Milligans Beds) is overlain by probable deltaic sediments, the conglomerates of the Waggon Creek Formation suggest a faulted basin-margin setting. In a comparable setting in the Eocene-Oligocene of the Santa Ynez mountains of California, conglomeratic turbidites were initially deposited at the toe of a steep, non-depositional slope formed by faulting. This lay seaward of, and separate from, a shallow water environment (van de Kamp and others, 1974). In time the separate environments were connected as the basin became shallower. Similarly, in the Bonaparte Gulf Basin, Early Carboniferous deltaic sediments above the Milligans Beds may have been deposited on the shallow shelf, and the Waggon Creek Formation deposited at the toe of the slope. As the basin shallowed, the shelf sediments prograded over the Waggon Creek Formation and Milligans Beds. Cambrian clasts in the Waggon Creek Formation were derived from the west, suggesting faulting in this direction.

The Waggon Creek Formation occupies a valley between the Ningbing and Pretlove Hills. Laws (1981) suggested that the northern side of the valley represented the original depositional edge of the Devonian carbonate platform. Fluviatile erosion in the Early Carboniferous has also been postulated (Veevers and Roberts, 1966). However, interpretation of the Waggon Creek Formation as submarine fan and the channel form of the westernmost outcrop suggests that the valley may have formed by submarine erosion in the Early Carboniferous.

CONCLUSION

The Waggon Creek Formation is an Early Carboniferous coarse-textured submarine fan, associated with shallow marine shale and sandstone of a basin-fill sequence. Distinctive boulders of Cambrian stromatolitic and oolitic dolomite, and sandstone with Cambrian trilobites were derived from several kilometres to the west of the present Waggon Creek Formation outcrop, suggesting that the fan developed in response to faulting in the area to the west. Two facies associations are recognized in the Waggon Creek Formation. The lower coarse-grained facies association was deposited in an upper fan channel, and is characterized by conglomerate and pebbly sandstone. Thin- and thick-bedded structured sandstone and massive sandstone are also present. Turbidity currents deposited most facies, and the texture, fabric and internal structures of each facies depended partly on its site of deposition within the channel, and partly on the flow regime of each turbidity current. Debris flows were probably important in depositing matrix-supported conglomerate and pebbly sandstone. Boulders of laminated dolomite up to 15 m in diameter were locally derived from the underlying Devonian Hargreaves Member of the Cockatoo Formation. Abundant reworked shales suggest lateral channel migration.

The overlying fine-grained facies association of thin-bedded structured sandstone and shale, and massive sandstone were deposited in the mid-fan area, in interchannel and braided channel environments respectively. Turbidity currents were the main depositional process but massive sandstones were probably affected by late stage fluidization.

The valley now occupied by the Waggon Creek Formation may have been formed by submarine erosion associated with the fan in Early Carboniferous time.

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GEOCHEMISTRY OF ARCHAEAN METABASALTIC LAVAS, DIEMALS, WESTERN AUSTRALIA

by

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ABSTRACT

The Archaean sequence of Diemals (Southern Cross Province of the Yilgarn Block) contains a variety of metabasalts ranging in composition from tholeiites to high-magnesian basalts. Thirty new analyses, covering both major and trace elements (as well as rare-earth-element (REE) analyses for two of the samples), are presented. Four distinctive rock groups can be recognized: (1) a low-TiO_2 tholeiitic group (8-10% MgO); (2) a low-MgO (6-8%) group characterized by ocelli textures; (3) a spinifex-textured high-TiO_2, high-MgO (10-18% MgO) group, in which sprays of amphibole pseudomorph clinopyroxene; and (4) a low-TiO_2, high-MgO (8-11%), spinifex-textured group. Apart from the ocelli-textured group, the metabasalts all display consistent chemical characteristics which allow the subdivisions to be made. Group 3 and 4 are texturally similar to rocks commonly referred to as komatiitic basalts, but their geochemistry prohibits derivation from komatiites. In particular, their low-Ti/Zr (<75) and light-REE enrichment are difficult to model by fractionation of olivine and/or clinopyroxene from a komatiitic liquid. Conversely, the low-TiO_2 tholeiites (group 1) could be the fractional crystallization products of komatiites. It is argued that those basalts displaying spinifex-type pyroxene textures (i.e. groups 3 and 4) represent close-to-primary melt compositions; the differences in MgO and TiO_2 contents being controlled by depth and amount of melting. A further characteristic of these two groups is their high SiO_2 contents and it is suggested that this is due to the presence of H_2O during melting. Since the term 'komatiitic basalt' has a genetic connotation, its use should be restricted to those basalts whose geochemistry demonstrates the linkage to komatiite melts. In the case of the Diemals metabasalts, it is the tholeiites which best fit this criterion.

INTRODUCTION

Detailed geochemical studies of Archaean metabasaltic lava sequences in the last decade (e.g. Hallberg, 1972; Hart and others, 1970; Nesbitt and Sun, 1976) have served to provide a comparative data base for genetic models of Archaean crustal evolution. Despite this work, there is still no clear picture of the genetic relationships between komatiites (i.e. sub-alkaline, volcanic rocks with >18% Mg0), komatiitic basalts (i.e. sub-alkaline, 10-18% Mg0 basalts associated with komatiites), high-magnesian basalts (i.e. sub-alkaline, 10-18% Mg0 basalts) and tholeiites (in the sense of Hallberg, 1972).

The confusion over magmatic genetic links is compounded by the combined effects of the mineralogical, chemical and textural overprinting suffered by Archaean sequences. This overprinting varies from place to place both in its intensity and nature, with some areas retaining much of the texture and mineralogy of the original rocks whilst others have been completely recrystallized and chemically altered.

Despite these problems, several models have been generated which seek to explain the genesis and genetic linkage of the komatiite-basalt spectrum. These models are commonly based on field, petrographic and geochemical data obtained from well-documented, well-preserved areas and in particular the Munro Township area, which has tended to dominate current thinking (e.g. Pike and others, 1973; Arndt and others, 1977). The basic model developed from work at Munro is one in which high-magnesian liquids (about 28-30% MgO) fractionate through olivine loss, to high-magnesian basaltic rocks (komatiitic basalts). In this model, the associated tholeiites are either totally unrelated or represent inital melts removed from the ultimate source of the komatiites (e.g. Naldrett and Turner, 1973). In an alternate model, Sun and Nesbitt (1978a) suggested that komatiitic basalt, (particularly those with pyroxene spinifex texture) are primary melts and are not the products of komatiite fractionation. A possible corollary of this model, which was not stated by Sun and Nesbitt (1978a), is that there is a relationship between komatiites *s.s.* and tholeiites, in that the latter are the fractional crystallization products of the former. This model has also been proposed by Francis and Hynes (1979) for the Proterozoic basaltic sequence of Ungava, and in this paper we present data which supports this genetic linkage.

For the purpose of field description, we will use the term high-magnesian basalt for those rocks having MgO between 8 and 18%. Within this group, we arbitrarily refer to those basalts with pyroxene spinifiex texture as komatiitic basalts. Such basaltic types are common in parts of the Australian Archaean, e.g. the upper hanging-wall basalts at Kambalda (Ross and Hopkins, 1975), the Negri Volcanics in the Pilbara (Sun and Nesbitt, 1978a) and parts of the Mount Monger sequence (Williams, 1972). Tholeiitic metabasalts in this area commonly have 6-9% MgO and have typical basaltic textures, characterized particularly by the presence of plagioclase laths. They always lack pyroxene spinifex texture and tend to be higher in Al_2O_3 than the high-magnesian basalts.

FIELD AND PETROLOGICAL RELATIONSHIPS

In this study, we have investigated a series of basaltic rock-types from a well-established stratigraphic section at Diemals. The area is about 200 km by road, north of Southern Cross and occurs within the Southern Cross Province (Gee and others, 1981) of the Yilgarn Block. Structurally the area is dominated by an open south-plunging antiform, the Diemals antiform (Fig. 1) which folds a volcanic succession of basalts, overlain by banded iron-formation, fine-grained metasediments and silicic volcanics. These lithologies. have been metamorphosed to greenschist-low amphibolite facies of regional metamorphism. This metamorphism was of a static style and hence there is good preservation of original textures. At Diemals, the massive komatiitic metabasalts form a volcanic pile up to 1.1 km thick (best seen west of the Diemals air-strip) and are characterized by flows with pyroxene spinifex-textured flow tops which grade down into massive cumulate zones. We shall refer to these as Group 3 basalts. In parts, these basalts develop spherical ocelli (Group 2 basalts), which elsewhere (e.g. Gelinas and others, 1976) have been attributed to liquid immiscibility. Medium-grained metabasalts of tholeiitic type conformably overlie the komatiite basalts and these have a thickness of 2.2 km in the core of the antiform (Group 1). On the west limb of the antiform and apparently overlying the tholeiitic sequence is a sequence of komatiitic basalts which we informally refer to as 'west limb basalts' (Group 4).

Large sills and dykes of medium- to coarse-grained metadolerites and gabbros intrude the various lithologies of the succession. These have not been studied in this investigation.

Petrographically, Group 1 basalts (samples 63654-63659) are characterized by their even-grained nature. Typically they consist either of randomly oriented fine-grained sheaves of tremolite-actinolite interspersed with plagioclase laths (e.g. 63654) or a slightly coarser grained (up to 0.7 mm) rock with well-developed basaltic texture (e.g. 63655, 63656). In this second category plagioclase reaches 40-45%. Both textural types have small amygdales, infilled with epidote and chlorite. Sample 63652 is fine-grained (grain size is about 0.1 mm) and in thin section displays fine-scale layering. We interpret this material to be tuffaceous. Mineralogy of this specimen is difficult to positively identify, but tremolite-actinolite and epidote are certainly present.

Group 2 basalts (63660-63664) consist of a group of ocelli-textured basalts which present a sampling problem as far as geochemistry is concerned. Sample 63660 has obvious spherical ocelli about 2 mm in diameter, consisting of a micrographic intergrowth of tremolite-actinolite and clear plagioclase. The matrix of the rock is made up of a fine-grained (about 0.3 mm) mass of tremolite-actinolite sheaves with minor plagioclase. The remaining 4 samples have less conspicuous ocelli and are characterized by skeletal plagioclase laths and needles, sometimes occurring in radial form. In these rocks (65661-64) the amphibole (tremolite-actinolite) occurs in stubby form (after clinopyroxene).

The dominant texture in the nine samples of the Group 3 basalts is one of random needles to stubby crystals of tremolite-actinolite set in a matrix of the same material plus clear plagioclase. In some samples, spectacular amphibole (after clinopyroxene) sprays are developed and we refer to these as 'clinopyroxene spinifex texture'. Commonly, the grain size of the sprays shows a progressive decrease of polarity, reminiscent of the spinifex texture (Nesbitt, 1971) found at the tops of komatiite flows. It is this pyroxene texture which is often taken to be diagnostic of komatiitic basalts.

Group 4 (63674-63678) basalts come from the western limb of the Diemals antiform. Some of the samples (particularly 63675 and 63676) have an impressive development of the spinifex or radiating pyroxene (now amphibole) texture, seen in the Group 3 basalts. Plagioclase is always present and is of variable abundance (20-40%). Sample 63678 is coarser grained, with the amphibole being of a stubby nature. We interpret this rock type as being a cumulate.

GEOCHEMISTRY

Twenty-eight rocks have been analyzed for this investigation. All, with the exception of 59546 came from the Diemals area; and in Table 1, they are listed as belonging to one of four groups. Sample 59546 is a komatiite with characteristic altered olivine plates from Mount Manning, some 45 km to

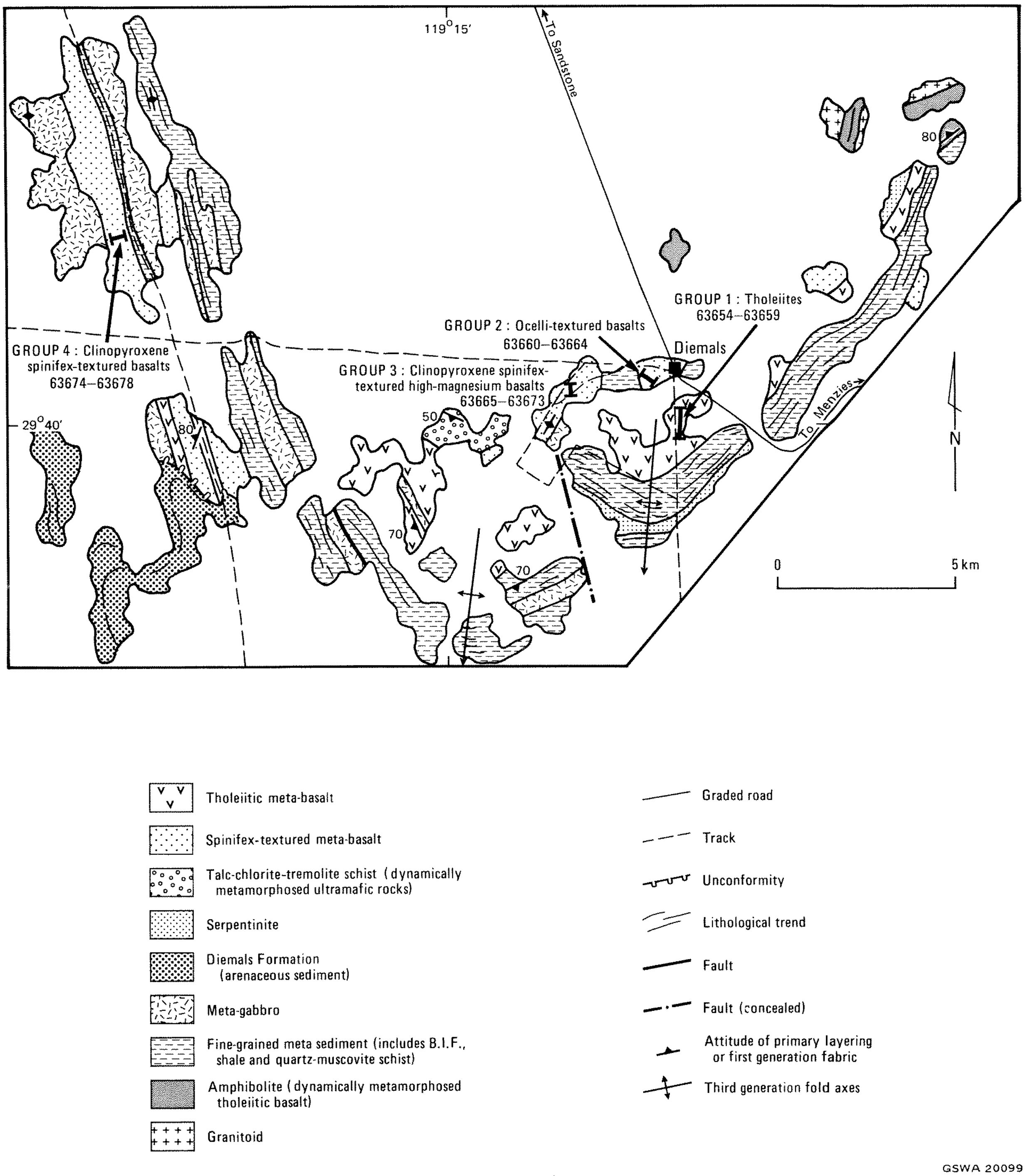

Figure 1. Geological map of Diemals area showing sample locations.

the southeast of Diemals and was analyzed for comparative purposes (Table 1). Because of textural changes across this specimen, three separate slabs were cut off and analyzed (a, b, c). As Table 1 indicates, the textural change (largely changes in morphology of olivine) is not strongly reflected in the geochemstry.

MAGNESIUM-TITANIUM

The trends for these two elements are well established for komatiitic and tholeiitic rocks (Nesbitt and Sun, 1976). MgO concentration reflects the dominance of olivine (clinopyroxene) and can be envisaged as a fractionation and/or partial-melt indicator. TiO_2 reflects the general behaviour of those elements commonly referred to as 'incompatible'. Figures 2A and B illustrate the behaviour of these elements for those basalts analyzed by Hallberg (1972) and for those from Diemals (A and B resepctively). Figure 2A illustrates the spread in the Hallberg data, with specific localities clustering in different parts of the diagram. There is little doubt that these basalts

TABLE 1. GEOCHEMICAL DATA FOR DIEMALS BASALT AND MOUNT MANNING SPINIFEX-TEXTURED KOMATIITE

	Mt Manning Komatiite			Group 1 Tholeiites						Group 2 Ocelli-textured basalts				
	59546A	59546B	59546C	63654	63655	63656	63657	63658	63659	63660	63661	63662	63663	63664
SiO_2	50.93	50.93	50.72	52.09	52.75	53.66	52.66	53.00	53.22	56.94	54.45	53.05	54.26	53.60
Al_2O_3	9.88	9.60	10.26	13.75	13.52	13.35	11.36	14.46	13.35	9.22	13.41	12.61	12.87	11.93
Fe_2O_3	11.20	11.61	10.89	10.87	10.85	10.35	12.78	10.79	13.06	12.18	12.03	12.66	11.57	12.73
MnO	0.17	0.19	0.16	0.17	0.17	0.18	0.22	0.19	0.17	0.22	0.20	0.18	0.19	0.22
MgO	17.53	18.07	16.98	9.22	8.96	8.74	10.03	8.02	6.50	6.45	6.28	8.12	6.58	6.02
CaO	7.49	6.90	7.86	9.85	9.85	9.96	9.90	10.51	8.89	12.76	8.48	8.35	9.77	10.85
Ma_2O	2.09	2.01	2.16	3.36	3.20	3.37	0.68	2.20	3.34	1.05	4.03	3.78	3.71	3.74
K_2O	0.16	0.15	0.14	0.12	0.08	0.08	0.90	0.39	0.09	0.11	0.13	0.12	0.14	0.15
TiO_2	0.40	0.37	0.41	0.62	0.64	0.60	1.31	0.64	1.19	1.09	1.04	1.20	1.08	0.97
P_2O_5	0.06	0.07	0.05	0.10	0.09	0.08	0.13	0.09	0.12	0.12	0.13	0.13	0.13	0.11
Total	99.91	99.90	99.63	100.15	100.11	100.37	99.97	100.29	99.93	100.14	100.18	100.20	100.30	100.32
Loss	1.68	1.99	1.72	1.86	2.05	1.75	2.76	1.62	1.95	0.95	1.59	1.85	1.25	0.58
Zr	24	n.d.	n.d.	40	43	40	83	43	78	84	80	89	81	77
Nb	1	n.d.	n.d.	1	2	3	4	1	4	4	4	6	4	5
Rb	4	4	4	2	1	2	17	9	2	2	2	2	2	2
Sr	145	130	133	85	35	34	66	175	42	106	51	55	58	59
Y	11	11	12	18	18	17	22	19	24	38	38	28	30	24
Ba	70	96	35	48	33	36	543	149	15	29	45	65	61	60
Sc	36	35	39	48	44	42	38	46	41	42	37	46	39	39
Ni	419	485	436	108	134	135	159	114	92	85	95	142	98	61
Cr	1852	1826	1787	494	598	549	479	340	169	120	95	206	114	285
V	199	192	206	266	244	234	304	257	303	276	279	313	276	271

	Group 3 Clinopyroxene spinifex-textured high-magnesian basalts											Group 4 Clinopyroxene spinifex-textured basalts				
	63665	63666A	63666B	63666C	63667	63668	63669	63670	63671	63672	63673	63674	63675	63676	63677	63678
SiO_2	52.94	50.53	52.66	51.95	53.10	53.18	53.28	52.58	51.67	51.29	49.40	49.22	54.24	52.83	52.09	53.95
Al_2O_2	8.84	9.14	8.81	8.48	8.44	9.00	9.06	8.80	8.93	7.91	7.60	12.93	11.95	13.32	13.07	11.97
Fe_2O_3	12.80	14.09	12.85	13.33	12.76	12.51	12.64	12.95	13.24	12.07	13.12	13.48	11.16	10.70	11.01	11.89
MnO	0.20	0.22	0.20	0.19	0.21	0.20	0.20	0.20	0.21	0.21	0.21	0.23	0.20	0.16	0.21	0.16
MgO	10.55	11.39	10.93	11.44	10.56	10.82	10.36	10.60	10.88	16.99	18.45	11.31	8.54	8.55	8.68	11.52
CaO	9.36	9.84	9.55	9.84	9.73	9.06	9.18	9.47	9.70	8.29	8.27	9.96	11.14	11.41	12.22	8.42
Na_2O	3.96	3.66	3.83	3.68	3.89	4.07	4.13	3.95	3.90	2.25	1.55	1.53	1.64	1.89	1.44	1.05
K_2O	0.12	0.19	0.14	0.14	0.10	0.19	0.11	0.13	0.18	0.06	0.05	0.18	0.22	0.15	0.13	0.10
TiO_2	1.04	1.13	1.01	1.02	1.01	1.05	1.06	1.05	1.04	0.79	0.78	0.73	0.68	0.75	0.83	0.71
P_2O_5	0.11	0.12	1.10	0.10	0.11	0.10	0.11	0.11	0.10	0.12	0.11	0.10	0.11	0.10	0.10	0.09
Total	99.92	100.31	100.08	100.17	99.91	100.18	100.13	99.84	99.85	99.98	99.54	99.67	99.88	99.86	99.78	99.86
Loss	0.83	0.93	0.94	0.88	1.33	0.93	0.81	0.87	0.85	2.49	3.3	1.97	0.58	0.74	0.52	2.51
Zr	79	85	75	77	77	76	82	81	80	59	58	60	57	62	69	57
Nb	4	5	5	4	5	5	5	5	5	3	3	3	3	3	3	3
Rb	1	5	3	4	1	7	1	3	3	2	2	4	3	4	2	3
Sr	105	95	101	93	103	124	106	92	111	54	46	61	114	79	47	31
Y	21	23	21	21	20	19	22	21	20	14	17	20	19	20	21	19
Ba	136	46	282	147	346	32	200	109	525	13	41	40	86	48	19	19
Sc	41	42	39	40	38	39	42	40	41	32	31	42	41	43	46	40
Ni	190	264	224	203	183	202	184	201	204	794	780	177	133	110	107	188
Cr	1402	1721	1513	1391	1394	1451	1386	1312	1700	2929	2834	726	664	530	534	1019
V	267	297	263	274	260	281	275	271	270	215	217	282	267	285	306	276

NOTE: The three samples of Mount Manning komatiite (59546A-C) come from the same sample but cover different tectural types. Samples 63666A-C come from the same specimen and cover an increasing grain size of pyroxene needles. Samples analysed by XRF and conventional wet chemistry at the University of Adelaide; methods are described in Nesbitt and Stanley (1980).

represent evolved liquids (because of their low Mg/Mg + Fe ratios), and therefore, to some extent, the scatter can be ascribed to the removal of varying proportions of olivine, plagioclase, and pyroxene. It can, however, also be argued that the scatter also reflects the variation in the composition of their parental liquids. The two olivine-control lines shown on Figure 2A are taken from the data of Nesbitt and Sun (1976) and Nesbitt and others (1979), and bracket the range in compositions of komatiitic liquids. The two lines are constructed so as to cut the abcissa at 50% MgO. Also shown on Figure 2A is the field of mid-ocean ridge basalt glasses (Melson and others, 1977). This wide-spread field is largely produced by the removal of plagioclase and clinopyroxene from melts having about 10% MgO and 0.6% TiO_2. It is worth noting at this point that many of the Archaean basalts of Hallberg (1972), including his grand average, lie on the MgO poor side of the MORB spectrum.

Turning now to the Diemals data (Fig. 2B), the data like those of Hallberg group into specific localities. Group 3 (the pyroxene spinifex basalts) are notable in that they have a combination of high TiO_2 and MgO and fall outside the olivine control lines delineated by komatiitic liquids. It follows that they cannot be fractional crystallization products of the commonly occurring komatiites. This point is emphasized by the position of the Mount Manning spinifex-textured komatiite (Fig. 2B).

The Group 1 basalts (=tholeiites) plot close to the "west limb basalts" (Group 4), and, on this diagram, are similar to the most primitive MORB glasses. Both groups of liquids could have evolved from komatiitic liquids since they lie within the projected olivine fractionation trends. Group 2 (the ocelli-textured basalts) appear to form an unusual trend which is not seen in any group of basalts. We prefer not to speculate on these ocelli-textured basalts at this stage. Clearly, an understanding of their geochemistry must entail a study of the ocelli which immediately poses a sampling problem.

Figure 2B highlights the position of two apparently anomalous specimens. The first (63657)

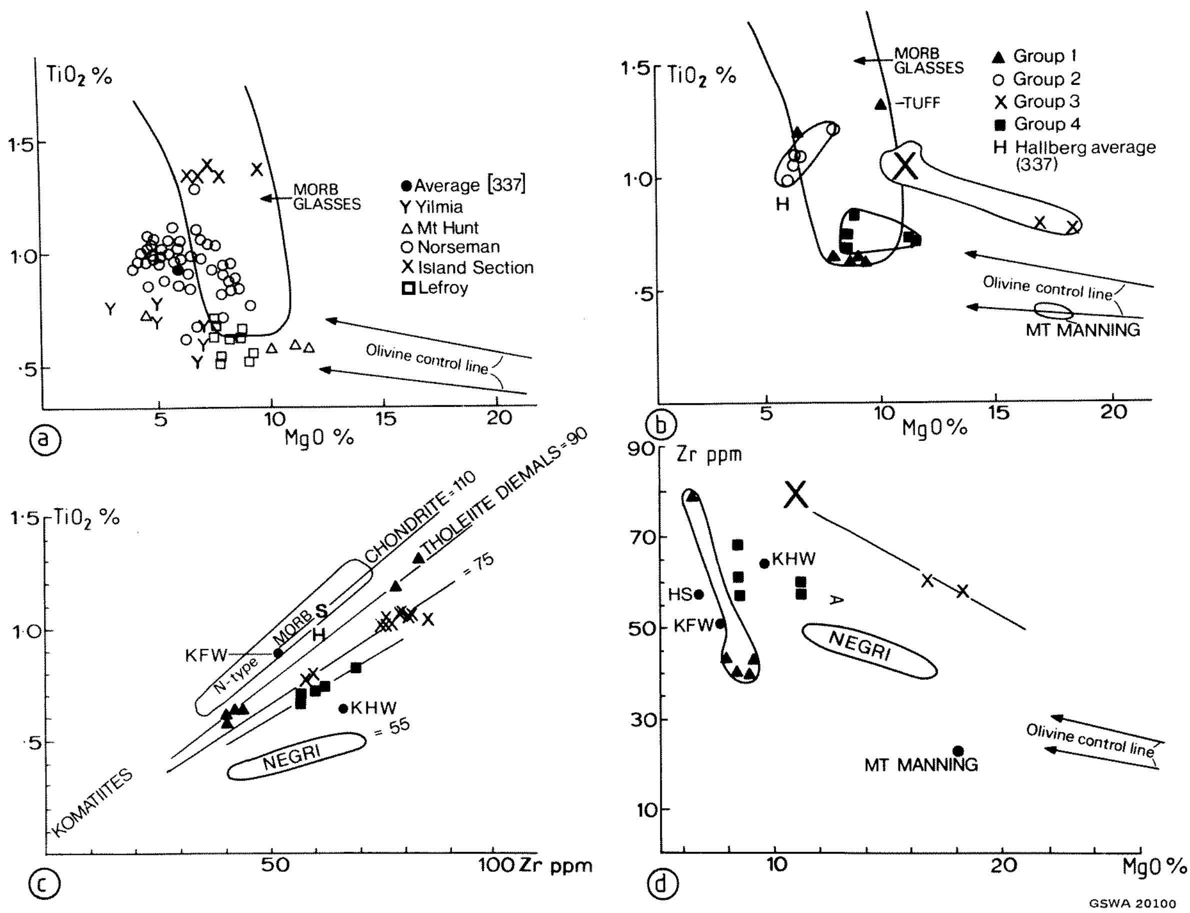

Figure 2. (a) TiO_2—MgO plot of Hallberg's (1972) basalt data from the Kalgoorlie-Norseman belt. The field of mid-ocean ridge basalts is outlined. The olivine control lines bracket the known compositional range of komatiites (Nesbitt and others, 1979).

(b) TiO_2—MgO plot of Diemals' data. The large X symbol for group 3 basalts covers 9 sample points.

(c) TiO_2—Zr data; KFW=Kambalda footwall basalt, KHW=Kambalda Hanging Wall basalt, S=Scotia footwall basalt, H=average of Hallberg data (see Fig. 2a). The indicated values are for Ti/Zr ratios.

(d) MgO—Zr data.

is the tuff of the Group 1 tholeiites and the second (63659) is an apparently fractionated tholeiite at the top of the tholeiite section (Group 1).

MAGNESIUM-ZIRCONIUM

In their original study of the behaviour of trace elements in Archaean high-magnesium liquids, Nesbitt and Sun (1976) pointed to the coherent chemistry of Ti and Zr. Despite extensive mineralogical alteration, it is a remarkable fact that the Ti/Zr ratio of the majority of komatiites *s.s.* is close to that of carbonaceous chondrites (110). Hence, we can predict that the general conclusions reached from the MgO-TiO_2 diagram would also hold for MgO-Zr. These data are presented in Figure 2D. Again the pyroxene spinifex-textured basalts (STB) of Group 3 outline a fractionation trend outside that of the common komatiite liquids. This supports the view (and our final conclusion) that these must be close to primary liquids in their own right. Group 1 basalts (tholeiites) form a fractionation group (with sample 63659) which is entirely predictable on the basis of plagioclase and clinopyroxene removal. The data do not exclude the possibility that these liquids originate from high-magnesium liquids of komatiite type (e.g. the Mount Manning liquids). Group 4 ('west limb basalts') have higher Zr contents than the tholeiites, and in this respect, their relative position in this diagram differs from that in the MgO-TiO_2 diagram. Such a position is compatible with fractionation from a komatiite liquid, provided clinopyroxene removal began at about 12-14% MgO. Alternatively, since the Ti/Zr ratio is low, this may indicate a liquid of Group 3 type (or Negri type), i.e. with an inherently low Ti/Zr ratio. The ocelli basalts of Group 2 (not plotted on Figs. 2C, D) fall close to sample 63659.

On Figure 2C, the positions of the Kambalda and Scotia footwall basalts, are plotted (Nesbitt, unpublished data). The data plot close to the tholeiite fractionation trend of Group 1 tholeiites. The position of the Kambalda hanging-wall basalt is also plotted on Figure 2C and indicates that it is of significantly different composition to the Kambalda footwall sequence (see also Sun and Nesbitt, 1978).

TITANIUM-ZIRCONIUM

Figure 2C is a plot of TiO_2-Zr (ppm), but the ratios shown on the diagram are for Ti/Zr. This diagram illustrates the subtlety of Ti and Zr as discriminant elements. Group 1 basalts (tholeiites) all have ratios close to 90 whilst Group 4 basalts ('west limb') have the lowest ratio (72). It is interesting to note that the tholeiitic tuff (63657) fits the Ti-Zr pattern of the surrounding tholeiites, which suggests that its aberrant position on Figure 28 is due to Mg metasomatism. The Ti/Zr ratio of 90 for the Group 1 basalts is consistent with a model of fractionation from a high-MgO liquid of komatiite type. If this is the case, then it is necessary to envisage some Ti loss due to clinopyroxene, since komatiites commonly have Ti/Zr ratios of 110.

The positions of Kambalda footwall- and hanging-wall basalts, as well as that of Scotia and the Hallberg average, are shown on Figure 2C. These data are consistent with what has been deduced from the MgO-Zr plot *viz* that the footwall basalts are of tholeiitic type, whilst the hanging-wall basalt has a low Ti/Zr ratio, which is characteristic of basalts of this type. Finally, Figure 2C shows the position of the Negri Volcanics, which have very well developed clinopyroxene spinifex texture. These basalts have very low Ti/Zr ratios (55), and their unusual chemistry is a characteristic of basalts of this type (e.g. Group 3).

The important aspect of Figure 2C is the way each set of basalt types conforms to a series of unique but different radiating lines. This suggests that we are dealing with a series of individual liquids whose parental liquids had differing compositions.

ZIRCONIUM-VANADIUM AND ZIRCONIUM-SCANDIUM

Figures 3A and 3B further illustrate the point previously made from the Ti-Zr diagram. Both Zr-V and Zr-Sc plots consist of a set of positive trends, converging on the origin. The V/Zr ratio varies from 6 (Group 1, tholeiites, Kambalda footwall basalt) through to 3.4 (Group 3, Kambalda hanging-wall basalt and Negri Volcanics). The behaviour of V is controlled primarily by pyroxene, and primary melts leaving the mantle reflect the partition of V into the liquid and residual pyroxene. Thus high V/Zr ratios signify in general, high degrees of mantle melting (komatiites are about 8). The same conclusions can be drawn from Sc/Zr ratios, since Sc is also held by the pyroxene structure and we can predict that high values for the ratio indicate little or no pyroxene left in the residue. It also follows (as for V) that pyroxene extraction during fractionation will lower the ratio. We interpret the positions of the two tholeiite samples (63657 and 63659), with ratios much lower than the other tholeiites, as a result of this factor. The Sc/Zr ratios for the Group 1 (tholeiites) basalts are the highest found in the Diemals area whilst Group 3 (clinopyroxene spinifex-basalts) have the lowest (0.5). The 'west limb' basalts (Group 4) have intermediate values and are similar to those found in the Negri volcanics. The Kambalda hanging-wall basalt is close to Group 3 basalts as would be predicted from its texture.

ZIRCONIUM-YTTRIUM

Sun and others (1979) have suggested that the relative behaviour of Zr and Y (in effect the Zr/Y ratio) give some indication of the slope of the heavy-rare-earth pattern (HREE). Figure 3C illustrates this point. The chondrite value of Zr/Y is about 2.5 (Nesbitt and Sun, 1976), and this is very close to the value obtained for the Group 1 tholeiites, which conforms to the value found in komatiites. As for Sc and V, Y is a good indicator of pyroxene involvement and this produces higher Zr/Y ratios in the two fractionated tholeiite samples from the Group 1 basalts. The high Zr/Y ratios (about 3.6) of the Group 3 basalts is not a function of fractionation, since they plot on a good array with a near constant ratio. Thus the basalts of this group with the highest MgO content (18%) have the same high ratio as those with 10% MgO. The logical interpretation of these data is that the source for the pyroxene spinifex-textured Group 3 basalts also had this ratio. We can therefore predict that they will show heavy REE depletion relative to the middle REE.

The consistent relationships between the Group 1 (tholeiite) basalts and the basalts from the footwall sequence of Kambalda and Scotia are again seen here. Similarly, the hanging-wall basalts at Kambalda plot with Group 3 basalts.

ALUMINIUM-TITANIUM

The Al_2O_3/TiO_2 ratios (Fig. 3D) for the most common type of komatiite (not the Barberton-type) ranges from 20-24 (Nesbitt and others, 1979) and this value is close to the range found in carbonaceous chondrites. Similarly, the most primitive MORB have this ratio, as do the Group 1 tholeiites from Diemals. Sun and Nesbitt (1977) conclude that a close-to-chondite value indicated that most of the Al_2O_3 in the source of the melt had been released into the melt. They suggested that this was mainly controlled by the melting of pyroxene. We can conclude from this, that the Group 1 tholeiites, like komatiites, represent extensive melting of a mantle source (or alternatively, a re-melting of an already depleted source). Similar arguments can be advanced for the 'west limb' basalts (Group 4), as well as the Scotia and Kambalda basalts (both hanging and footwall). This is an interesting and perhaps important point, bearing in mind the suggestion that Group 4 basalts and the Kambalda hanging-wall basalts have HREE depletion. The data suggest that in these melts, Ti is decoupled from the middle REE and is in fact depleted. Thus, the low Ti/Zr ratios found in the Kambalda hanging-wall basalts and Group 4 basalts are due to Zr (= middle and light REE) enrichment.

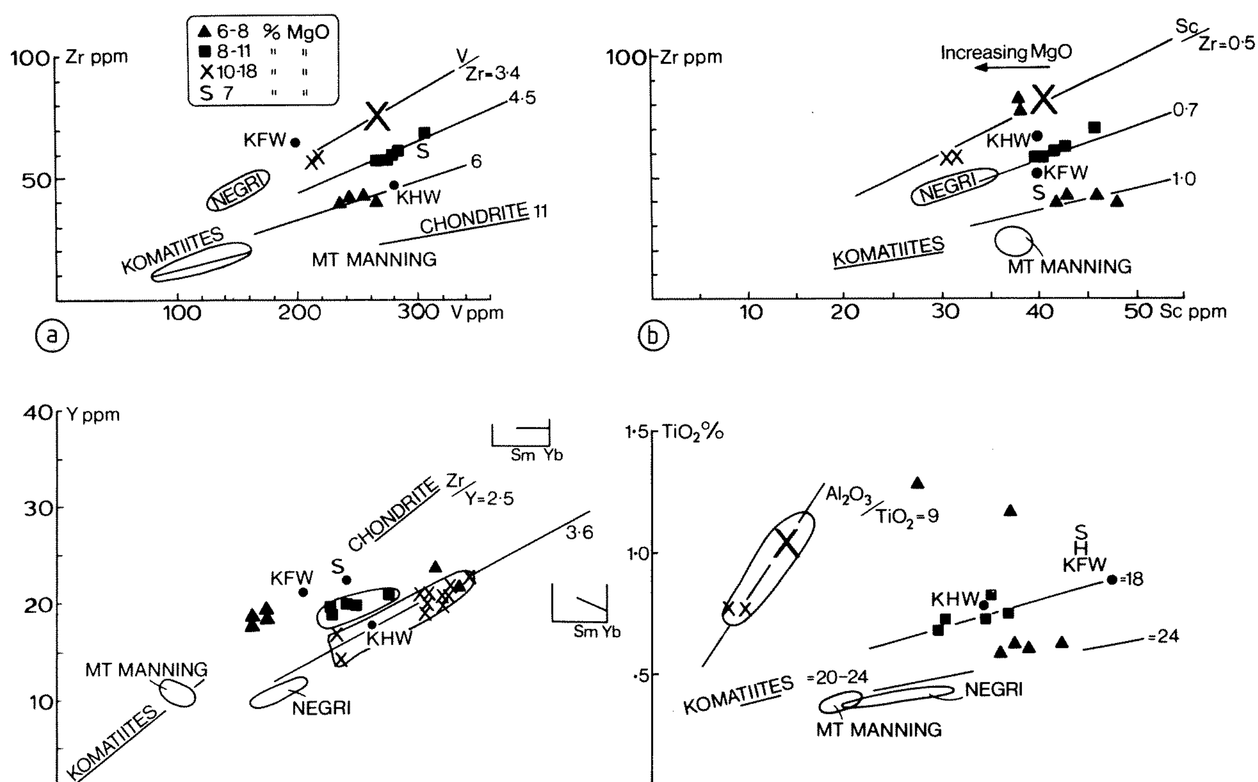

Figure 3. (a) Zr—V, (b) Zr—Sc, (c) Zr—Y, (d) TiO_2—Al_2O_3 plots for Diemals data. The pseudo-rare earth element plots in Figure 3c indicate the correlation between increasing Zr/Y ratio and HREE depletion. Symbols as for Figure 2. Chondrite values from Nesbitt & Sun (1980).

Uniquely, the Group 3 Diemals' basalts have low Al_2O_3/TiO_2 ratios (about 9) even in the high MgO members. This suggests that the ratio is that of the parental melt and we suggest it is probably produced by the retention of Al_2O_3 in the source. Such data constrain possible models of melt genesis and the most plausible is that the Group 3 basalts represent small amounts of melting of a mantle source (to limit the Al_2O_3 entering the melt). However, in order to generate 18%-MgO-melts at small degrees of melting it would be necessary to produce the melt at higher pressure than say the tholeiites of Group 1.

CHROMIUM-TITANIUM

The use of Cr and Ti as discriminants (Fig. 4A) has been advocated by several authors, principally Pearce (1975), and Pearce and Flower (1977). If a plot of Cr/Ti *vs* Ti is used, liquid lines of descent are shown as negative, steeply sloping lines. The negative slope is developed because more primitive liquids have high Cr and low Ti and as fractionation proceeds Cr is rapidly stripped from the liquid, by spinel, clinopyroxene and olivine. Conversely Ti tends to increase in value in the liquid, because the crystal-liquid distribution coefficients for this element are less than one of the common silicate minerals.

In Figure 4A, the data are plotted as Cr/Ti *vs* Ti. It can be seen that each of the 3 groups of basalts from Diemals forms discrete domains, approximately parallel to one another. Also plotted on the diagram are fractionation lines for plagioclase, olivine and clinopyroxene, with the latter mineral being most effective in removing Cr. The most important conclusion we can draw from this diagram is the fact that Group 1 basalts cannot be derived from Group 3 by any fractionation mechanism involving commonly occurring basaltic minerals. It would appear that Group 1 basalts evolved from a parental liquid having a much higher Cr/Ti ratio (like the Group 3 basalts) but lower Ti (unlike Group 3).

The absolute position of Group 3 basalts relative to Groups 1 and 2 is important. If we consider the three groups at a fixed value of Ti, it can be seen that the Cr/Ti ratio rises from Group 1 through to Group 3. This change also equates with an increase in MgO. One obvious model to account for the data is to produce the Group 3 liquids at higher pressure and by smaller degrees of melting.

RARE-EARTH-ELEMENTS

Figure 4B shows two rare-earth-elements (REE) patterns for the Diemals basalts. The two samples are 63655 (Group 1) and 63668 (Group 3). As we predicted from the trace element geochemistry, the two REE patterns are significantly different. The Group 1 basalt, has a flat, heavy-REE pattern, a slight positive Eu anomaly and a flat, light-REE pattern up to Nd. The increase in La and Ce relative to other REE may be due to an intrinsic magmatic process (probably a source characteristic) or may be

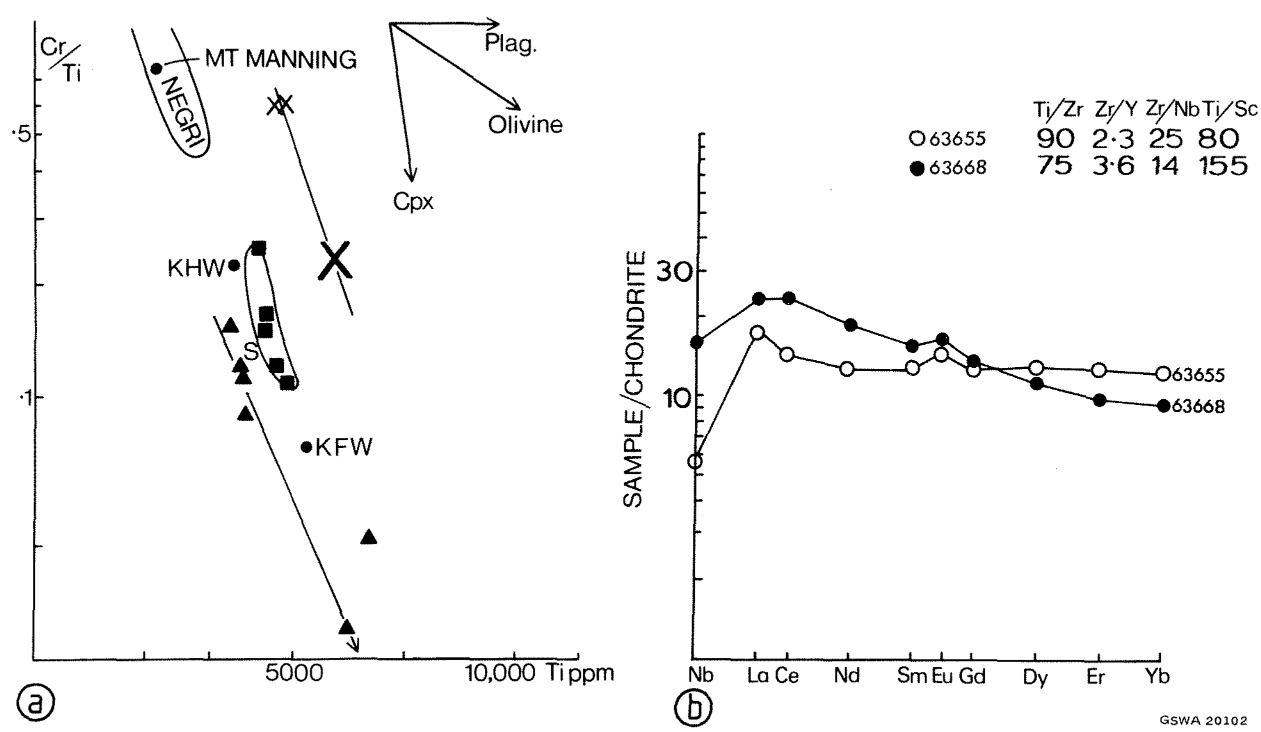

Figure 4. (a) Log Cr/Ti—log Ti plot; fractionation vectors are taken from Pearce & Flower (1977). Symbols as for Figure 2, large X= 9 data points for Group 3.
(b) Rare earth element data for sample 63655 (Group 1) and 63668 (Group C) REE by isotope dilution, Nb by XRF.

a product of alteration. We would need to measure several other samples to make a decision on this problem. The pyroxene spinifex-textured Group 3 basalt (63668) shows significant heavy-REE depletion with (Yb/Gd) N = 0.68. This heavy-REE depletion is matched by a light-REE enrichment pattern, typical of such basalts (e.g. the Negri Basalts described by Sun and Nesbitt, 1978).

The difference in the two REE patterns is fundamental and cannot be related by a crystal fractionation process (*see* Sun and Nesbitt, 1978; and Arth and others, 1977 for further discussion). We conclude that the two patterns reflect different source characteristics.

DISCUSSION

Using textural considerations, we can identify three types of basalt, *viz* tholeiitic (Group 1), pyroxene spinifex-textured basalts (Groups 3 and 4) and ocelli-textured pyroxene-rich basalts (Group 2). Geochemically, the Group 3 and 4 basalts become distinct both from each other and the tholeiites. Unfortunately, we can say little about the Group 2 ocelli-textured basalts because there appears to be little system in their geochemical characteristics. However, we can make some generalizations concerning the other three groups. Primarily, the data indicate that the so-called komatiitic basalts (i.e. those with sprays or long needles of clinopyroxene) cannot be related to the commonly occurring komatiitic *s.s.* rocks by any known crystal fractionation process. Indeed, the fractionation trends suggested by the geochemistry are those connecting the komatiites to the tholeiites. We do not know of any material (i.e. > 20% MgO) capable of being parental to the Group 3 (= pyroxene spinifex) basalts and we therefore believe they must be close to primary liquids. Such a conclusion has previously been reached by Sun and Nesbitt (1978), Arth and others (1977) and Arndt and Nesbitt (1982). Furthermore, there appears to be a wide diversity in the geochemistry of the pyroxene spinifex basalts (e.g. Groups 3 and 4).

The bulk of the chemical data indicate that the Group 3 basalts in particular have unusual chemical characteristics compared to the other groups. Notable is the high TiO_2 in rocks with high MgO as well as the rather low Al_2O_3 contents. These characteristics (including the REE pattern) are best explained by producing a high-magnesian liquid at high pressures (say 300 MPa). In such a model, melting is not extensive and an aluminous phase (pyroxene ± garnet) remains in the residue, thus holding back Al_2O_3 and the heavy-REE. The low percentage melting would also explain the high TiO_2, Nb and possibly the light-REE enrichment.

The clinopyroxene texture, which is so characteristic of these rocks, is a major problem since liquids with 12-18% Mg0, would be expected to precipitate copious olivine. However, both Group 3 and Group 4 basalts are notable in their relatively high (about 52%) $Si0_2$ contents, a factor which explains the lack of olivine. One possible explanation for the high $Si0_2/Mg0$ ratio is to provide it by fractionation. If Group 3 and Group 4 basalts had a more magnesian parent (> 20% Mg0) the precipitation and removal of olivine would automatically produce a trend of increasing $Si0_2$. However, the light-REE enrichment, low $A1_20_3/Ti0_2$ and low Ti/Zr ratios preclude these basalts fractionating from common komatiitic liquids. This is not necessarily an argument against the model for one could postulate that the parental liquid was unable to reach the surface without losing olivine. However, if the parent liquid contained 45% $Si0_2$ (as for komatiites) then about 60% olivine extraction would be necessary to arrive at a liquid with 52% $Si0_2$. This would require a starting liquid of about 30% Mg0 (close to that of komatiites) but (unlike komatiites) it would be unusually rich in $Ti0_2$ (about 0.6%). Furthermore, it is probable that 60% olivine removal would lower the Ni content of the resultant liquid well below the 200 ppm found in the Group 3 clinopyroxene spinifex-textured basalts.

Taking the *mg* values (100 Mg/(Mg + Fe^{2+})) of these liquids into account, it is clear that some fractionation must be involved since their *mg* values are too low to be in equilibrium with pyrolite. On the other hand, Group 3 samples 63672-3, containing about 18% Mg0 are of obvious cumulative origin and must therefore represent maximum Mg0 parental compositions. We conclude that the parental liquid for the Group 3 lavas, contained about 16% Mg0. The problem thus resolves into formulating a model which will explain a relatively high $Si0_2$ content with only limited olivine fractionation from an initial liquid of 16% Mg0. One such model involves wet melting of pyrolite. Although there has been considerable debate (e.g. Green, 1973; Kushiro, 1974; Tatsumi and Ishizaka, 1981) over exactly how siliceous a melt can be produced by wet melting of pyrolite, there is equally a general consensus that siliceous melts do result. In the case of the Diemals' lavas with about 52% $Si0_2$, these would easily fall below the most pessimistic view of possible silica enrichment by wet melting. We thus arrive at a possible model in which mantle melting in the presence of H_2O (but not water saturated) produces a 16-18% Mg liquid, unusually rich in elements such as TiO_2, but is low in alkalis. Fractionation of olivine (± clinopyroxene) drops the MgO content of the liquid to about 10-12% MgO at which time the liquids erupt.

Arndt and Fleet (1979) have suggested that the spectacular needle-shaped clinopyroxene crystals found at the flow tops of some Archaean flows (the so-called "string-beef" texture) indicate strong undercooling. Such an explanation is in accord with that proposed by Nesbitt (1971) for the spinifex-textured olivines found at the tops of komatiite flows. The presence of the 'string-beef' texture however, does seem to have a positive correlation with unusual chemistry, as previously outlined. It would therefore appear that the conditions necessary to produce liquids with low Ti/Zr, light REE enrichment, high SiO_2/MgO ratios also naturally led to the production of clinopyroxenes with "quench" morphologies. It is this morphology which has led to their correlation with komatiites—a view which is refuted by the data from Diemals.

CONCLUSIONS

Geological and geochemical data on the basaltic sequences at Diemals, Western Australia, led to the following conclusions:

(1) The various stratigraphic levels have basaltic types which evolved from parents with differing compositions.

(2) The succession at Diemals has very well developed high-magnesian basalts with distinctive clinopyroxene spinifex (or 'string-beef') texture. Because of this texture, the basalts are commonly referred to as komatiitic basalts, but geochemistry precludes any connection with common komatiitic liquids.

(3) The high-magnesian basalts are characterized by their clinopyroxene morphology, by low Ti/Zr ratios (even with 18% MgO) and light-REE enrichment. We suggest that they evolved from a 16-18% MgO primary liquid by olivine, followed by clinopyroxene fractionation.

(4) The clinopyroxene morphology of these basalts, is only developed near the margins of flows and resembles spinifex texture in that it displays progressive grain size changes with respect to the cooling surface. We are in agreement with Arndt and Fleet (1979) that this represents non-equilibrium cooling under conditions of undercooling.

(5) The dominance of clinopyroxene in such high-magnesian liquids is caused by slightly enriched SiO_2 values. This may be a function of wet melting in the source region. However, the high TiO_2, Zr, Nb, light-REE and high MgO, also suggest that low degrees of melting took place at pressures higher than those which generated the accompanying basaltic types.

(6) Tholeiitic basalts, very similar in composition to those described by Hallberg (1972) are believed to represent the fractional crystallization products of komatiitic (i.e. > 18% MgO) liquids.

(7) Since all of the various basalt types are temporally and spatially related, we assume that extensive melting occurred over a significant depth interval. Thus although the basalts are not genetically related in the petrologic sense, they are the products of the same tectono-thermal event.

ACKNOWLEDGEMENTS

Part of this work was carried out whilst R. W. Nesbitt was a recipient of ARGC support. We acknowledge the analytical assistance of Mr John Stanley, Mr M. Ogasawara, Dr John Foden and Mr P. McDuie and the advice of Dr S. S. Sun and Dr R. D. Gee.

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MORTIMER HILLS PEGMATITE URANIUM PROSPECT A ROSSING-TYPE URANIUM DEPOSIT IN THE GASCOYNE PROVINCE

by J. D. Carter

ABSTRACT

A uraninite-bearing pegmatite of large dimensions in the Gascoyne Province is described. The pegmatite is compared with the Rossing uranium ore body of South West Africa and the two are shown to have common characteristics.

Exploration recommendations for Rossing-type uranium mineralization in the Gascoyne Province are made.

INTRODUCTION

Though the Gascoyne Province, with its multitude of small uranium deposits, could be classed as a uranium province, no deposit of this metal of obvious commercial dimensions has been found there, despite more than 10 years of sustained exploration. For example, Carter (1981) lists 63 items of the microfilm open-file in the library at Mineral House, Perth, which concern recent abandoned exploration for uranium in the province. Of these operations however, one (Item No. 723 in the microfilm catalogue), attracts attention because of its description of a large body of pegmatite carrying small amounts of uranium, situated just north of the Mortimer Hills. This pegmatite appears to have features in common with the low-grade ore body at the Rossing uranium mine in South West Africa, probably the world's largest uranium-in-granite mine. In an endeavour to assess whether Rossing-type mineralization may be present in the Gascoyne Province, characteristics of the pegmatite prospect and the Rossing ore body are reviewed and comparisons made.

The uraninite-bearing pegmatite lies three kilometres north of the Mortimer Hills (lat. 24°36″, long. 116°17″) and some 17 kilometres northeast of Yinnetharra, and is shown by symbol "U" on the Mount Phillips 1:250 000 geological sheet to occur within members of the Morrissey Metamorphic Suite of the Lower Proterozoic. Agip Nucleare Australia Pty Ltd explored the pegmatite between 1974 and 1978. The account of this prospect is drawn largely from reports of this company and a brief examination of the pegmatite and surrounding country made by the writer in September 1981.

ROSSING URANIUM DEPOSIT

The large but low-grade uranium occurrence at Rossing in South West Africa is composed of alaskitic granite*, pegmatite and aplite containing disseminated uraninite, betafite and secondary uranium minerals (Berning and others, 1976). These rocks were collectively called "pegmatite" and "potash granite" by early investigators before the term "alaskite" was employed.

The Rossing alaskites are situated within the central zone of the late Precambrian to early Palaeozoic Damara Orogenic Belt. Individual bodies range from lenses to large intrusive and replacement bodies differing widely in texture, size and replacement habit. Both concordant and discordant relationships are shown with marble, schist and gneiss of enclosing country rock. The alaskite occurs in syntectonic intrusions.

Disseminated uraninite (55% of the total uranium content of the ore) is included in quartz, feldspar and biotite but also occurs interstitially to these minerals, and along small cracks within them. It is accompanied by betafite (less than 5% of the uranium) and by secondary uranium minerals, including beta-uranophane and carnotite, which account for 40% of the total uranium content. The deposit is mined by a low-cost open-pit method and an acid leach process is used to extract uranium oxide.

Toens and Corner (1980) discussed the origin of the uraniferous alaskites:

"The polyphase Damara metamorphism produced high-grade metamorphic assemblages, migmatites and syn-, late- and post-tectonic anatectic granites through reactivation of the basement and overlying Damara rocks. During anatexis the

* Alaskite is used for granitic rock containing only a few per cent of dark minerals. It is characterized by essential alkali feldspar and quartz, and very little dark component.

incompatible elements, particularly the uranium derived from these formations, were incorporated into the melts which then rose . . .

"Fractional crystallisation during ascent and increased water content concentrated the uranium into residual melts which finally crystallized as alaskitic pegmatitic granite.

"Structural episodes played an important part in the emplacement of the uraniferous granites and the presence of marble bands was an important factor in . . . providing a structural trap for the alaskitic melts . . ."

MORTIMER HILLS PEGMATITE URANIUM PROSPECT

Exploration Status

The prospect was held by Agip Nucleare under MCs 09/1980 and 09/2174-2175. Uranium mineralization was initially detected by an airborne radioactivity survey, and the pegmatite became the target of intermittent investigations between 1974 and 1978. These included large-scale geological mapping (1:1 000), ground radioactivity surveys and drilling 33 non-core holes for a total of 440 metres. Drilling demonstrated a high geochemical content of uranium but was unable to locate ore-grade mineralization.

Geology

The Gascoyne Province, the tectonic setting of the Mortimer Hills pegmatite, is believed to have evolved during the interval 2 000 to 1 600 m.y. when an orogenic event modified Proterozoic shelf and trough sediments to form the Morrissey Metamorphic Suite. The suite, which includes amphibolite-facies rocks and migmatite, was intruded by Proterozoic granitoids. This orogeny possibly relates to a major world-wide event at about 1 900 to 1 700 m.y., this period being 'the earliest that uranium is known to have been mobilized and concentrated in veins' (Bowie, 1979). There is close correlation between the regional disposition of uranium-bearing pegmatites and the Morrissey Metamorphic Suite (Williams and others, 1979).

Uranium-bearing pegmatite forms two arcuate belts within migmatized Morrissey Metamorphic Suite rocks, as shown in Figure 1. Basement gneiss of uncertain age (either Archaean or Proterozoic) lies between these two belts and itself has above average background radioactivity. Williams and others (1979) considered that the basement gneiss was probably the source for the clastic arkosic rocks which were subsequently metamorphosed and migmatized to form the Morrissey Metamorphic Suite.

The emplacement of the pegmatites that contain the primary uranium mineralization post-dates the metamorphism and appears to be related to the late-stage tourmaline-bearing granites in the Nardoo area. Williams and others (1979) suggested that uranium in the pegmatite could have been scavenged from the meta-sedimentary rocks by volatile-rich hydrothermal fluids.

The generally uraniferous nature of this area is also shown by the number of calcrete uranium prospects that are spatially related to the primary pegmatite deposits.

The Mortimer Hills pegmatite lies within part of the Yinnetharra pegmatite belt which extends southeastwards from the Morrissey Hill district to Camel Hill. Pegmatites of this belt are well known for the small-scale production of mica (muscovite), beryl and bismuth. Uranium minerals are found among the accessory minerals, and pitchblende and euxenite have been identified, together with various secondary uranium minerals.

North of Mortimer Hills the pegmatite forms a low, northerly trending ridge. The main body has approximate dimensions of 1 000 metres in length and up to 400 metres in width, and was proved by drilling to extend to more than 81 metres in depth. Coarse quartz and potash and soda feldspars, the principal constituents, are accompanied by small amounts of muscovite, tourmaline, garnet, magnetite and calcite with a few scattered grains of metamict uraniferous pyrochlore. One specimen contained 90% potash feldspar, 5% quartz, 3% plagioclase feldspar and less than 1% each of muscovite, tourmaline, biotite and opaques. An analysis of a second sample returned the following results:

Al_2O_3 = 14.0%
CaO = 0.69%
MgO = 0.08%
Na_2O = 3.65%
K_2O = 4.05%
Fe_2O_3 = 0.71%

A third sample (Specimen GSWA No. 40773) is composed of albite, quartz and muscovite with a little almandine-spessartine, magnetite and calcite with a few scattered grains of metamict uraniferous pyrochlore and yellow joint stains of beta-uranophane. It assayed 210 ppm uranium (Government Chemical Laboratories Lab. No. 81 M2528). Drilling indicated that the pegmatite is predominantly muscovite bearing.

There is no obvious zoning in the pegmatite. Agip Nucleare reports that the contacts with the country rock, principally biotite schist of the Morrissey Metamorphic Suite, are diffuse along the eastern margin in contrast to the western flank where the contact is more abrupt.

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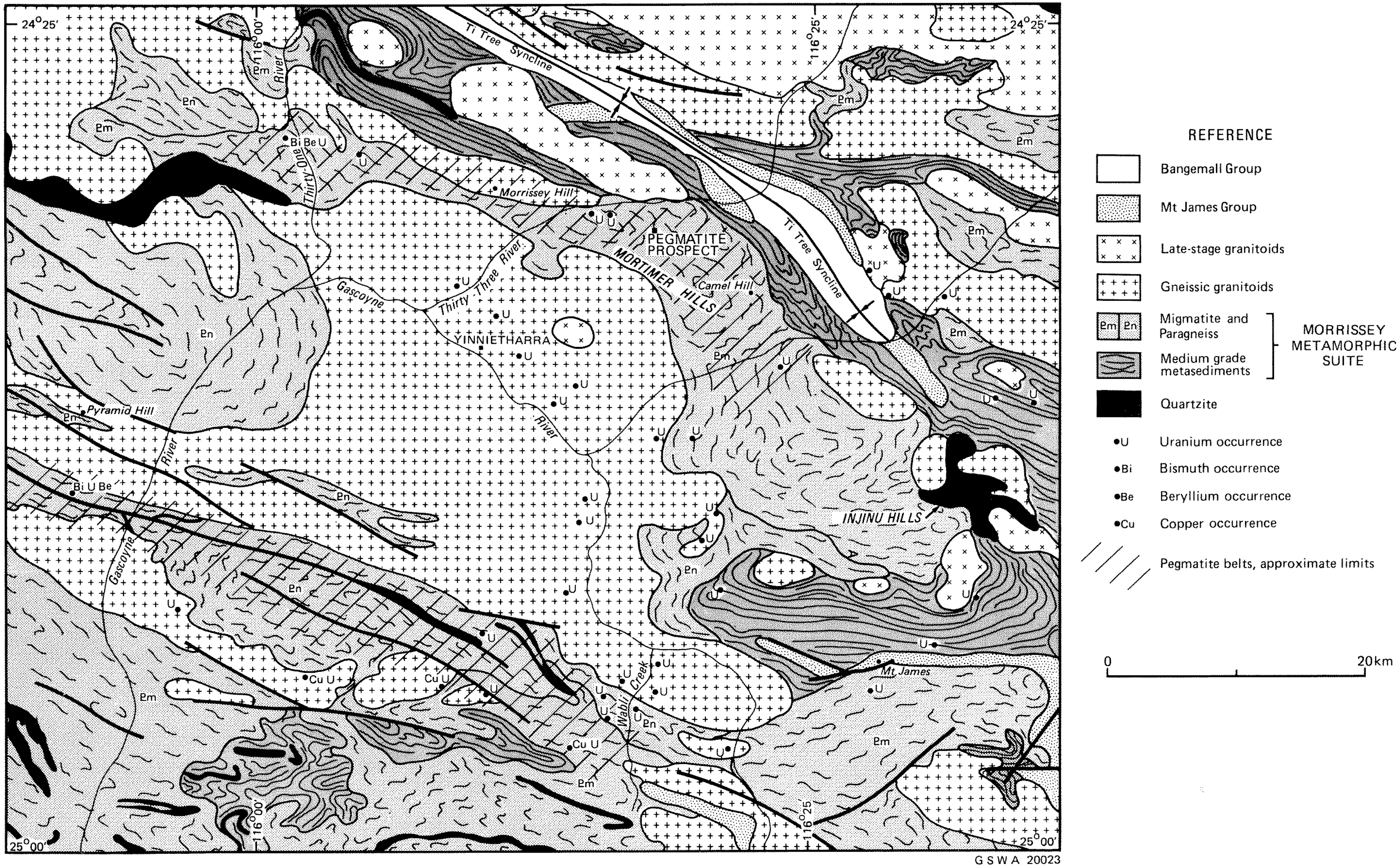

Figure 1. Geological map of the Yinnetharra district, showing distribution of two main pegmatite belts, the distribution of significant uranium and other mineral occurrences, and the location of the Mortimer Hills pegmatite uranium prospect. Geology adapted from the Mount Phillips 1:250 000 geological sheet.

Uranium mineralization is represented by uraninite, uranophane and beta-uranophane, and uraniferous pyrochlore. Uraninite occurs in small grains, some of which are embedded in mica flakes and in garnet grains. The best uranium value obtained by drilling was 150 ppm U over one metre.

Of six percussion drill holes sunk by Agip Nucleare, two reached 81 metres in depth. Most holes were sited over radiometrically anomalous high spots in the pegmatite and obtained sporadic, moderately anomalous uranium values throughout their lengths. There was, however, no recognizable correlation of anomalous zones between any of the holes nor apparent structural control of the uranium mineralization. Drilling near the western contact failed to detect evidence of uranium concentration in host rocks.

CHARACTERISTICS OF THE ROSSING GRANITE AND MORTIMER HILLS PEGMATITE

In Table 1, characteristics of the Rossing granite and Mortimer Hills pegmatite are set out for ease of comparison. Many similarities between Rossing granite mineralization and the Mortimer Hills pegmatite prospect are shown. The lithologies of the mineralized rocks, the nature of mineralization, the structures of the host rocks and their probably modes of emplacement correspond closely.

Of the dissimilarities, no importance can be discerned in differences of age and time in relation to orogenic events which determine structural settings. A further difference is the proportion of biotite and muscovite. Toens and Corner (1980), in discussing criteria favourable for uranium mineralization, found biotite to be an essential accessory mineral and state "that muscovite . . . should be present only in small amounts". The reverse is true in the case of the Mortimer Hills pegmatite.

These authors also believe the "level of erosion is extremely critical in determining the current economic potential of a mobile belt" and state that "In general, the older the belt the more erosion it has been subjected to". A result could be the stripping of high-level, mineralized granitic differentiates. Examples are provided from South Africa: the Damara (c. 500 m.y.), the Namaqua (c. 1 000 m.y.) and the Limpopo (c. 1 950 m.y.) belts where uraniferous alaskitic granites, while known in the Damara belt, are rare in the Namaqua belt and are unknown in the Limpopo belt.

TABLE 1

Characteristics	*Damara Orogenic Belt and Rossing granite (Berning and others, 1976; Toens and Corner, 1980)*	*Gascoyne Province and Mortimer Hills pegmatite (Agip Nucleare)*
Structural setting	Orogenic belt	Orogenic belt
Age	Late-Precambrian to early Palaeozoic; Rossing granite: c. 470 m.y.	Lower Proterozoic 2 000-1 600 m.y. Pegmatite: (?)c.980 m.y.* (but most probably older than 1 100 m.y.)
Country rocks	High-grade metamorphic rocks and migmatite intruded by syn-, late- and post-tectonic anatectic granites	High-grade metamorphic rocks and migmatite intruded by early- and late-tectonic granitoids
Mineralized rocks	Late-tectonic alaskitic granite, pegmatite and aplite	Post-orogenic alaskitic pegmatite
Principal accessory mineralogy	Biotite, muscovite and amphibolite minerals in small amounts	Muscovite the major accessory, and tourmaline; biotite in small amounts
Uranium minerals	Uraninite, betafite and secondary uranium minerals	Uraninite, uraniferous pyrochlore and secondary uranium minerals
Grade of mineralization	Not known but probably very low, may be much less than 1 000 ppm U_3O_8 (?); reported daily milling rate is 40 000 tonnes with annual production 5 000 s tons U_3O_8	Best drill intersection 150 ppm U over 1 metre
Structure	Massive bodies of alaskite	Compact and massive pegmatite
Mode of emplacement	Passive metasomatic process	Passive emplacement
Structural control	Marble bands apparently entrapped uranium-rich volatiles	None recognized
Level of erosion of structural setting	Considered to be shallow as "high-level" mineralized granites are exposed	Probably deeply eroded

*See Wilson and others, 1960.

This generalization does not hold for the Mortimer Hills pegmatite, a mineralized differentiate within an older mobile belt where exposures of rocks of amphibolite facies suggest deep erosion has taken place. Also, the pegmatite was generated either at a late stage of, or after the evolution of the Gascoyne Province. The age of the pegmatite (c. 980 m.y.), published in 1959, is considered to be too young. Gascoyne Province pegmatites are older than Bangemall Group rocks and these are dated c. 1 100 m.y. The Mortimer Hills pegmatite, exposed with rocks of the amphibolite facies and older than c. 1 100 m.y., therefore belies the importance attached by Toens and Corner (1980) to levels of erosion, and to ages of c. 1 000 m.y. or less, factors which could otherwise down-grade the potential of the Gascoyne Province for Rossing-type uranium mineralization.

Another factor is the apparent role of marble bands which acted as traps for alaskitic melts and associated uranium-rich volatiles at Rossing, to which reference has already been made. Toens and Corner (1980) state that "in alaskites with high oxygen fugacity at the magmatic stage, the uranium will be mostly in the hexavalent state and the uranium will leave the magma with the solution during the boiling of the magma and the alaskite will thus not be mineralized". Marbles appear to have played an important role as an entrapment agent at Rossing by forming impermeable barriers to mineralized volatiles. No structural control of the Mortimer Hills pegmatite was noticed. This may account for the low tenor of uranium mineralization.

SUMMARY

The Mortimer Hills uraniferous pegmatite is regarded as a weakly mineralized representative of Rossing-type uranium mineralization. An immediate question is: are there more strongly mineralized alaskitic rocks elsewhere in the Gascoyne Province? In light of the lack of success of extensive exploration for uranium in this mobile belt, it must be assumed that high-grade mineralization of the Rossing-type with strong radiometric signals easily detected by airborne radioactivity surveys is either not present, or is not exposed. To test the latter possibility, exploration attention should be given to unexposed sections or extensions of the "two arcuate belts" containing pegmatites in the country south of Yinnetharra.

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THE BUNBURY SHALLOW-DRILLING GROUNDWATER INVESTIGATION

by D. P. Commander

ABSTRACT

The Bunbury shallow-drilling project extended over an area of about 600 km^2 within the southern Perth Basin. Pairs of bores consisting of a deep bore (about 100 m) and a shallow bore (less than 20 m) were drilled at twenty-six sites to investigate the stratigraphy and hydrogeology, and to provide a network of bores for long-term monitoring of water levels and salinities. An additional five test-pumping bores were also drilled at selected sites.

The superficial formations (Quaternary) cover the coastal plain to a maximum depth of about 20 m. In the east they are relatively clayey, and the salinity locally exceeds 4 000 mg/L. They are used for on-farm domestic and stock water.

The underlying Leederville Formation (Lower Cretaceous) consists of interbedded sands and shales and has a maximum thickness of 354 m in the axis of the Dardanup Syncline. The formation is recharged directly from rainfall on its outcrop on the Blackwood Plateau and groundwater flow is in a northerly direction, discharging to the sea near Leschenault Inlet. The salinity ranges from 300 to 700 mg/L and the formation is used for town supply at Dardanup and Australind, and on a small scale for industry near Bunbury. Annual throughflow is estimated to be 11 million cubic metres.

The major groundwater resources of the area are in the Yarragadee Formation, which is predominantly sandy. Between 200 m and 900 m of the formation contain groundwater, most of which ranges in salinity from 200 to 400 mg/L. Estimated annual abstraction from the formation is 18 million cubic metres, compared with a throughflow of about 66 million cubic metres per year, derived from recharge to the south of the study area.

INTRODUCTION

LOCATION

The Bunbury shallow-drilling project was carried out within an area of about 600 km^2 in the southern Perth Basin 150 km south of Perth (Fig. 1). Bunbury (pop. 21 000) is a regional centre for the processing and export of agricultural and forestry products, and mineral sands.

Water supplies for Bunbury and the nearby towns of Australind, Boyanup, Capel, Donnybrook and Eaton, and also for industry, are drawn from local groundwater resources.

PURPOSE AND SCOPE

The Bunbury shallow-drilling project was carried out by the Geological Survey to investigate the geology and the hydrogeology of the aquifers in the Perth Basin to a depth of 100 m; to provide a network of monitoring bores to measure the natural water level and salinity variations in the aquifers; and to monitor the effects of groundwater abstraction in and near Bunbury.

CLIMATE AND LAND USE

The Bunbury area has a Mediterranean-type climate with hot dry summers and cool wet winters.

The average annual rainfall is 886 mm at Bunbury but it increases to about 1 000 mm along the Darling Scarp. Rainfall exceeds evaporation during the five months, May to September.

Much of the land on the coastal plain has been cleared for agriculture, and in the Dardanup area pastures are irrigated using water from the Wellington Dam, on the Collie River east of the Darling Scarp.

The uplands to the east remain largely uncleared and are covered by native eucalypt forest. Intensive vegetable and fruit growing is carried out in the Preston River valley, between Donnybrook and Boyanup.

PREVIOUS WORK

The occurrence of artesian water at Bunbury was reported by Maitland (1898), but little further information on groundwater was published until the 1960s when bores were drilled for town supply at Eaton and Capel, and for the titania refinery at Australind (Passmore, 1962; Emmenegger 1963 a, b, c).

Exploratory drilling in the area by the Geological Survey of Western Australia (GSWA) commenced in 1967 with the drilling of the western part of the

Quindalup Line (QL), described by Probert (1968), which was subsequently completed in 1979-80 (Wharton, 1980).

As a result of concern that overdrawing of the aquifers in Bunbury may have been taking place, a report on the hydrogeology with recommendations on a monitoring network was prepared by Whincup (1968). Subsequent reports by Barnes (1970) and Harley (1973) led to the drilling of Picton Line (PL) 1 bore in 1974 to a depth of 1 200 m. Three further Picton Line bores were completed in 1978 (Wharton 1980), and in 1981 four deep bores (Smith, pers. comm.) were drilled 13 km to the south along the Boyanup Line (BL).

The subsurface geology and hydrogeology of the city of Bunbury, including discussion of the effects of groundwater abstraction, has been described by Commander (1981).

DRILLING AND TESTING

The Bunbury shallow-drilling programme, which commenced in 1975 and completed in 1980, consisted of sixty-five bores at twenty-six sites, including shallow bores for monitoring the water table; deeper bores to a depth of about 100 m to monitor the confined aquifers; and five test-pumping bores to provide aquifer characteristics of the confined aquifers (Commander, 1976; Leech, 1977).

The bores were drilled by the Mines Department Drilling Section, using mud-rotary techniques. In bores where basalt was intersected, casing was run to the top of the basalt, and drilling continued with a

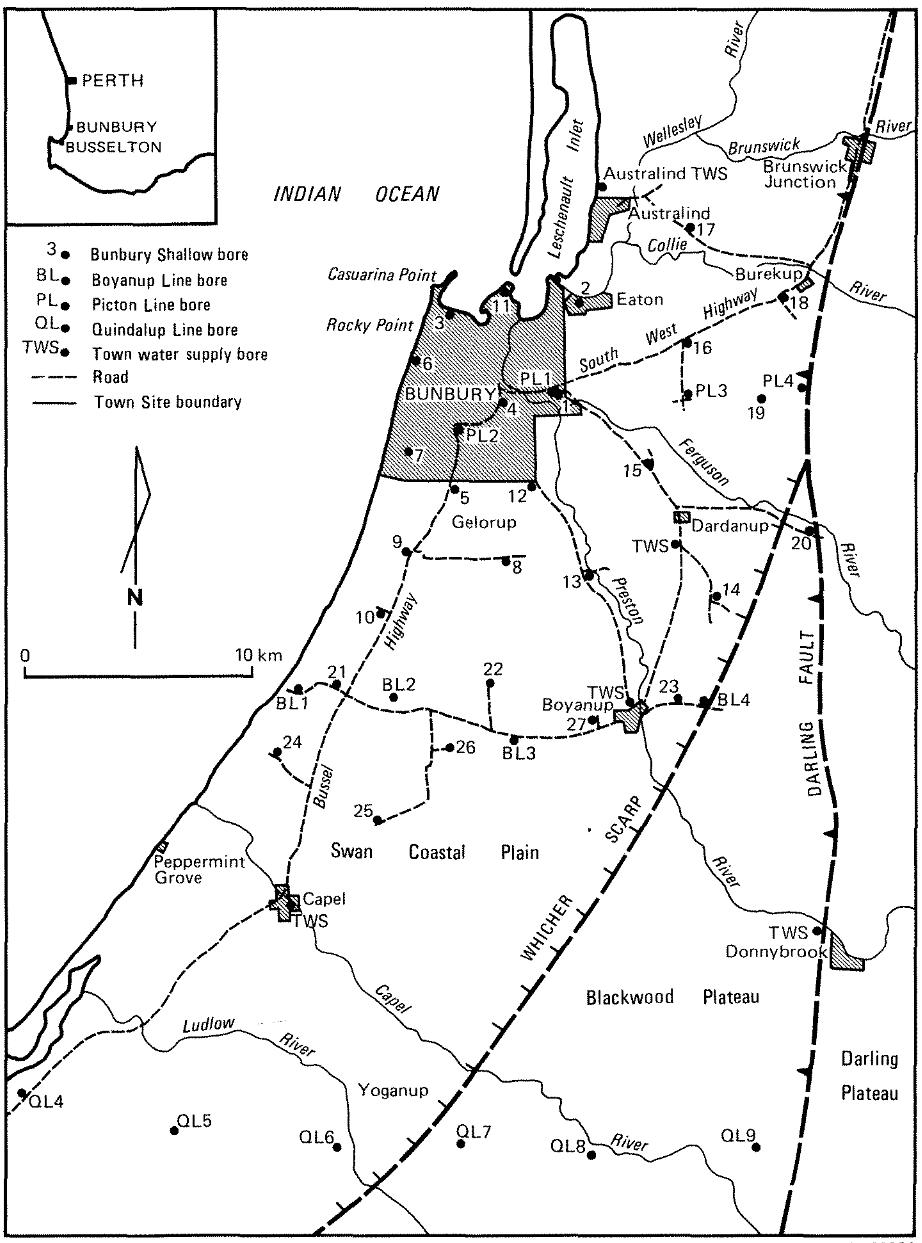


Figure 1. Locality and bore location map

down-hole hammer (air circulation) until the basalt was completely penetrated; then mud-rotary drilling was recommenced.

At each site, a bore was drilled to about 100 m (Table 1) and screened in a suitable sand. Galvanized iron-casing, 80 mm in diameter, was then inserted, usually with 80 mm in-line stainless-steel screens. In some bores, 50 mm or 40 mm telescoping screens were inserted after cement grouting, then 80 mm casing or blank casing was used and later perforated at the observation interval with explosive charges.

A shallow bore at each site was subsequently drilled and screened just below the water table, or where there was clay at the surface in the shallowest sand. At one site (BS4) three bores were drilled to monitor the Leederville and Yarragadee Formations as well as the water table.

Strata samples were taken at 3 m intervals and are stored in the GSWA core library. Gamma-ray logs have been run in all the bores, some prior to casing (in conjunction with resistivity logs) and others after casing.

Development and sampling of the bores was by air-lifting, and the water samples were analysed by the Government Chemical Laboratories (Table 2).

All the bores have been levelled to Australian Height Datum (AHD) by the Mines Department Surveys and Mapping Division or by the Public Works Department (PWD).

Since the completion of the bores, water levels have been monitored by the Public Works Department, and bore hydrographs collated in reports by Boyd (1979) and Ventriss and Boyd (1981).

Pumping bores were drilled at seven sites selected by Leech (1977). Of these sites only five were tested.

A pumping bore drilled at BS27 encountered basalt at the depth screened by BS27A, thus preventing aquifer testing, and at BS25 testing was abandoned when the screen lodged within the casing and could not be retrieved.

The pumping bores were located 30 to 50 m from the exploratory bore, which was used for observation during the pumping tests, and were cased with 155 mm steel casing with 6 metres of 100 mm-diameter stainless steel screen. A 100 mm-diameter electric submersible pump capable of a maximum pumping rate of 1 208 m^3/d was used. Step drawdown-tests were carried out to determine the bore efficiency followed by a constant-rate pumping test of up to 8 hours duration (Table 3).

Transmissivities and storage coefficients were calculated by matching drawdown-time data from the observation bore to standard type curves (Table 3).

PHYSIOGRAPHY

The area consists of a coastal plain about 15 km wide, separated from inland plateaux by erosional scarps.

LANDFORMS

Blackwood Plateau

The Blackwood Plateau (Playford and others, 1976) is bordered in the east by the Darling Scarp, which separates it from the Darling Plateau; and in the west by the Whicher Scarp, which has resulted from marine erosion and forms the boundary to the Swan Coastal Plain (Fig. 1). The plateau is a dissected lateritized surface, developed on Cretaceous sediments, and reaches a maximum elevation of about 160 m.

Swan Coastal Plain

The Swan Coastal Plain (McArthur and Bettenay, 1974) is bounded in the east by the Whicher and Darling Scarps (Fig. 1). It can be subdivided into a number of physiographic units consisting of an alluvial plain (Pinjarra Plain) in the east, with low irregular sand dunes (Bassendean Dunes) on its western margin; and a coastal belt, extending up to 7 km inland, of parallel ridges (Spearwood and Quindalup Dunes) with interdunal swamps, lagoons and inlets.

Rocky Point and Casuarina Point, on the coast at Bunbury, are formed by outcrops of basalt.

DRAINAGE

The area is drained by rivers flowing from the Darling Plateau, and by shorter streams which rise on the Blackwood Plateau and Darling Scarp. All drainage is into Leschenault Inlet (Fig. 1), with the exception of the Capel and Ludlow Rivers.

On the Pinjarra Plain there are numerous swamps, and in the Dardanup-Brunswick area drainage ditches have been constructed.

Most of the surface water flow is during winter in response to rainfall, but small base-flows in the summer are from groundwater discharge.

Key to Table 1 ▶

(a) below ground level
(b) "Superficial formations"

Q "Superficial formations"
Kl Leederville Formation
Juy Yarragadee Formation
AHD Australian Height Datum
TDS Total Dissolved Solids

TABLE 1. BOREHOLE DATA

Bore	Elevation Top Casing (m)	Total Depth (m)	Observation Interval (m)[a]	Aquifer [b]	Potentiometric Head (m) above AHD (10/12/80)	Salinity mg/L TDS conductivity x 6.4	Status
1A		90	—				Abandoned
1B	7.796	87	78-84	Kl	15	380	Observation bore
1C	7.781	19	12-18	Q	6.18	1 210	do
2A	2.609	98	91.5-97.9	Kl	-0.16	470	do
2B	2.209	6	0-6	Q	0.61	420	do
3A	1.353	100	94-100	Juy	0.23	350	do
3B	1.348	6	3-6	Q	-0.13	4 460	do
4A	8.444	80	80-81	Juy	1.44	420	do
4B	8.549	8	5-8	Q	5.91	540	do
4C	8.264	20	17-20	Kl	1.77	2 130	do
5A	8.046	110	99-105	Juy	4.84	770	do
5B	8.029	9	6-9	Q	4.72	510	do
6A	1.913	98	91.5-97.5	Juy	-0.87	630	do
6B	1.923	8	5-8	Q	0.37	8 190	do
7A	7.434	102	96-102	Juy	1.39	620	do
7B	7.564	12	6-12	Q	3.12	1 460	do
8A	24.420	106	99.5-105.5	Juy	6.12	380	do
8B	24.310	6	3-6	Q	21.36	200	do
9A	11.715	102	96-102	Juy	5.11	440	do
9B	11.730	12	6-12	Q	7.30	320	do
10A	10.457	102	—	Juy	5.71	250	Abandoned
10B	10.557	12	6-12	Q	6.43	860	Observation bore
10C	—	77	70.8-76.8	Juy	—	—	Pump bore
10D	—	76	68-74	Juy	—	—	Observation bore
11A	—	66	—	—	—	—	Abandoned
11B	6.388	110	87-98.6	Juy	0.96	380	Observation bore
11C	6.224	18	15-18	Q/Kl?	0.99	42 100	do
12A	16.703	102	96-102	Kl/Juy	5.90	414	do
12B	16.718	5	2-5	Q	15.18	380	do
13A	24.180	84	77-82	Kl	23.28	760	do
13B	24.225	27	19.5-25.5	Kl	16.31	1 100	do
13C	24.210	72	47-50	Kl	22.42	400	do
14A	42.943	98	79-85	Kl	29.46	520	do
14B	43.088	21	18-21	Kl	33.34	305	do
14C	—	85	79-85	Kl	—	—	Pump bore
15A	19.437	93	69-75	Kl	19.43	280	Observation bore
15B	19.492	19	13-19	Q	18.99	2 080	do
16A	14.428	99.6	74-80	Kl	13.38	290	do
16B	14.538	18	15-18	Q	13.74	2 810	do
16C	—	80	74-80	Kl	—	—	Pump bore
17A	13.580	108	75-81	Kl	8.58	330	Observation bore
17B	13.705	17	14-17	Q	7.50	1 250	do
18A	18.887	100	76-82	Kl	12.84	510	do
18B	18.972	15	12-15	Q	13.41	4 970	do
18C	—	82	76-82	Kl	—	—	Pump bore
20A	47.410	103	55-67	Kl	26.99	420	Observation bore
20B	47.505	19	15-18	Kl	42.82	2 240	do
21A	14.025	105	84-90	Juy	6.51	350	do
21C	13.526	25	18-24	Juy	4.42	880	do
22A	25.171	100	77-83	Juy	8.79	—	do
22B	25.168	15	9-15	Q	21.66	1 200	do
22C	—	83	77-83	Juy	—	820	Pump bore
23A	39.496	96	84-90	Kl	34.86	700	Observation bore
23B	39.548	20	15-18	Q	35.29	170	do
24A	2 602	18	13-16	Kl	0.8	790	Observation bore
24B	2.978	106	92-97	Kl/Juy	6.2	290	do
25A	15.873	100	89-95	Kl/Juy	12.31	490	do
25B	15.919	15	12-15	Q	15.34	1 720	do
25C	—	95	86-92	Kl/Juy	—	—	Abandoned
26A	21.641	100	90-96	Juy	8.09	1 110	Observation bore
26B	21.884	15	12-15	Q/Juy	19.48	1 110	do
27A	36.280	100	77-83	Kl	30.78	690	do
27B	36.261	25	19-25	Kl	30.52	1 220	do
27C	—	86	—	—	—	—	Abandoned
27D	—	85	76-85	Kl	—	—	do

TABLE 2. CHEMICAL ANALYSES OF WATER SAMPLES

Bore	TDS C x 6.4	Hardness	Mineral matter in mg/L						
			Ca	Mg	Na	K	Cl	SO_4	HCO_3
					Superficial Formations				
BS1C	1 209	105	6	22	345	8	443	158	94
BS2B	416	74	10	12	88	10	140	42	44
BS3B	4 460	906	129	142	1 160	52	1 970	246	549
BS4B	537	78	10	13	136	4	193	11	116
BS5B	505	255	43	36	56	7	55	280	20
BS6B	8 192	1 569	179	273	2 260	79	4 040	550	377
BS7B	1 459	400	91	42	299	6	498	85	290
BS8B	204	25	2	5	48	4	76	11	19
BS9B	320	56	6	10	72	3	117	13	46
BS10B	864	179	34	23	195	7	342	21	128
BS11B	42 100	8 800	641	1 750	14 100	455	25 700	3 390	323
BS12B	384	99	25	9	75	18	90	19	169
BS13B	1 100	184	8	40	251	9	461	46	51
BS14B	307	61	8	10	54	3	86	19	79
BS15B	2 080	283	36	47	485	3	880	22	98
BS16B	2 809	497	33	101	715	7	1 350	97	70
BS17B	1 254	311	34	55	267	11	522	90	90
BS18B	4 966	1 208	79	246	1 200	10	2 490	230	104
BS20B	2 240	460	41	87	527	8	1 020	87	101
BS21C	883	166	14	32	199	8	383	39	37
BS22B	1 241	195	6	44	257	5	497	68	8
BS23B	166	14	1	3	43	2	55	21	15
BS24B	288	76	19	7	49	19	58	8	150
BS25B	1 721	272	12	59	458	8	850	67	
BS26B	1 107	217	18	42	260	3	501	34	55
BS27B	1 216	217	18	42	290	5	528	69	49
					Leederville Formation				
BS1B	377	62	7	11	75	14	129	20	48
BS2A	473	118	31	10	94	13	131	14	171
BS4C	2 131	413	60	64	524	13	886	123	234
BS13A	755	154	14	29	117	18	328	24	0
BS13C	396	58	2	13	85	14	160	20	18
BS14A	518	81	8	15	117	7	210	17	38
BS15A	275	48	8	7	57	9	92	11	52
BS16A	294	46	7	7	62	10	101	13	46
BS17A	332	56	8	9	72	12	106	15	79
BS18A	512	158	32	19	82	14	187	8	101
BS20A	422	80	6	16	82	13	174	15	18
BS23A	697	148	25	21	143	15	257	40	102
BS27A	691	182	32	25	139	11	279	36	85
					Yarragadee Formation				
BS3A	352	95	25	8	55	31	79	14	156
BS4A	422	100	19	13	79	21	134	18	112
BS5A	768	158	29	21	173	7	306	28	101
BS6A	627	127	13	23	126	13	265	27	20
BS7A	620	99	20	12	144	13	239	26	79
BS8A	377	83	12	13	68	18	123	17	78
BS9A	435	62	12	8	101	7	167	5	61
BS10A	249	42	7	6	48	19	64	17	76
BS11B	377	83	17	10	74	14	118	14	99
BS12A	416	121	37	7	68	18	102	16	152
BS21A	345	84	19	9	65	20	82	21	142
BS22C	819	134	6	29	215	5	386	37	27
BS24A	787	170	47	13	188	6	264	29	211
BS25A	486	83	7	16	105	15	194	22	43
BS26A	1 107	161	7	35	274	9	498	49	18

TABLE 3
PUMPING-TEST RESULTS

Boresite	Pump Rate m^3/d	Aquifer	Transmissivity m^2/d	Hydraulic Conductivity m/d	Storage Coefficient x 10^{-4}
BS10	1 208	Yarragadee	109	18	2.0
BS14	89	Leederville	40	(a) 13	2.4
BS16	1 080	Leederville	88	14	10
BS18	1 118	Leederville	130	21	2.4
BS22	670	Yarragadee	15	(b) 2.5	1.5

(a) Screened interval partially in clay, 3 m operative length assumed.
(b) This result is low, possibly due to poor hydraulic connection between bores.

GEOLOGY

SETTING

The Bunbury area lies within the southern Perth Basin in the Bunbury Trough (Playford and others, 1976), which contains up to 8 000 m of sediments, bounded on the east by the Darling Fault and the Precambrian crystalline rocks of the Yilgarn Block.

The near-surface stratigraphic succession for the Bunbury area is given in Table 4.

STRATIGRAPHY

Cockleshell Gully Formation

The Cockleshell Gully Formation was not encountered in the Bunbury shallow bores but has been intersected by deep bores in the Boyanup and Picton Lines (Smith, pers. comm; Wharton 1980, 1981). A thickness of 634 m was penetrated in Picton Line 1, although the maximum thickness is believed to be about 1 500 m (Playford and others, 1976).

The formation consists of fine to granular, moderately sorted, weakly consolidated quartz sand with accessory garnet and pyrite, which is interbedded with grey silty-shale and carbonaceous shale in beds up to 12 m thick, often containing beds of soft lignite. It is a continental deposit of Early Jurassic age.

Yarragadee Formation

The Yarragadee Formation conformably overlies the Cockleshell Gully Formation. It subcrops beneath the Bunbury Basalt or the Leederville Formation, and beneath the superficial formations in a small area south of Bunbury (Fig. 2), and was intersected at 18 sites.

The formation is probably about 1 300 m thick in the axis of the Bunbury Trough, however the maximum thickness intersected was 1 115 m, in QL9 (Wharton, 1981). The formation thins northwards to 187 m in PL2 (Wharton, 1980), owing to removal of the upper part by erosion.

TABLE 4
STRATIGRAPHY OF THE BUNBURY AREA

Age	Formation	Maximum Thickness (m)	Lithology
CAINOZOIC			
Quaternary			
(Holocene)	Safety Bay Sand	70	Sand
(Pleistocene)	Tamala Limestone	50	Limestone, sand
	Bassendean Sand	20	Sand
	Guildford Formation	25	Clay, sand
Pliocene?	Yoganup Formation	20	Sand
	UNCONFORMITY		
MESOZOIC			
Cretaceous	Leederville Formation	380	Sand, siltstone, shale
(Lower)	Bunbury Basalt	85	Basalt, in places weathered to clay
	UNCONFORMITY		
Jurassic	Yarragadee Formation	1 300	Sand, minor shale
(Upper-Middle)			
(Lower)	Cockleshell Gully Formation	1 500	Sand and Shale

The formation is composed of interbedded sand, shale and siltstone. The basal part of the formation is predominantly sand, but the proportion of sand decreases to 25 per cent in the upper 500 m in QL9 (Wharton, 1981).

The sand is predominantly pale-grey quartz, ranging from fine sand to fine gravel with moderate to good sorting, and is weakly consolidated. Layers containing heavy minerals and pyrite are common.

The shale is dark-grey to brown-grey, slightly silty or sandy and moderately consolidated. Carbonaceous material is common, ranging from carbonaceous shale to hard, vitreous coal, occurring in lenses and seams rarely up to 2 m thick (Wharton 1980).

Near Bunbury, where the Yarragadee Formation is directly overlain by Bunbury Basalt and by the superficial formations, the shales are weathered yellow and the sand grains coated with yellow iron-oxides.

The formation was laid down in a continental environment, and ranges in age from Middle to Late Jurassic.

Bunbury Basalt

The Bunbury Basalt unconformably overlies the Yarragadee Formation and is overlain by the Leederville Formation. It crops out between Rocky Point and Casuarina Point at Bunbury and is

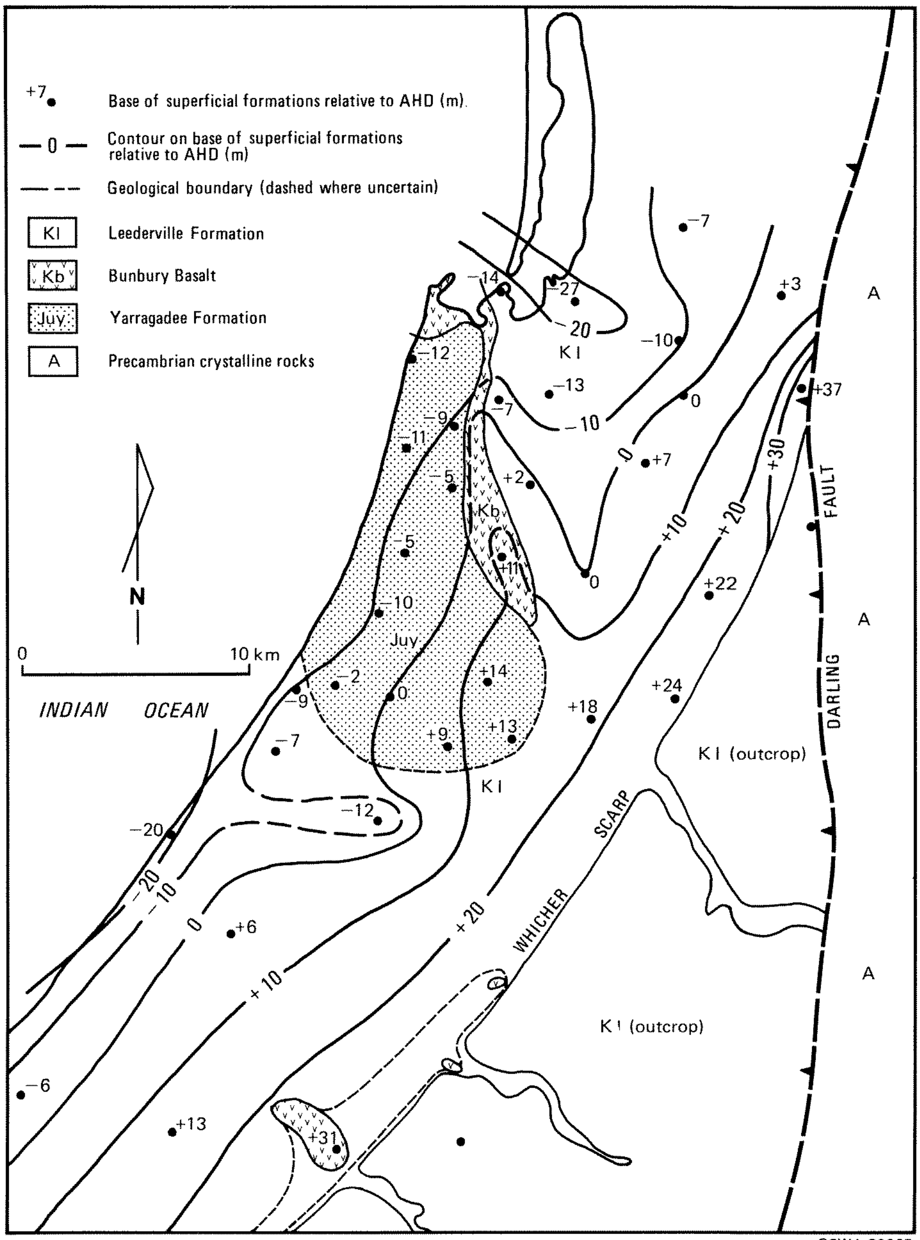


Figure 2. Sub-outcrop map and structure contours on the base of the superficial formations

exposed in the Gelorup quarry and mineral-sand pits at Yoganup (Burgess, 1978; Wharton 1981). In the subsurface it occurs as a sinuous body extending northwards from Yoganup to Boyanup and Bunbury (Fig. 5). Its presence can be determined locally by ground-magnetic surveys and inferred regionally from the aeromagnetic data (Bureau of Mineral Resources, 1960).

The basalt is described as a porphyritic tholeiitic basalt (Trendall, 1962; Burgess, 1978; Wilde and Walker, 1979). In outcrop it is fresh and displays columnar jointing, but in the subsurface, the top and bottom of the basalt are commonly weathered to a chocolate-brown or bluish clay. In places, the full thickness of basalt is altered, as in PWD Eaton 1 where the clay is 24 m thick (Emmenegger, 1963b); weathered horizons also occur within the basalt and Trendall (1962) has described a scoriaceous horizon in the Sunnywest Boyanup bore separating distinct "flows" (Fig. 3). Sand and sedimentary clays have also been reported from within the basalt and such a clay from QL6 may be of Early Cretaceous age (Wharton, 1981).

The maximum thickness intersected by drilling in the area is 85 m at Boyanup, but the thickness may change rapidly in a short distance. Drilling at BS27 has shown that the top of the basalt differs in elevation by at least 24 m in bores only 50 m apart, and in Bunbury the thickness increases by 50 m between BS24 and the Bunbury Water Board (BWB) Robertson bore, a distance of n.p. 200 m.

Coastal erosion prior to the deposition of the superficial formations in Bunbury has formed steep cliffs of basalt which have subsequently been covered by Tamala Limestone or Safety Bay Sand, except on the beach at Casuarina and Rocky Points. The position of these cliffs is known from borehole evidence within Bunbury (Commander, 1981).

The basalt is postulated to be either a number of surface flows from a source near the Darling Fault deposited in deeply incised valleys (Lowry, 1965), or the result of extrusion along fault lines (Burgess, 1978). Evidence from boreholes for either origin is inconclusive, but the rapid changes in thickness and the position of the basalt along the possibly faulted western margin of the Dardanup Syncline (Fig. 3; Fig. 4), could be more readily explained as the result of extrusion from several centres along a fault line within the Perth Basin.

Leederville Formation

The Leederville Formation rests unconformably on the Yarragadee Formation and the Bunbury Basalt. It crops out on the Blackwood Plateau, where it has been lateritised to a massive laterite and pisolitic gravel; on the coastal plain it is covered by the superficial formations. The formation is thickest in the Dardanup Syncline (Fig. 4) and the maximum known thickness of 384 m was penetrated in QL9 (Wharton, 1981).

The formation consists of interbedded sand, siltstone and shale, with rare conglomerate and coal seams. It can be broadly divided into a lower predominantly shaley section, and an upper sandy section, but individual beds are not persistent and cannot be correlated with certainty between boreholes.

The sands are composed of weakly consolidated, poorly to moderately sorted, fine- to very coarse-grained quartz with accessory feldspar and heavy minerals. The siltstones and shales are generally dark grey, brown grey and grey green, micaceous and commonly carbonaceous and pyritic. Red clay which occurs in bores at the mineral sand mines near Capel may represent derived basaltic material at the base of the Leederville Formation.

Quartzite pebbles are common in the Boyanup-Dardanup area in a lower part of the formation, and Maitland (1913) describes a quartzite pebble bed, 25 m thick, in the Dardanup bore (Fig. 3).

Carbonaceous material ranges from carbonaceous shale and carbonised plant material to lignite, and occurs mainly as thin lenses or disseminated chips in shale; thin coal seams up to 1 m thick are indicated on wireline logs (Wharton, 1981).

Palynological analyses indicates that the formation is of Early Cretaceous age and was mostly laid down in a non-marine environment, with local marine and lagoonal sedimentation close to the present coastline.

Superficial formations

The superficial formations consist of a number of littoral, alluvial, eolian and estaurine sediments of Pliocene to Holocene age. They rest on a gently west-sloping unconformity surface on the coastal plain (Fig. 2) and extend up the main valleys in the Blackwood Plateau. The slope of the unconformity surface is broken by more resistant islands of Bunbury Basalt near Bunbury and Yoganup, and by a deeper channel at the mouth of the Collie River.

Yoganup Formation: The Yoganup Formation (Low, 1971) is a shore-line deposit along the base of the Whicher Scarp consisting of leached and ferruginized beach sand and conglomerate containing mineral sands (Baxter, 1977; Wilde and Walker, 1979).

The formation was encountered in BS23 where it is a medium to coarse quartz-sand with accessory heavy minerals and minor clay.

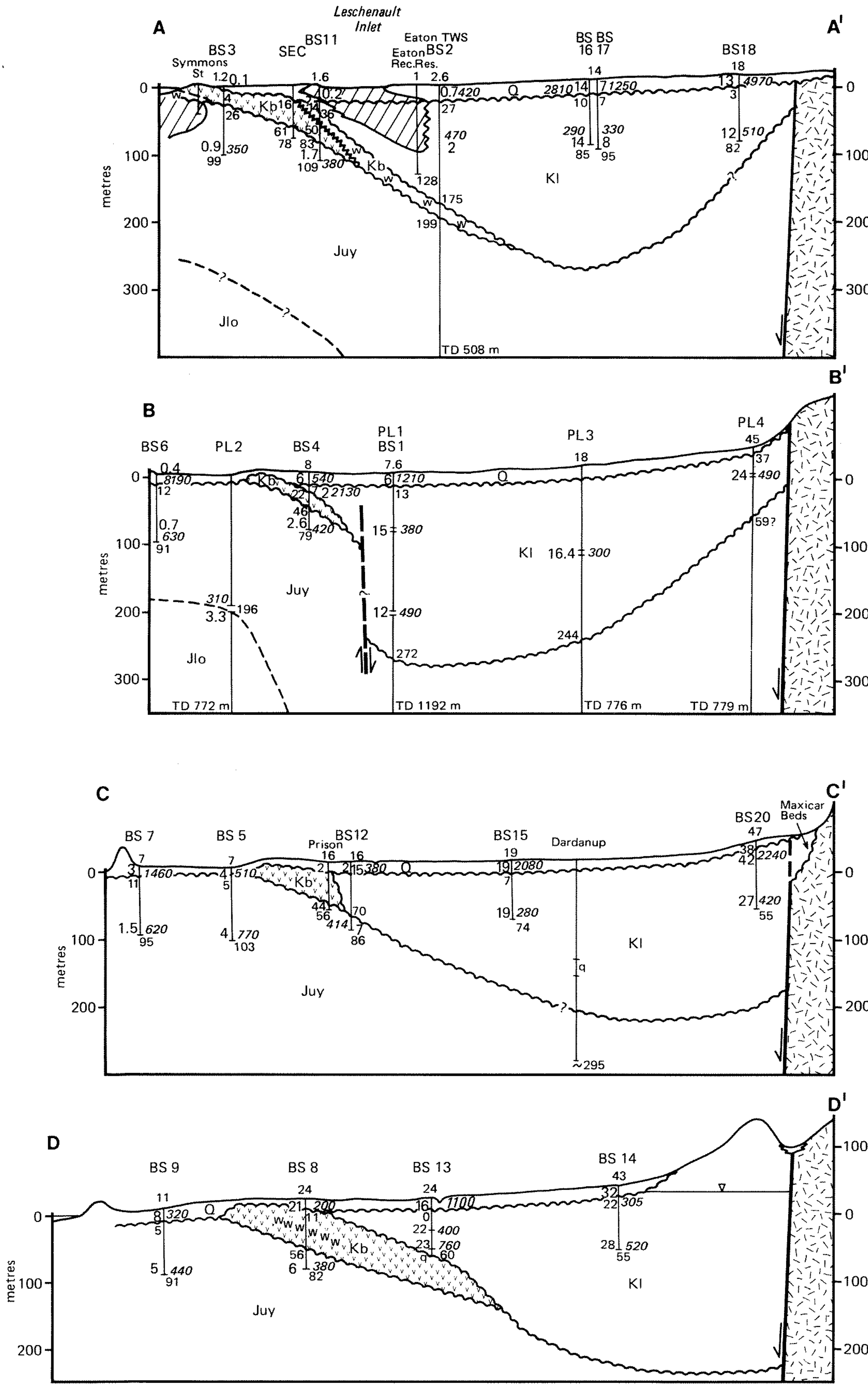
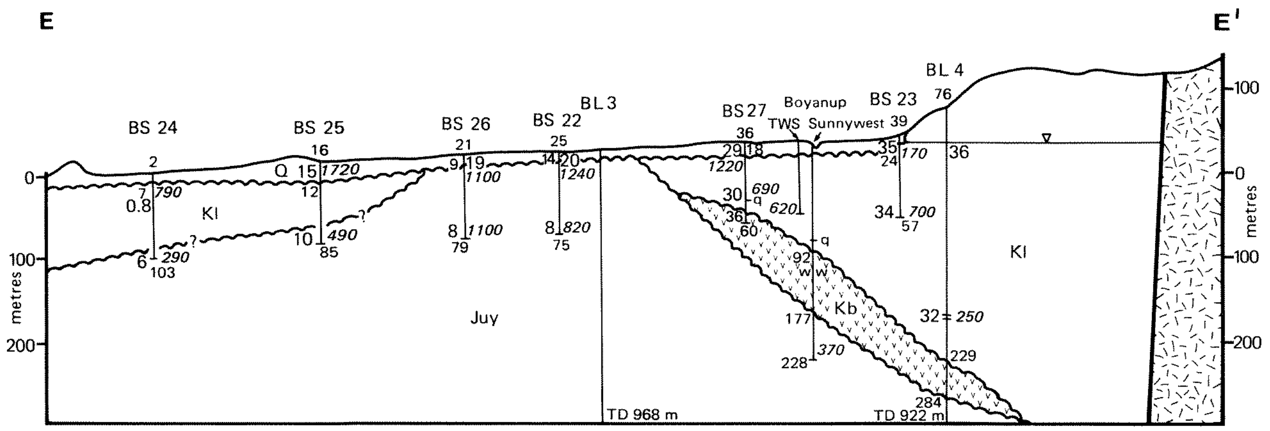
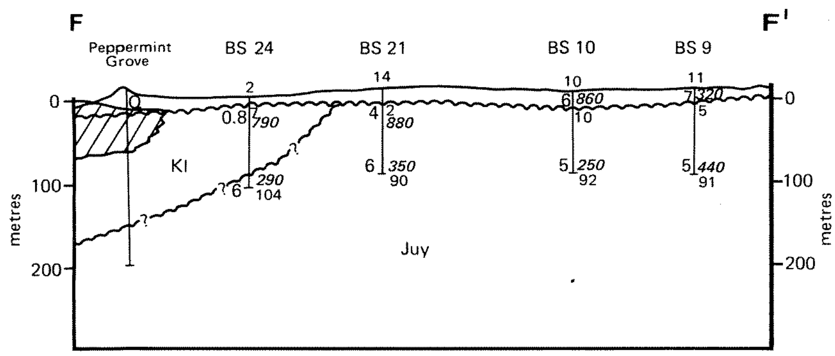
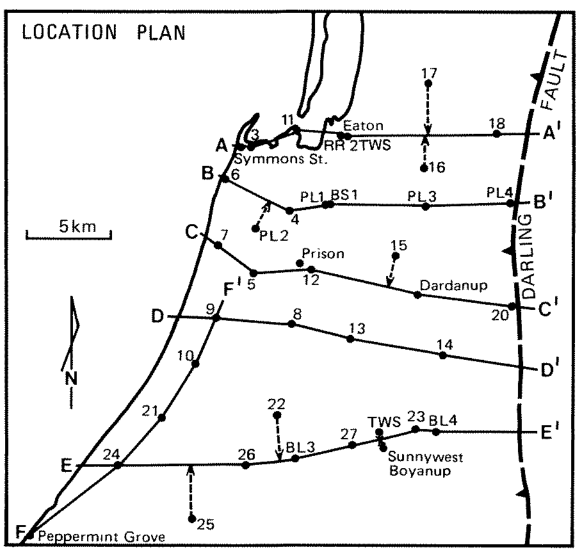


Figure 3. Hydrogeological cross-section







5 km

$\frac{V}{H} = \frac{1}{20}$

REFERENCE

- Q — Superficial formations
- Kl — Leederville Formation
- q — Quartz or quartzite pebbles
- Kb/w — Bunbury Basalt (fresh/weathered)
- Juy — Yarragadee Formation
- Jlo — Cockleshell Gully Formation
- Precambrian crystalline rocks
- 9 — Elevation of natural surface above AHD (m)
- 90 — Bore depth below AHD (m)
- 2 — Unconformity (metres above or below AHD)
- 170 — Formation boundary (metres above or below AHD)
- 16 — Potentiometric head (metres above AHD)
- *520* — Salinity, mg/L TDS
- Extent of saline water
- Water table

GSWA 20066

Guildford Formation: The Guildford Formation (Low, 1971) is an alluvial deposit extending westwards from the Yoganup Formation and underlying the Pinjarra Plain. Similar alluvium occurs in the valleys of the Ferguson, Preston, Capel and Ludlow Rivers within the Blackwood Plateau.

The formation consists mainly of brown, or dark-grey clay with thin beds of sand towards the base. It ranges in thickness from 15 m to 30 m.

Bassendean Sand: The Bassendean Sand (Playford and Low, 1972) is a series of dunes forming a discontinuous zone of low hills. The formation reaches a maximum thickness of about 20 m in the west, where it directly overlies Mesozoic sediments, and thins eastwards where it overlies, or interfingers with, the Guildford Formation.

The formation consists of medium- to coarse-grained white quartz sand, with mineral-sand deposits (Capel shoreline) at its base in the Capel area (Baxter, 1977).

Tamala Limestone: The Tamala Limestone (Playford and others, 1976) is an eolian calcarenite which forms elongated dunes in a 4-5 km-wide belt parallel to the present coastline. It extends from about 10 m below to about 48 m above sea-level and overlies the Yarragadee Formation, Bunbury Basalt and Leederville Formation. Its eastern margin is believed to overlie the Bassendean Sand. The formation ranges from coarse-grained unconsolidated quartz-sand to lithified calcarenite.

Safety Bay Sand: The Safety Bay Sand (Playford and others, 1976) is a narrow strip of vegetated and

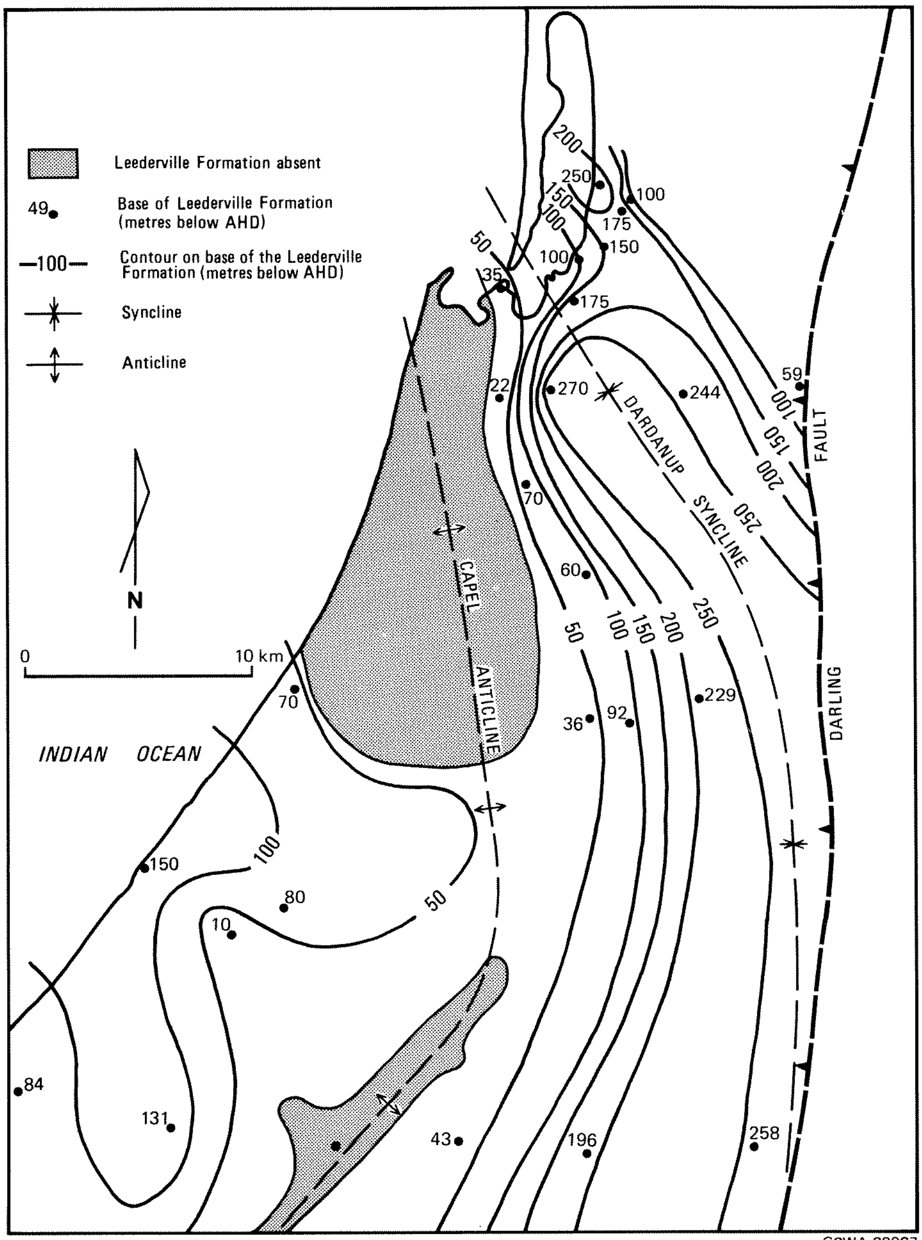


Figure 4. Leederville Formation; extent and structure contours on the base

mobile dunes, consisting of unlithified calcareous sand, along the coastline. It extends to 68 m above sea-level and overlies the Tamala Limestone, Bunbury Basalt, and alluvial and estuarine clays.

Miscellaneous alluvial and estuarine deposits: A number of black, brown, green and red clays intercalated with sands and calcarenites underlie the west of Bunbury (Commander 1976, 1981) and rest directly on basalt or Mesozoic sediments. These units presumably represent Quarternary alluvial or estuarine sediments, including clays reworked from weathered basalt.

Lagoonal muds separate the Safety Bay Sand and the Tamala Limestone beneath the peninsula, west of Leschenault Inlet (Barnes, 1974), and similar muds have been intersected in BS21 and BS24 where they directly overlie the Yarragadee or Leederville Formations.

Alluvium of Holocene age occurs along the rivers which traverse the coastal plain.

STRUCTURE

The structure of the area is illustrated by the geological sections (Fig. 3).

The Yarragadee and Cockleshell Gully Formations are east dipping and abut the Precambrian crystalline-rocks along the Darling Fault (Smith, pers. comm; Wharton 1980, 1981).

The Leederville Formation is gently folded so that its thickest development is in the Dardanup Syncline (Fig. 4), the axis of which parallels the Darling Fault

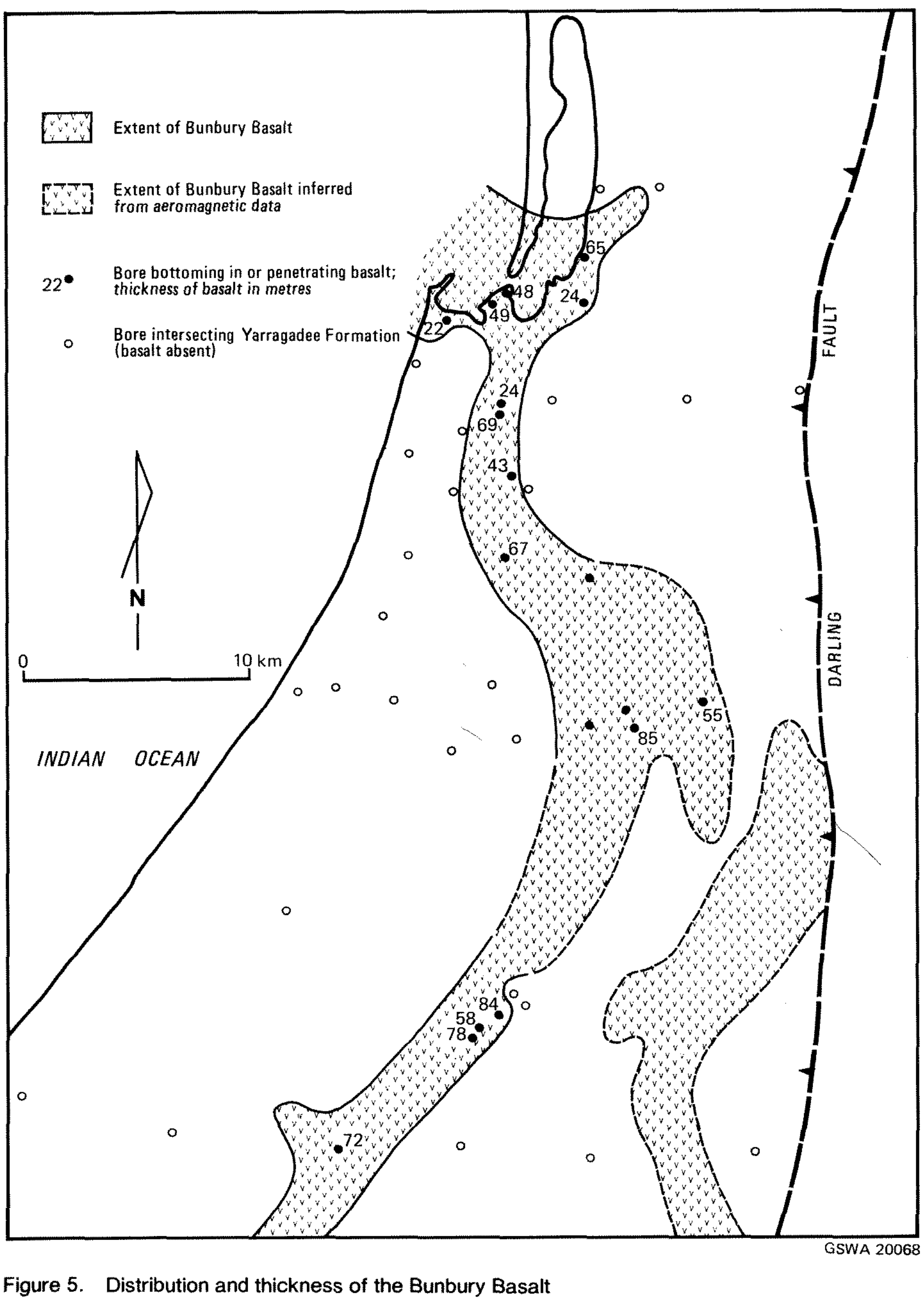


Figure 5. Distribution and thickness of the Bunbury Basalt

south of Donnybrook and trends northwestwards from Donnybrook to Eaton. The formation thins westwards where it has been eroded from the crest of the Capel Anticline (Fig. 4). The Dardanup Syncline and Capel Anticline are probably developed over fault blocks in the Jurassic sediments. It is possible that faulting extends into the Leederville Formation just west of PL2, where there is a steep apparent dip (Fig. 3, Cross-section BB).

HYDROGEOLOGY

AQUIFERS

Superficial Formations

Groundwater Flow: The superficial formations together form a relatively thin and predominantly clayey unconfined aquifer in which groundwater flow is generally in a westerly direction. However, vertical flow is significant in the areas of low relief on the Pinjarra Plain where there are often substantial vertical hydraulic-gradients in both upwards and downwards directions. Groundwater relationships between the superficial formations and the underlying aquifers are illustrated on Figure 6.

Recharge to the superficial formations (Fig. 7) is mostly from rainfall. Some recharge, by upward groundwater flow, takes place from the Leederville Formation in areas where there are upward hydraulic heads (Fig. 8).

Groundwater discharges to the ocean and the coastal swamps near Capel, to the Collie and Preston Rivers (as indicated by the water-table contours, Figure 7), and to drains in the Dardanup area. Discharge also takes place by direct evaporation from swamps and evapotranspiration from vegetation where the water table is shallow, especially in the Guildford Formation near Dardanup where detailed studies have shown the potential exists for upward groundwater-flow (George, 1980). Groundwater flow from sandy superficial formations into the Yarragadee and Leederville Formations occurs where the hydraulic head is downwards at BS 5, 7, 9 and 10, and to a lesser extent BS 22, 25 and 26 where the strata are more clayey (Fig. 8).

The average seasonal variation in the elevation of the water table (Fig. 8) is about 1 m, but is lower (0.3-0.6 m) in sandy sediments near the coast, and higher (2-3 m) in clayey sediments in the southeast. There have been no long-term trends in water levels apparent since 1977, except in BS1C where there has been a slight decline (Ventriss and Boyd, 1981), the reason for which is unknown.

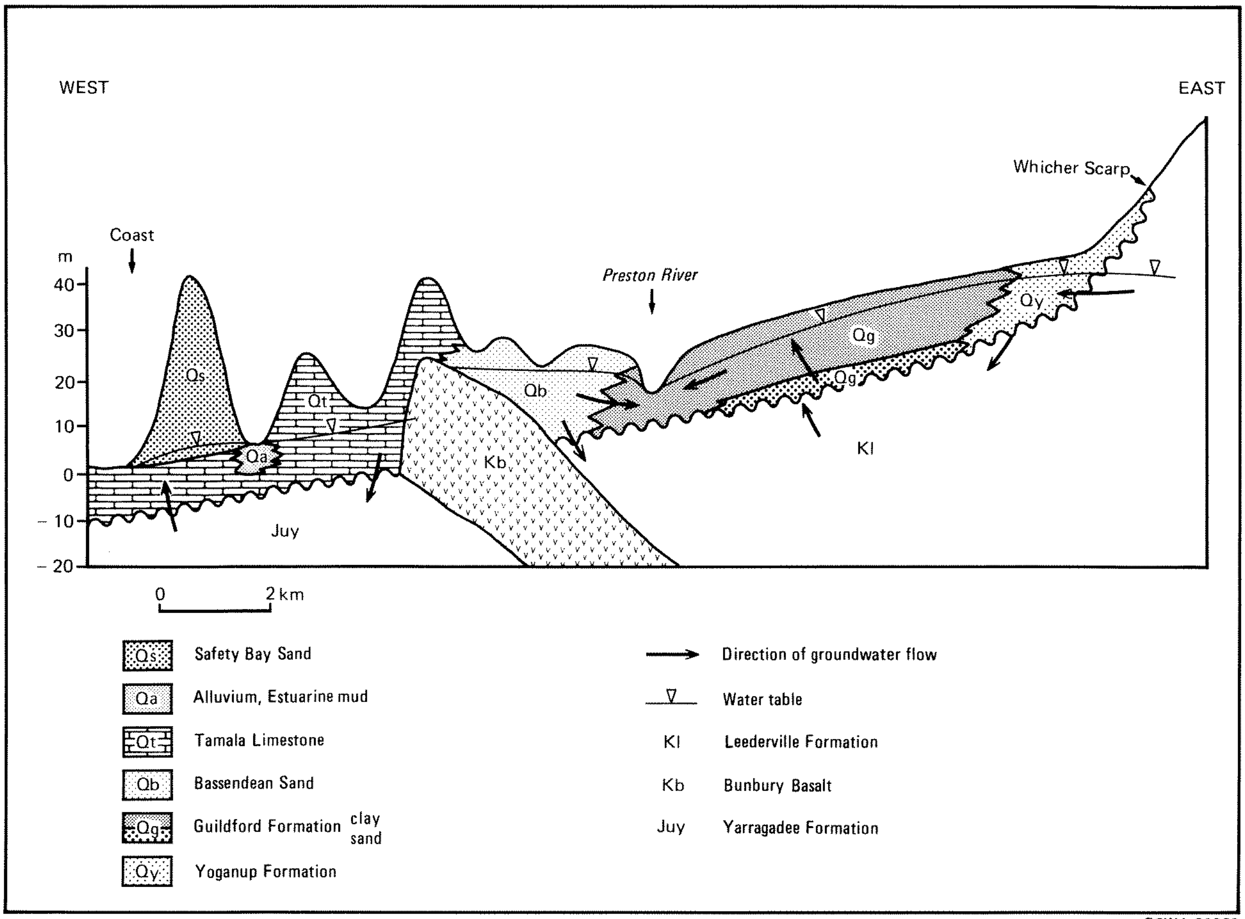


Figure 6. Diagrammatic section of the superficial formations illustrating directions of groundwater flow

Groundwater Quality: Groundwater tends to be fresh in areas of sand, and brackish to saline in areas of clay (Fig. 9). In the Yoganup Formation (BS23B) and nearby (BS14B), and in the Bassendean Sand (BS8B, BS12B), the salinity is less than 500 mg/L (Table 2). The salinity is less than 1 000 mg/L in the Tamala Limestone, but close to the coast in the Safety Bay Sand salinities are higher (Fig. 9), due in some cases to mixing with sea water.

The groundwater in the Guildford Formation exceeds 1 000 mg/L and ranges up to 5 000 mg/L between Dardanup and Burekup. The high salinities are in areas of heavy clay soils where the water table is shallow, surface drainage poor and where upward groundwater-discharge concentrates salts near the surface. Soil-salinity problems also occur in these areas of naturally high groundwater-salinity and these are made worse by irrigation, using water from Wellington Dam (George, 1980).

The major ions analysed in the groundwater are given in Table 2. Nitrate is present in significant amounts in BS7B and BS3B (40 mg/L, 22 mg/L) and in BS10B and BS17B (4 mg/L) and BS20B (3 mg/L); fluoride and boron concentrations do not exceed 0.6 mg/L and 0.7 mg/L respectively. The sulphate concentration in BS5B (280 mg/L) is anomalously high.

Development: Groundwater from the superficial formations is used only for on-farm domestic and stock supply and for irrigation of gardens in the urban areas of Bunbury, Australind, Eaton and Gelorup.

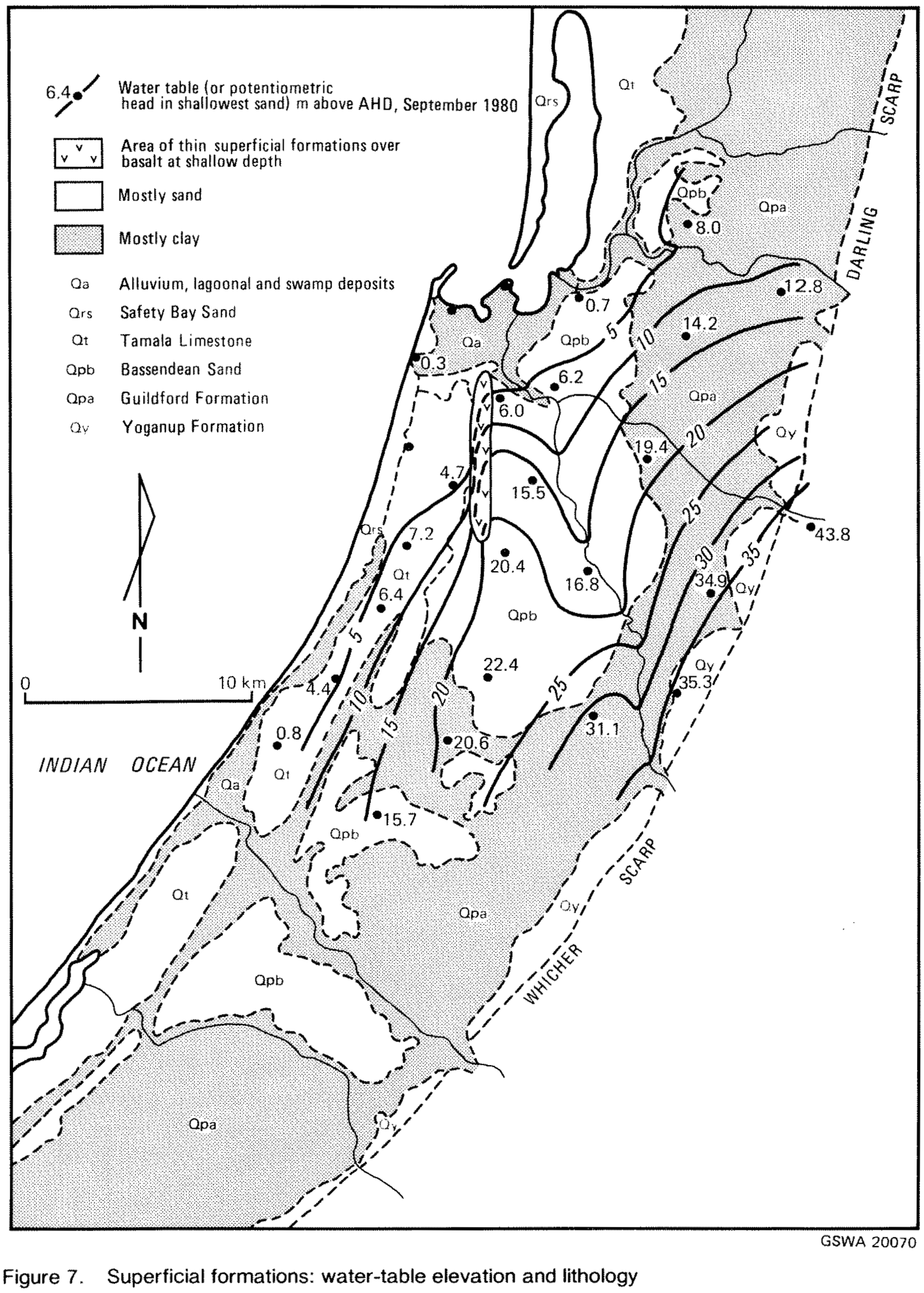


Figure 7. Superficial formations: water-table elevation and lithology

Leederville Formation

Groundwater Flow: A groundwater flow-system occurs in the Leederville Formation in the Dardanup Syncline, which is apparently partly connected with another flow-system in the Leederville Formation to the west of the Capel Anticline (Fig. 10).

Recharge to the eastern flow-system takes place by direct infiltration from rainfall and minor streams on the Blackwood Plateau. There is also some recharge through the Yoganup Formation and Bassendean Sand on the coastal plain where the hydraulic head is downwards (Fig. 8).

The Preston and Capel River valleys are not sources of recharge because they are incised below the regional potentiometric surface; flowing bores (e.g. QL8) may occur in these valleys.

Groundwater flow is northerly from the recharge areas on the Blackwood Plateau and is laterally restricted by the Darling Fault to the east and by the Capel Anticline to the west. The flow system is confined by the clays of the Guildford Formation on the coastal plain.

There are large vertical differences in hydraulic head within the formation. In the Blackwood Plateau the hydraulic head decreases with depth, and in QL8 there is a head difference of at least 30 m between the top and bottom of the formation. On the coastal plain the highest heads are in the middle of the

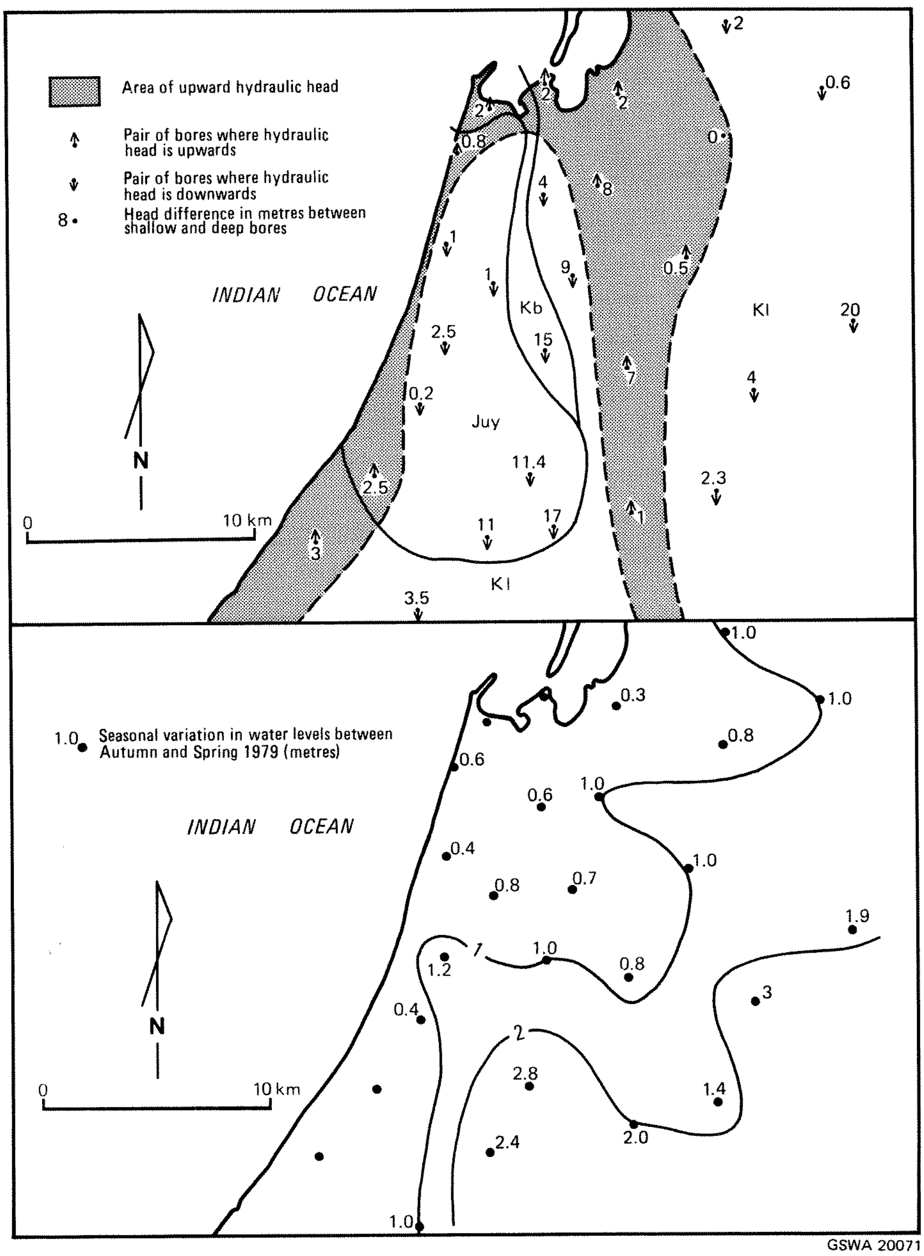


Figure 8. Superficial formations: hydraulic-head difference with the confined aquifers and seasonal variation in water table elevation

formation, with upward groundwater-flow to the superficial formations and downward groundwater-flow to the Yarragadee Formation—in which the hydraulic head (Fig. 11) is generally much lower. Because of the large, vertical, head differences within the formation, the water levels measured in the Bunbury Shallow bores are not strictly comparable and consequently the potentiometric-head map (Fig. 10) is only approximate.

Near Leschenault Inlet, groundwater flow is northwestward and groundwater discharge presumably takes place along the inlet above a body of intruding sea-water (Fig. 10). This is present in the upper part of the formation and overlies fresh water (Plate 1, Section AA).

The sea-water interface in the Leederville Formation occurs along the southeast shore of Leschenault Inlet (Fig. 10), and extends to depths of 45 m in the Bunbury Foods bore (Commander 1981), 100 m in the Eaton Recreation Reserve bore and to about 100 m in the Laporte 5 bore, but is west of the Australind town-water-supply bores.

West of the Capel Anticline the direction of groundwater flow is probably northwestwards (Fig. 10). Recharge takes place from the superficial formations east of the Bussell Highway where there are downward hydraulic-heads, and there is possibly some flow from the main flow-system in the Dardanup Syncline between the subcropping areas of Bunbury Basalt and Yarragadee Formation, shown on Figure 4.

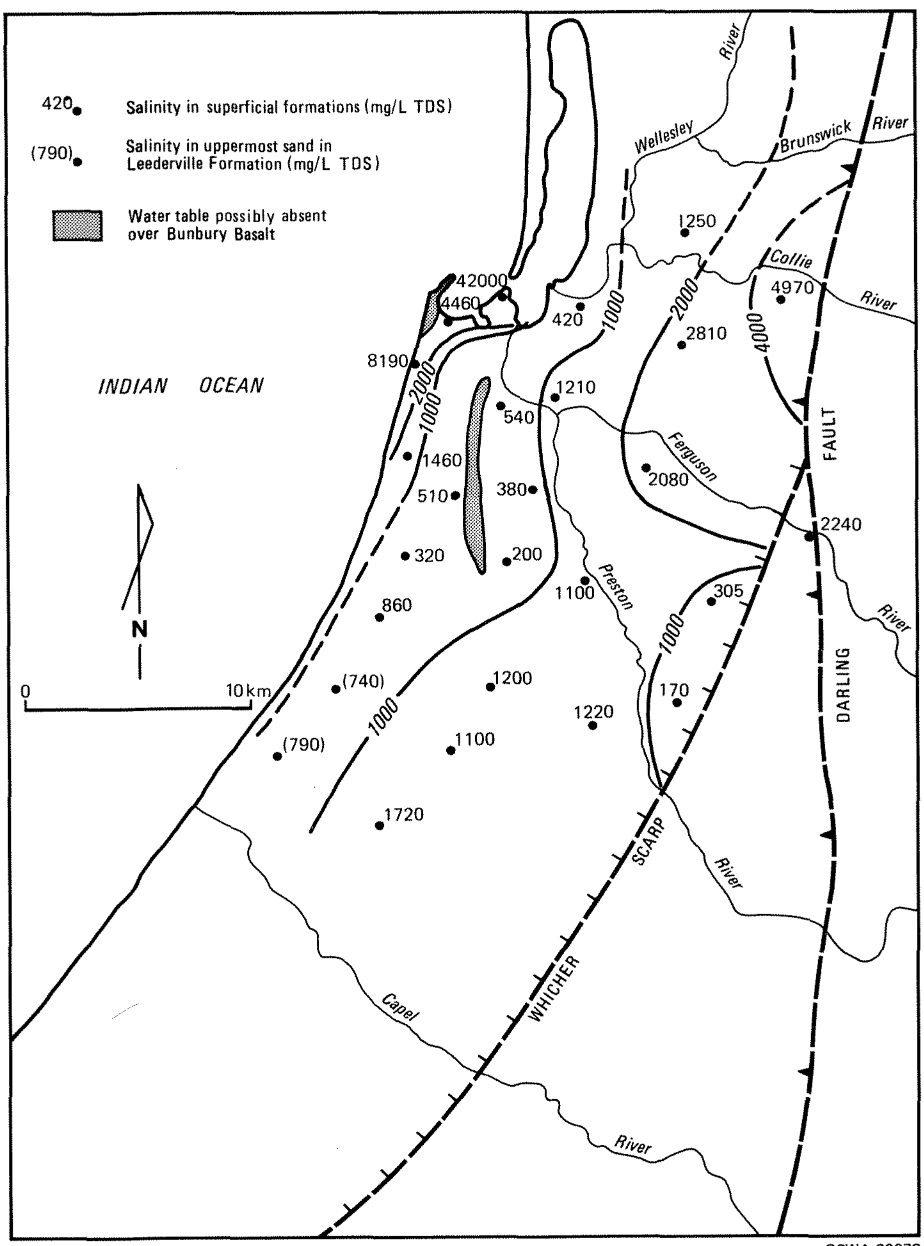


Figure 9. Superficial formations: salinity (mg/L TDS)

Discharge occurs into the coastal swamps through the superficial formations. A seawater-freshwater interface identified in the uppermost 60 m of the formation at Peppermint Grove provably extends along the coast (Fig. 10).

Throughflow: The throughflow (Q) in the Leederville Formation, across the width of the Dardanup Syncline, can be calculated from the equation:

$$Q = k\, b\, i\, l \text{ —(1)}$$

where k is the hydraulic conductivity of the sands
b is the average thickness of sand
i is the hydraulic gradient
l is the width of the section

using k = 15 m/day, derived from pumping tests (Table 3)

b = 100 m, based on lithological logs of bores and the cross sections (Fig. 3)

$i = 1.3 \times 10^{-3}$ (from Fig. 10) and

i = 15 000 m (along the 20 m potentiometric contour on Figure 10),

$Q = 15 \times 100 \times 1.3 \times 10^{-3} \times 15\,000$
$= 29\,250 \text{ m}^3/\text{day}$
$= 10.7 \times 10^6 \text{ m}^3$ per year
$\simeq 11 \times 10^6 \text{ m}^3$ per year.

There is insufficient data to calculate the throughflow west of the Capel Anticline.

Groundwater Quality: Groundwater salinity in the Leederville Formation is less than 1 000 mg/L, except close to the sea water interface.

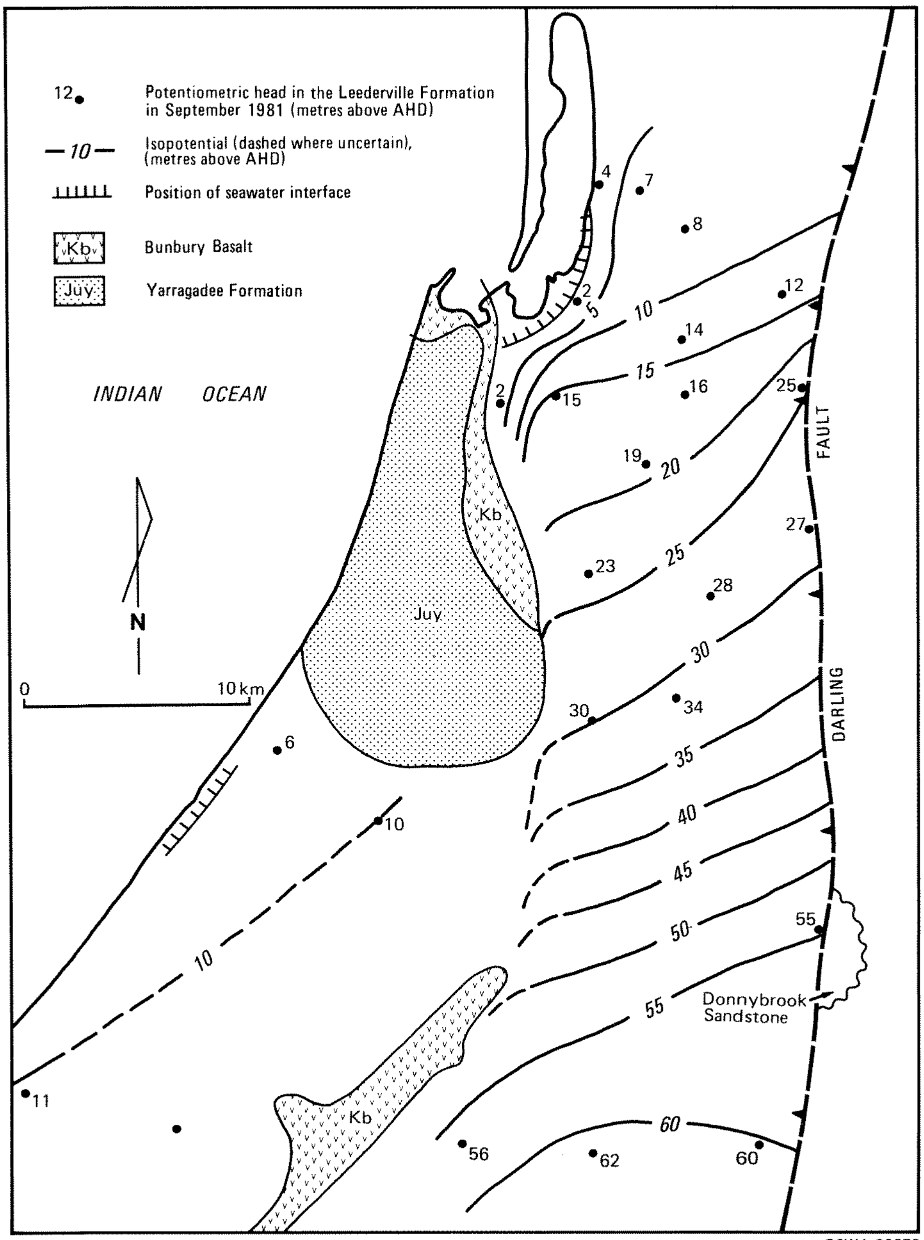


Figure 10. Leederville Formation: potentiometric head

In the Dardanup Syncline the lowest-salinity water (less than 300 mg/L in BS15 and BS16) occurs in the uppermost, sandy part of the formation which is preserved in the centre of the syncline. In the lower, more clayey part of the formation the salinity ranges up to 800 mg/L.

The salinity in BS4C of 2 131 mg/L is somewhat anomalous, but may be caused by local recharge of brackish water from the superficial formations.

Most groundwater in the Leederville Formation is of sodium-chloride type (Table 2) although in BS2A the proportion of bicarbonate exceeds that of chloride. Analyses for iron were not made because the samples were aerated, but the concentration of iron is low enough (less than 0.3 mg/L) in the Dardanup and Australind town-water-supply bores not to warrant treatment. Boron and fluoride concentrations do not exceed 0.3 mg/L.

Development: Groundwater from the Leederville Formation is used by the Australind, Dardanup and Donnybrook town-water supplies; by a few industrial consumers between Dardanup and Eaton; and by farms for domestic and stock water especially in areas where the groundwater in the overlying superficial formations is brackish or saline.

The estimated abstraction is less than 1 x $10^6 m^3$ per year, about one tenth of the estimated throughflow, consequently there is potential for further development. In the Eaton-Australind area there may be future problems with inland movement

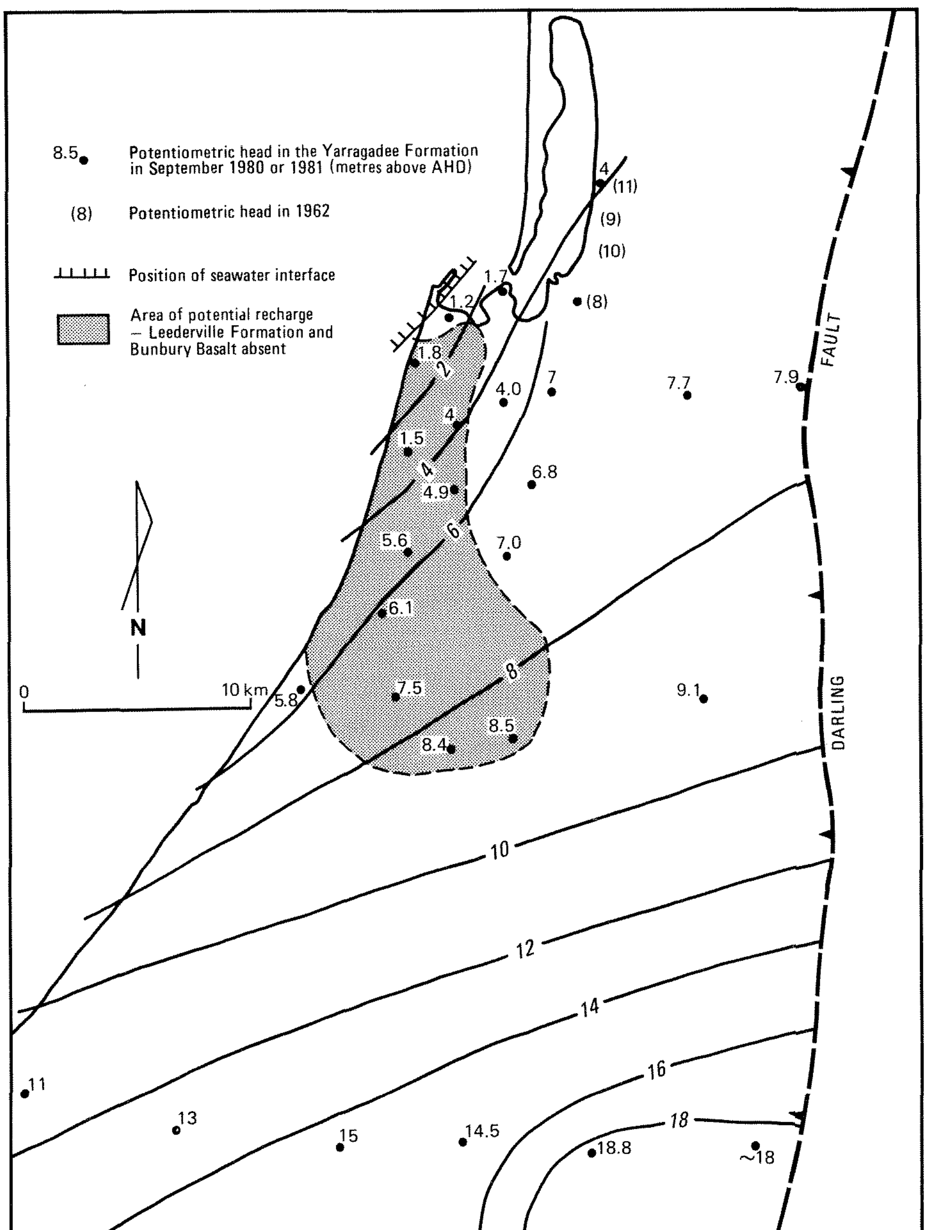


Figure 11. Yarragadee Formation: potentiometric head

of the sea water interface. At BS2A the water level has been progressively lowered by nearby groundwater abstraction and is now below sea-level for several months each year, indicating that there is potential for landward movement of the sea water interface.

Yarragadee Formation and Cockleshell Gully Formation

Groundwater Flow: A major fresh-groundwater flow-system occurs in the Yarragadee Formation and extends throughout the Perth Basin in the Bunbury area. The base of the flow system is an interface with saline or hypersaline groundwater and this often coincides with the contact between the sands of the Yarragadee Formation and the interbedded sands and shales of the Cockleshell Gully Formation.

The interface is at a depth of about 1 000 m in the Quindalup Line bores, within the Yarragadee Formation (Wharton, 1981); at a depth of about 800 m in the Boyanup Line bores, at the contact of the Yarragadee and Cockleshell Gully Formations (Smith, pers. comm.); and at a depth of 600 m in the Picton Line bores at the contact of the Yarragadee and Cockleshell Gully Formations, except in PL2 where the formation contact is shallower and the flow system also occurs in the upper part of the Cockleshell Gully Formation.

Most of the groundwater flow is in the lower, sandy part of the formation because the upper part, which is preserved close to the Darling Fault (Smith, pers. comm.; Wharton 1980, 1981) is predominantly clayey.

The Bunbury shallow bores which encountered the Yarragadee Formation (Fig. 11), penetrated only a small proportion of the total thickness of the formation. There are only small vertical variations in potentiometric head so that a relatively reliable isopotential map can be drawn. The isopotential map shows that the groundwater flow is from south to north, and to the northwest close to Bunbury. The main recharge to the aquifer is inferred to take place on the Blackwood Plateau south of the Quindalup Line. Recharge also takes place from the Leederville Formation and from the superficial formations on the coastal plain.

In the shaley upper part of the Yarragadee Formation in PL4 and QL9 there are large vertical hydraulic gradients. The groundwater salinity in this part of the Yarragadee Formation is similar to that in the overlying Leederville Formation, and groundwater flow is presumed to occur between the two formations.

The potentiometric head in the Laporte (Australind) and Eaton bores in 1962/3 was 9 to 11 m above sea level (Passmore 1962, Emmenegger, 1963a). These heads are significantly higher than those presently recorded in the Picton Line bores (Fig. 11), suggesting either that there has been a decline in head over a sufficiently large area to affect the Picton Line bores, or that there is a local source of recharge from the north, presumably by leakage through the Leederville Formation.

The natural seasonal variation in water level in the aquifer is about 0.6 m, but near to Bunbury the annual change in water level is increased due to abstraction for Bunbury water supply (Commander, 1981). Hydrographs (Ventriss and Boyd, 1981) show that in bores affected by pumping the water levels are lowest in February, whereas in bores elsewhere the levels are lowest in March or April.

Discharge from the Yarragadee Formation occurs via the superficial formations into the ocean southwest of Bunbury, where the confining Leederville Formation and Bunbury Basalt are absent.

The sea-water interface is probably a complex series of sea-water wedges and is mostly offshore, presumably parallel to the isopotentials. The interface has been encountered by drilling, only in the Symmons Street bore near Casuarina Point, where saline water occurs below the Bunbury Basalt (Rowston, 1969). The interface here may have been drawn inland by the reduction in potentiometric head in the upper 50 metres of the Yarragadee Formation, caused by pumping for Bunbury water-supply.

Throughflow: The throughflow (Q) in the Yarragadee Formation across the 10 m potentiometric-head contour (Fig. 11) can be estimated from equation (1). Using a hydraulic conductivity (k) of 20 m/day (derived from pumping tests at BS10 and from BWB bores Table 3), an average thickness (b) of 600 m of sand in the formation, (from information along the Boyanup Line), and a hydraulic gradient (i) of 0.4 x 10^{-3} between PL2 and the 14 m potentiometric contour, the throughflow across the 38 km length (l) of the 10 m potentiometric-head contour on Figure 11 is—

$Q = 20 \times 600 \times 0.4 \times 10^{-3} \times 38\,000 \simeq$
$180\,000\ m^3/d \simeq 66 \times 10^6\ m^3$ per year.

Groundwater Quality: The groundwater salinity of the flow system in the Yarragadee Formation and Cockleshell Gully Formation is mostly less than 500 mg/L. It is lowest in the Quindalup Line bores (less than 200 mg/L), and increases northwards to 300-360 mg/L in the Picton Line bores (Wharton 1980, 1981).

At the base of the flow system there is a rapid salinity increase to 10 000 mg/L or more, within 100 m. (Smith, pers. comm.; Wharton 1980, 1981). A maximum salinity of 51 700 mg/L occurred about 400 m below the interface in PL1 (Wharton, 1980).

In the Laporte bores at Australind (Passmore, 1962) the salinity ranges up to 1 133 mg/L, which may be due to local brackish recharge from the Leederville Formation.

The major ionic constituents analysed in the Yarragadee Formation groundwater, from the Bunbury shallow bores, are sodium chloride or sodium bicarbonate (Table 2). Relatively high concentrations of iron are a feature of groundwater in Bunbury where concentrations of as much as 6.6 mg/L occur (Commander, 1981) and treatment is usually necessary for town-water-supply use. Manganese concentrations of 4.3 mg/L and 8.0 mg/L have been measured from two BWB bores (Commander, 1981), but are small elswhere. Boron and fluoride concentrations are usually less than 0.2 mg/L, except in BS21A (0.5 mg/L) and BS10A (0.6 mg/L).

Development: The Yarragadee Formation is used for town-water supply, industry, and mineral-sand processing. Estimates of usage are given in Table 5.

Groundwater abstraction in Bunbury has caused a lowering of the potentiometric head in the upper part of the aquifer within the city, and a steepening of the hydraulic gradient to the east. The amount by which the potentiometric surface has been drawn down since abstraction began is unknown, but records of SEC bores drilled in 1955 show that the potentiometric head was 3 to 4 metres above AHD, whereas in spring 1980 the head was less than two metres above AHD, suggesting that there has been a decline in head of only one to two metres in 25 years. The seasonal pumping in Bunbury has caused a variation in water levels of as much as 5 m in observation bores close to production bores (Commander 1981, Ventriss and Boyd, 1981).

TABLE 5
ESTIMATED GROUNDWATER ABSTRACTION FROM THE YARRAGADEE FORMATION

Consumer	Annual abstraction (x 10^6 m^3)
Town Supply (metered)	
Bunbury (Town supply)	7
(Parks and gardens)	1
Australind/Eaton	0.6
Boyanup	0.14
Capel	0.13
Industry (estimated from licensed bore capacity)	
Laporte (Australind)	3
Cable 1956 Ltd (Koombana Bay, Stratham)	1.4
State Energy Commission (Bunbury)	0.3
Australian Minerals Consolidated (Capel South)	2.5
WSL Group (Capel North, Yoganup)	2.5
TOTAL	18.57

There has been a substantial lowering of potentiometric head in the Eaton-Australind area since pumping began in the early 1960s. The potentiometric head in the uppermost part of the Yarragadee Formation, in PWD Eaton 3 bore, had declined from 8.5 m (AHD) in 1963 to a mean close to sea-level (Ventriss and Boyd, 1981), due to abstraction from the Laporte borefield.

In Bunbury there are seasonal fluctuations in the salinity of BWB bores close to the ocean due to landward movement of the salt-water interface (Commander, 1981).

CONCLUSIONS

The Bunbury shallow-drilling programme has refined the known extent and structure of the Bunbury Basalt and of the two major aquifers in the area, the Yarragadee and Leederville Formations.

The bores provide a grid which defines the potentiometric surface of the two major aquifers and has enabled the calculation of throughflow. It is estimated that annual throughflow is 66 x 10^6 m^3 in the Yarragadee Formation and 11 x 10^6 m^3 in the Leederville Formation.

Monitoring of the bores has provided data on the effects of groundwater abstraction in and near Bunbury, and will assist the future management of the aquifers.

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PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1981

by K. A. Crank and A. Janssens

ABSTRACT

The increase in petroleum exploration in Western Australia, noted in 1980, continued in 1981, although metres drilled decreased slightly. In 1981, 42 exploration wells were completed, compared with 32 in 1980, and eight were drilling ahead at the end of 1981 for a total penetration of 86 268 m, compared with 91 733 m in 1980. The decrease of 6% in metres drilled was caused by the drilling of a number of relatively shallow onshore wells in 1981. The average depth of wells spudded and drilled to total depth in 1980 and 1981 was 2 388 m and 1 796 m respectively. There was virtually no change in the number of rig months in 1980 (71.1 versus 73.2). Two development wells were drilled in the Barrow Island oilfield and four (including one water-disposal well) in the Dongara gasfield in 1981.

Highlights of the year included the oil discovery at Blina 1, the first commercial oil to be found in the Canning Basin; a major offshore gas discovery at Gorgon 1; and small gas discoveries in the Wyloo and Tubridgi wells in the onshore Carnarvon Basin.

Land seismic surveys increased by 144%, from 4 898 km in 1980 to 11 932 km in 1981, and marine seismic surveys increased by 14%, from 19 089 km in 1980 to 21 732 km in 1981.

INTRODUCTION

Exploratory drilling for petroleum in Western Australia over the past two years is illustrated in the following tables:

Type of well	Wells completed		Wells drilling on 31 December	
	1980	1981	1980	1981
New-field wildcats	21	19	4	2
New-pool wildcats	11	2	0	1
Extension tests	0	14	2	5
Stratigraphic tests	0	4	0	0
Shallower-pool tests	0	3	0	0
Total	32	42	6	8

Basin	Metres drilled—by Basin			
	1980 Onshore	1980 Offshore	1981 Onshore	1981 Offshore
Bonaparte Gulf	0	3 589	0	2 956
Browse	—	13 058	—	0
Canning	5 447	4 880	16 568	0
Carnarvon	11 554	11 845	14 209	17 191
"Exmouth Plateau"	—	16 284	—	926
Perth	18 383	0	32 572	1 770
Eucla	0	2 573	0	0
Officer	4 120	—	76	—
Totals	39 504	52 229	63 425	22 843
	91 733		86 268	

One oil discovery was made in 1981, at Blina 1 in the northern Canning Basin. Gas discoveries were made in the offshore Carnarvon Basin, in Gorgon 1, and onshore in the same basin near Onslow, in the shallow Wyloo 1 and Tubridgi 1 wells.

Figure 1 summarizes seismic activity since 1969. Geophysical survey activity in 1980 and 1981 is shown below.

Type of survey	Line km	
	1980	1981
Land seismic	4 898	11 932
Marine seismic	19 089	21 732
Land gravity	226	1 350
Marine gravity	1 328	1 645
Marine magnetic	3 587	1 289
Aeromagnetic	0	2 400

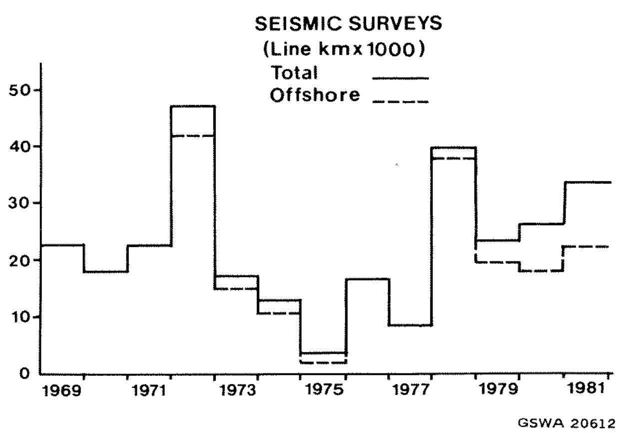

Figure 1. Seismic Surveys since 1969.

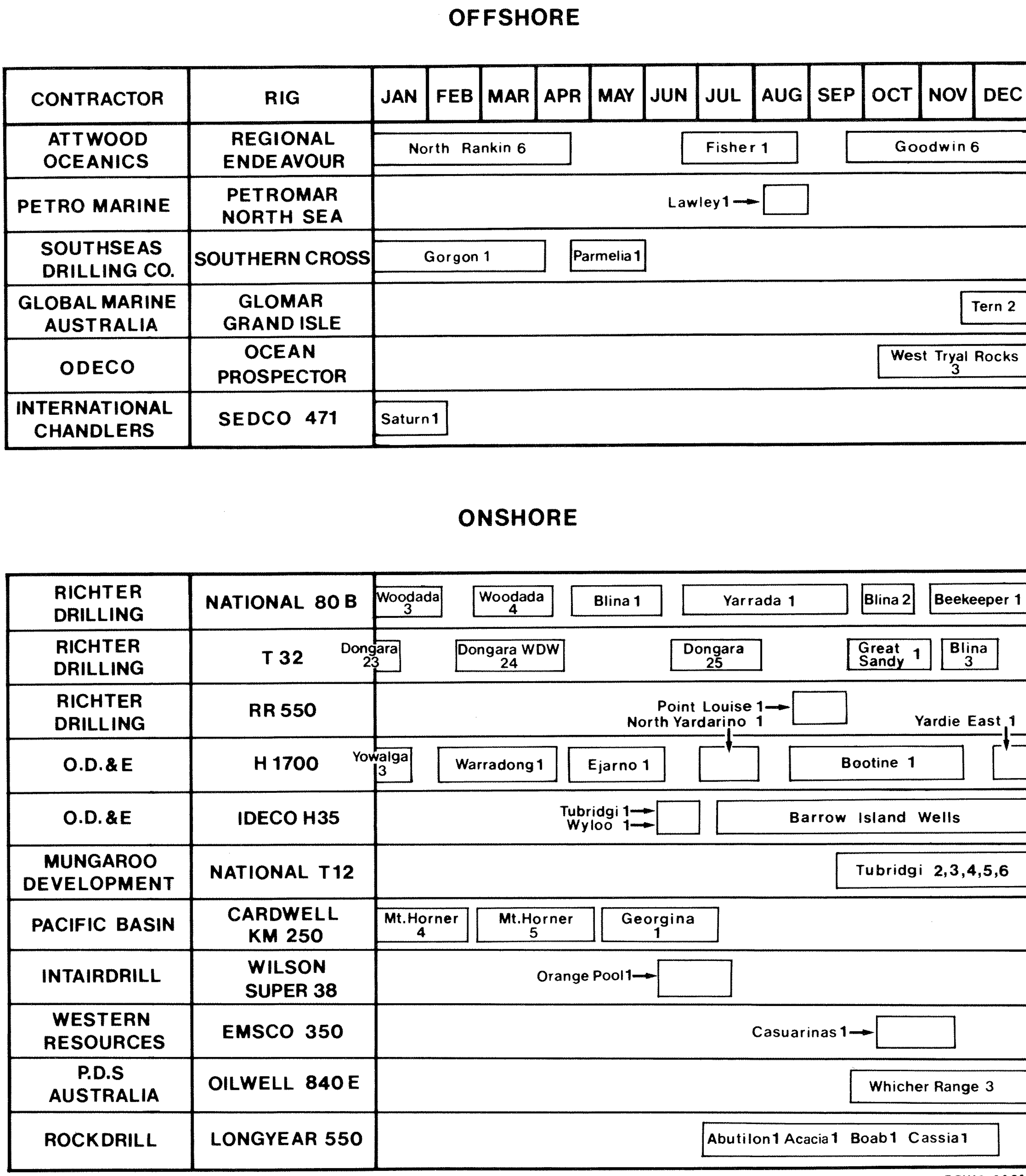

Figure 2. Rig Utilization, 1981.

DRILLING

DRILLING OPERATIONS

Expressed in rig months, there was a slight decrease in overall exploration operations from 73.2 in 1980 to 71.7 in 1981. Offshore operations decreased by 57% to 20.0 rig months in 1981 compared to 47.3 rig months in 1980. However, onshore there was an increase of 100% from 25.9 to 51.7 rig months.

These changes in rig utilization reflect a severe shortage of offshore drilling rigs and the interest generated by recent onshore discoveries at Blina, Tubridgi and Woodada. Three of the offshore rigs used in 1981 were only available for part of the year. After drilling Lawley 1 and Parmelia 1, respectively, the Petromar North Sea and the Southern Cross left Western Australian waters for Victoria, and, after drilling Saturn 1, the Sedco 471 left for the Ivory Coast. Towards the end of the year the Ocean Prospector arrived from Singapore and the Glomar Grand Isle from California.

A total of 17 rigs, six offshore and eleven onshore, operated in Westen Australia. Details of rig utilization are shown in Figure 2. Two tropical cyclones interrupted drilling operations offshore in January and February, and caused a loss of 30 rig days in the drilling of Saturn 1, Gorgon 1, and North Rankin 6.

Figure 3 is a summary comparison of drilling operations for the 14-year period 1968-1981.

WELLS COMPLETED IN 1981

The location of wells drilled for petroleum exploration in Western Australia during 1981 is shown in Figure 4. Details relating to wells drilled during the year are given in Table 1. All petroleum wells drilled in Western Australia up to the end of 1981 are listed in Janssens (1982). A summary follows of the principal results of drilling in each basin during 1981.

Bonaparte Gulf Basin

The only well spudded in the (offshore) Bonaparte Gulf Basin in 1981 was Tern 2, drilled by Australian Aquitaine Petroleum Pty Ltd. It is located approximately 10 km southeast of Tern 1, which was drilled by ARCO in 1971 and abandoned after testing up to 215.2 x 10^3 m^3 of gas per day from Upper Permian sandstones. Tern 2 at the end of the year was drilling ahead at 2 496 m.

Canning Basin

During 1981, four new-field wildcats, two extension tests, and four stratigraphic tests were drilled in the onshore Canning Basin; no drilling took place offshore. One of the wildcats discovered a probably commercial oil-pool.

Home Oil Australia Ltd drilled the new-field wildcat, Blina 1, as a structural test of the Devonian reefal section on the Lennard Shelf. On test, the reefal limestone section between 1 402 m and 1 478 m produced oil at at rate of 143.9 kL/day (906 bopd) with no gas. A dolomite section above the reef also produced an oil flow (6 kL/day; 37.6 bopd). The well has since been placed on a long-term production testing programme. Home Oil subsequently drilled two successful extension tests, Blina 2 and Blina 3. Previous to Blina 1, 95 wells (including six offshore) with a total penetration of 185 504 m had been

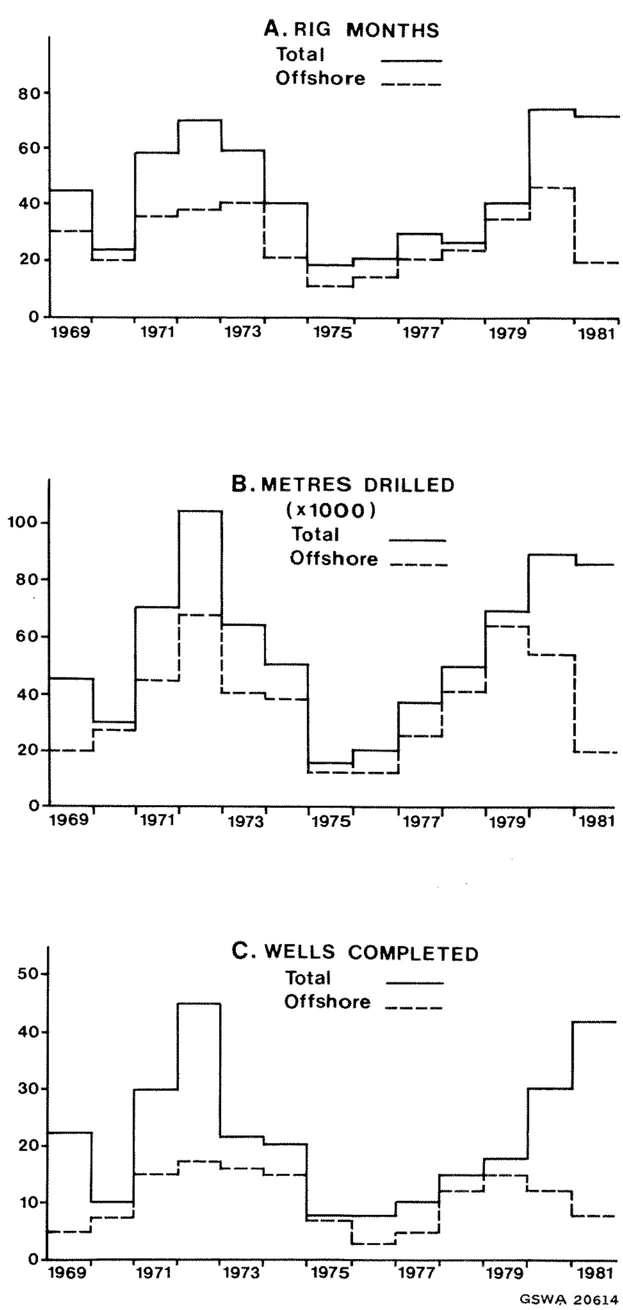

Figure 3. Drilling operations since 1968.

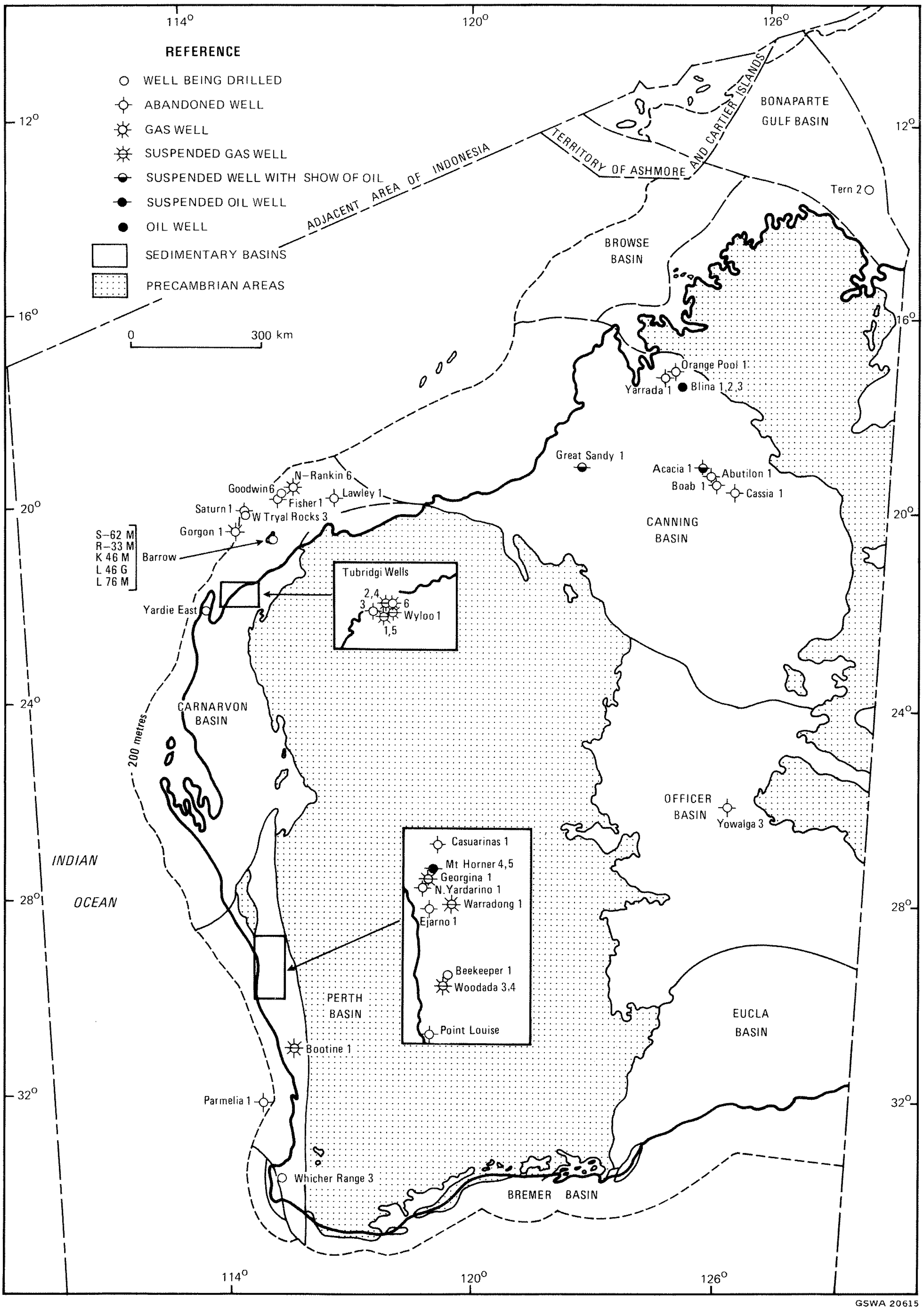

Figure 4. Map showing wells drilled for petroleum in Western Australia during 1981.

TABLE 1. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1981

Basin	Well	Concession	Operating Company	Type	Position		Elevation and water depth (m)			Dates			Total depth (or depth reached) (m)	Bottomed in	Status on 31 Dec.
					Latitude South	Longitude East	GL	RT	WD	Commenced	Reached TD	Rig Released			
Bonaparte Gulf	Tern 2	WA-18-P	Aquitaine	EXT	13°16′44″	128°07′58″	—	10	86	16/11/81	—	—	2 956	—	Drilling
Canning	Blina 1	EP129	Home	NFW	17°37′26″	124°30′02″	58	64	—	18/04/81	08/06/81	27/06/81	2 496	Devonian	Oil well
	Orange Pool 1	EP129	Home	NFW	17°18′18″	124°12′34″	29	34	—	21/06/81	14/07/81	22/07/81	1 171	Precambrian	Water well
	Yarrada 1	EP129	Home	NFW	17°22′00″	124°06′09″	21	26	—	29/06/81	20/09/81	23/09/81	3 295	Devonian	Dry, P & A
	Abutilon 1	EP143	WMC	STRAT	19°27′18″	125°07′00″	230	232	—	30/06/81	13/08/81	17/08/81	850	Devonian	P & A
	Acacia 1	EP143	WMC	STRAT	19°19′54″	124°59′42″	226	228	—	19/08/81	16/09/81	22/09/81	1 209	M. Ordovician	Oil shows, P & A
	Boab 1	EP143	WMC	STRAT	19°34′42″	125°08′45″	202	204	—	24/09/81	20/10/81	28/10/81	1 033	Silurian/Ordovician	P & A
	Great Sandy 1	EP164	Meridian	NFW	19°12′51″	122°21′11″	87	91	—	27/09/81	09/11/81	13/11/81	1 769	Ordovician	Oil shows, suspended
	Blina 2	EP129	Home	EXT	17°37′10″	124°29′46″	55	60	—	01/10/81	23/10/81	27/10/81	1 588	Devonian	Oil well
	Cassia 1	EP143	WMC	STRAT	19°44′12″	125°30′48″	194	196	—	02/11/81	14/12/81	15/12/81	1 577	U. Devonian	P & A
	Blina 3	EP129	Home	EXT	17°37′23″	124°29′48″	56	61	—	21/11/81	17/12/81	04/01/82	1 580	Devonian	Oil well
Carnarvon	Gorgon 1	WA-25-P	WAPET	NFW	20°34′43″	114°46′22″	—	21	259	11/10/80	11/01/81	19/04/81	4 401	Triassic	Gas well
	North Rankin 6	WA-1-L	Woodside	EXT	19°32′46″	116°08′27″	—	8	124	24/12/80	05/04/81	20/04/81	3 900	Triassic	Gas well, suspended
	Tubridgi 1	EP110	Otter	NFW	21°48′30″	114°48′55″	5	8	—	04/06/81	11/06/81	16/06/81	611	Triassic	Gas well, suspended
	Fisher 1	WA-28-P	Woodside	NFW	19°49′25″	115°42′32″	—	8	88	25/06/81	18/08/81	27/08/81	3 762	Triassic	Gas shows, P & A
	Wyloo 1	EP110	Otter	NFW	21°47′36″	114°51′16″	5	8	—	18/06/81	25/06/81	28/06/81	732	Triassic	Gas well, suspended
	Lawley 1	WA-58-P	Hudbay	NFW	19°54′21″	117°00′32″	—	10	60	10/08/81	24/08/81	29/08/81	1 120	Precambrian	Dry, P & A
	Barrow S-62M	PL1H	WAPET	NPW	20°45′43″	115°21′39″	9	12	—	29/08/81	09/09/81	01/10/81	1 094	Cretaceous	Suspended
	Goodwyn 6	WA-5-L	Woodside	EXT	19°43′24″	115°51′12″	—	8	124	28/09/81	—	—	4 664	—	Drilling
	Barrow R18	PL1H	WAPET	EXT	20°46′26″	115°22′08″	48	51	—	15/09/81	21/09/81	22/09/81	811	Cretaceous	Oil well
	Tubridgi 2	EP110	Otter	EXT	21°46′55″	114°50′48″	3	6	—	28/09/81	15/10/81	16/10/81	592	Triassic	Gas well, suspended
	West Tryal Rocks 3	WA-25-P	WAPET	EXT	20°09′18″	115°02′57″	—	25	162	02/10/81	01/12/81	—	4 035	Triassic	Testing
	Barrow R33M	PL1H	WAPET	NPW	20°46′56″	115°20′59″	18	22	—	03/10/81	16/10/81	18/10/81	1 080	Cretaceous	Suspended
	Tubridgi 3	EP110	Otter	EXT	21°47′22″	114°48′19″	5	8	—	20/10/81	30/10/81	04/11/81	597	Triassic	Dry, P & A
	Barrow R63	PL1H	WAPET	EXT	20°47′35″	115°21′01″	41	44	—	29/10/81	30/10/81	30/10/81	814	Cretaceous	Oil well
	Tubridgi 4	EP110	Otter	EXT	21°45′31″	114°50′00″	5	8	—	06/11/81	13/11/81	20/11/81	595	Triassic	Gas well, suspended
	Barrow L46G	PL1H	WAPET	SPT	20°48′48″	115°23′28″	49	53	—	07/11/81	10/11/81	11/11/81	585	Cretaceous	Suspended
	Barrow R43	PL1H	WAPET	EXT	20°47′03″	115°20′58″	11	14	—	12/11/81	17/11/81	17/11/81	829	Cretaceous	Suspended
	Barrow Q56M	PL1H	WAPET	SPT	20°47′18″	115°23′33″	50	54	—	19/11/81	07/12/81	07/12/81	1 052	Cretaceous	Suspended
	Tubridgi 5	EP110	Otter	EXT	21°48′37″	114°47′55″	5	8	—	22/11/81	28/11/81	04/12/81	593	Triassic	Gas well, suspended
	Tubridgi 6	EP110	Otter	EXT	21°44′41″	114°52′26″	0	3	—	05/12/81	12/12/81	—	594	Triassic	Testing
	Barrow K46M	PL1H	WAPET	SPT	20°48′43″	115°21′35″	57	60	—	09/12/81	24/12/81	25/12/81	1 004	Cretaceous	Suspended
	Yardie East 1	WA-24-P	WAPET	NFW	22°00′28″	113°55′34″	4	11	—	15/12/81	—	—	1 080	—	Drilling
	Barrow L76M	PL1H	WAPET	NPW	20°49′29″	115°23′31″	57	61	—	25/12/81	—	—	763	—	Drilling
"Exmouth Plateau"	Saturn 1	WA-84-P	Phillips	NFW	19°54′36″	114°56′41″	—	11	1 178	01/12/80	28/01/81	05/02/81	4 000	Triassic	Dry, P & A
Perth	Mt Horner 4	EP96	XLX	EXT	29°07′49″	115°05′24″	215	219	—	29/11/80	07/01/81	09/02/81	1 816	Permian	Oil shows, suspended
	Woodada 3	EP100	Hughes	EXT	29°45′17″	115°09′21″	42	47	—	10/12/80	11/01/81	08/02/81	2 540	Permian	Gas well, suspended
	Warradong 1	EP105	Mesa	NFW	29°18′05″	115°10′17″	97	103	—	04/02/81	15/03/81	14/04/81	3 717	Permian	Gas shows, P & A
	Woodada 4	EP100	Hughes	EXT	29°50′06″	115°08′33″	41	46	—	16/02/81	22/03/81	05/04/81	2 271	Permian	Gas well, suspended
	Mt Horner 5	EP96	XLX	EXT	29°07′37″	115°05′17″	213	216	—	24/02/81	05/04/81	22/04/81	1 819	Permian	Oil shows, suspended
	Ejarno 1	PL1	WAPET	NFW	29°18′54″	115°04′33″	73	80	—	21/04/81	20/05/81	24/06/81	2 868	Permian	Dry, P & A
	Georgina 1	EP96	XLX	NFW	29°08′41″	115°04′25″	143	146	—	28/04/81	11/06/81	12/07/81	1 831	Permian	Oil shows, suspended
	Parmelia 1	WA-13-P	WAPET	NFW	32°17′57″	115°04′32″	—	21	242	29/04/81	25/05/81	10/06/81	1 770	Cretaceous	Dry, P & A
	North Yardarino 1	PL2	WAPET	NFW	29°11′24″	115°02′24″	56	63	—	03/07/81	26/07/81	28/07/81	2 207	Permian	Dry, P & A
	Bootine 1	EP24	WAPET	NFW	31°10′39″	115°49′32″	166	173	—	10/08/81	06/11/81	22/11/81	4 306*	Jurassic	Suspended
	Point Louise 1	EP100	Mesa	NFW	30°02′22″	115°03′51″	36	39	—	28/08/81	16/09/81	17/09/81	950	Permian	Dry, P & A
	Whicher Range 3	EP130	BP	EXT	33°52′19″	115°23′33″	131	137	—	21/09/81	—	—	3 136	—	Drilling
	Casuarinas 1	EP111	Jervois	NFW	28°55′32″	115°09′06″	240	244	—	22/10/81	24/11/81	26/11/81	1 478	Permian	Water well
	Beekeeper 1	EP174	Aquitaine	NFW	29°42′52″	115°11′07″	48	53	—	09/11/81	23/12/81	—	3 012	Permian	Testing
Officer	Yowalga 3	EP178	Shell	NFW	26°09′03″	125°54′56″	476	483	—	19/08/80	09/01/81	17/01/81	4 197	Proterozoic	Dry, P & A

*Does not include sidetracked hole

Aquitaine: Australian Aquitaine Petroluem Pty Ltd
Home: Home Oil Australia Ltd
WMC: Western Mining Corp. Ltd
Meridian: Meridian Oil N.L.
Woodside: Woodside Petroleum Development Pty Ltd
Otter: Otter Exploration N.L.

Hudbay: Hudbay Oil (Aust.) Ltd
WAPET: West Australian Petroleum Pty Ltd
Phillips: Phillips Australian Oil Co
XLX: XLX N.L.
Hughes: Hughes & Hughes
Mesa: Mesa Australia Ltd

BP: BP Petroleum Development Aust. Pty Ltd
Jervois: Jervois Sulphates (N.T.) Ltd
Shell: The Shell Co. of Australia Ltd
NFW: New-field wildcat well
NPW: New-pool wildcat well
EXT: Extension test well

STRAT: Stratigraphic test well
SPT: Shallower-pool test well
P & A: Plugged and abandoned
GL: Ground level
RT: Rotary table
WD: Water depth

drilled without finding commercial hydrocarbons. It is considered to be the most important oil discovery in Western Australia since the Barrow Island field in 1964.

Following Blina 1, Orange Pool 1 and Yarrada 1 were drilled as new-field wildcats by Home Oil. Orange Pool 1 was drilled to test a seismic anomaly in a Devonian reef section about 50 km northwest of Blina 1, and Yarrada 1 was a similar test located on the southern margin of the Lennard Shelf. No hydrocarbons were found in the two tests, and Orange Pool 1 was abandoned and Yarrada 1 was left as a water well.

The fourth new-field wildcat, Great Sandy 1, was drilled by Meridian Oil N.L. on the Broome Platform; it found a good show of oil in Ordovician carbonates and a show of gas in the Poole Sandstone (Permian). A drillstem test of the interval 1 445-1 525 m in the Ordovician yielded less than 1 barrel of oil-cut mud. The well has been suspended and awaits further testing.

Four stratigraphic diamond-cored holes to test various types of seismic anomalies noted on the lines shot by the previous permit holder were drilled by Western Mining Corporation. One of these, Acacia 1, encountered excellent shows of oil in Ordovician carbonates, but it and the others (Boab 1, Abutilon 1, and Cassia 1) were plugged and abandoned because it was not possible to carry out extensive testing or logging in the narrow-diameter corehole. Western Mining intends to return to the Acacia location with a larger drilling rig in 1982 to evaluate the Ordovician section.

Carnarvon Basin

Two New-field wildcats, seven extension tests, two new-pool wildcats and three shallower pool tests were drilled in the onshore carnarvon Basin in 1981; offshore, three new-field wildcats and one extension test were drilled. In addition, drilling ahead or logging/testing at year end were two extension tests in the offshore, and one new-field wildcat, one extension and one new-pool wildcat in the onshore part of the basin.

Onshore, a shallow gasfield was discovered near Onslow by Otter Exploration N.L., which drilled the new-field wildcats, Wyloo 1 and Tubridgi 1, on anomalies located by a seismic survey, and found gas in the Birdrong Sandstone and a greensand within the Muderong Shale (Cretaceous). Wyloo 1 is located 4 km south-southwest of Onslow 1, drilled in 1966 by WAPET and abandoned with shows of oil and gas in the Birdrong Sandstone. Wyloo 1 tested 120 x 10^3m^3/day, and Tubridgi 1, 79 x 10^3m^3/day, both on 13 mm choke. Three successful Tubridgi extension wells and one dry hole were subsequently drilled, and the fifth extension well was being tested at the end of the year.

WAPET drilled two new-pool wildcat wells, three extension tests and three shallower-pool tests on Barrow Island, all of which are awaiting testing; one new-pool wildcat was drilling on Barrow Island at year end. The results of these wells are discussed in the Report of the Director of the Petroleum Division, in the Annual Report of the Department of Mines, 1981.

Offshore, WAPET drilled Gorgon 1 as a new-field wildcat on a horst-block closure on the southern extension of the Rankin trend. Seven drillstem tests were run over five different zones, six of which produced gas at rates up to a maximum of 770 000 m^3 per day. Most of the production is from the Mungaroo Formation (Triassic) but one zone in the Barrow Formation (Jurassic) also produced a gas flow (260 000 m^3 per day).

The testing indicates the discovery of a major gas field with reserves estimated at over 84 x 10^9m^3. The well is situated approximately 50 km southwest of West Tryal Rocks. At the end of the year WAPET had just reached total depth at West Tryal Rocks 3 which was drilled to further delineate the West Tryal field.

Woodside Petroleum Development Pty Ltd drilled North Rankin 6 in 124 m of water, approximately 2.1 km northwest of North Rankin 2, as an extension test to resolve structural and sedimentological uncertainties in the northwest area of the field. The well was temporarily suspended in April and re-entered to production test in September. On test, North Rankin 6 flowed at an aggregate rate of 1.586 x 10^6m^3 of gas per day.

Woodside's Fisher 1, an offshore wildcat, was drilled to test Triassic sands in a fault block down-thrown from the Rankin Platform. Although gas shows were encountered, no commercial reservoirs were found and the well was plugged and abandoned. Hudbay Oil Australia's Lawley 1 was drilled on a postulated horst of thin Triassic rocks resting on Precambrian basement with post-Middle Jurassic Sandstones draped over the horst. The objective sandstones proved to be water-wet and the well was abandoned as a dry hole.

At the end of the year Woodside was drilling an extension test, Goodwyn 6, in the southern part of the Goodwyn "main block" to evaluate the potential of deeper Triassic Sandstone reservoirs below the present pay section.

Barrow Island development wells

During 1981 only two wells (cumulative depth 2 529 m), classified as development wells, were completed by WAPET within the Barrow Island Oil Field. The status of these wells at year end is shown in Table 2.

TABLE 2 STATUS OF BARROW ISLAND DEVELOPMENT WELLS

Well Name	Total Depth	Status	Completed on
Y14-M............	1 273	Suspended	11/8/81
Y34-M............	1 256	Suspended	20/8/81

Exmouth Plateau area

The only well drilled on the Exmouth Plateau in 1981 was Phillips Australia Oil Company's Saturn 1. Spudded in 1980, the new-field wildcat had a Late Triassic sandstone objective on a tilted fault-block closure on the east flank of the Kangaroo Syncline. It was plugged and abandoned as a dry hole after no significant hydrocarbon shows were encountered.

Perth Basin

In 1981, seven new-field wildcats and four extension tests were drilled in the onshore Perth Basin; offshore, one new-field wildcat was drilled. In addition, one new-field wildcat and one extension test were drilling ahead onshore at year end.

Mesa Australia Ltd drilled Point Louise 1 and Warradong 1 to test Triassic and Permian rocks in the northern Perth Basin. Point Louise 1 was drilled on the west flank of the Beagle Ridge although no closed structure had been mapped. The main targets were limestones of the Carynginia Formation, which produced gas at Woodada, and the Irwin River Coal Measures. Only minor shows of gas and oil were reported and the well was abandoned as a dry hole. Warradong 1 was drilled near the Mondarra field on a small closure at the Lower Triassic level with the objectives the basal Triassic and Wagina Sandstones. Some gas shows were encountered but only minor gas flows were achieved on testing and the well was plugged and abandoned.

WAPET drilled Ejarno 1 in Production Licence No. 1, about 4 km southeast of the Dongara gasfield, with the principal objective being Permo-Triassic sandstones in a fault trap on the downthrown side of, and adjacent to, the Mountain Bridge Fault. The target sandstones were 700 m deeper than at Dongara but slightly higher than in Mondarra. Log data suggested some gas pay but testing showed it was not recoverable and the well was abandoned.

As farminee-operator, Mesa drilled Bootine 1 south of Gingin 1 in WAPET's permit EP 24. The objective was to test the Cattamarra Coal Measures Member, which had produced gas at Gingin 1, on the northern end of the Gingin anticline, which is on the west flank of the central part of the Perth Basin. After reaching 3 658 m the well had to be sidetracked around a fish, from 3 390 m to total depth (4 306 m). Several zones of interest were tested but mechanical problems forced a suspension of operations. A workover rig returned to the location in December and testing was proceeding at the end of the year.

Also in the northern Perth Basin, WAPET drilled North Yardarino 1 as a structural test of Triassic and Permian rocks. The location was on the downthrown side, and at the junction, of the Allanooka and Mountain Bridge Faults, 5 km north of the Dongara Field. The objective sandstones were not developed and the well bottomed in granitic gneiss at 2 199 m and was abandoned as a dry hole.

Hughes & Hughes drilled two extension tests (Woodada 3 and 4) as follow-ups to the gas discovery in fractured limestone in the Carynginia Formation (Permian) in Woodada 1 and 2; both extensions have been left as suspended gas wells pending further evaluation.

XLX N.L. drilled Mount Horner 4 and 5 and Georgina 1 as follow-ups to Mount Horner 3, which produced oil on test from Early Triassic sandstone and shale in 1980. All three wells have been left suspended for testing after reported oil shows. Georgina 1 is only 2 km south of Mount Horner but is separated from the main field by a fault.

Jervois Sulphates drilled Casuarinas 1, about 15 km north-northeast of the Dongara gas field, to test Permian and Triassic Sandstones on a faulted structural nose. No shows of hydrocarbons were encountered and the well was completed as a water well in the Yarragadee Formation.

At the end of the year two wells were operating in the onshore Perth Basin; Whicher Range 3, drilled by BP Petroleum Development Australia Pty. Ltd., and Beekeeper 1, operated by Australian Aquitaine. Whicher Range 3, in the southern Perth Basin, is a follow up to Whicher Range 1 which found gas in tight Permian sandstones on a faulted dome. Beekeeper 1 is located approximately 9 km north-northeast of Woodada 1 and was being tested at the end of the year.

The only offshore well drilled in the Perth Basin in 1981 was WAPET's Parmelia 1, located approximately 90 km southwest of Perth in 242 m of water. It tested Early Cretaceous sandstones on a palaeogeographic high but failed to find hydrocarbons, and was plugged and abandoned at a total depth of 1 770 m.

Dongara Field development wells.

Within the Dongara Field four development wells (including one water-disposal well), were drilled in

1981 for a total of 4 290 m of drilling. Details are shown below.

STATUS OF DONGARA FIELD DEVELOPMENT WELLS

Well Name	Total depth (m)	Status	Completed on
Dongara 23	1 765	drilled in 1980; gas well	10/1/81
Dongara WDW 1	652	shut in	23/2/81
Dongara 24	1 808	gas well	09/4/81
Dongara 25	1 830	gas well	05/8/81

Officer Basin

The Shell Company of Australia Ltd, in 1981, drilled the first petroleum exploration well in the Officer Basin since 1966. Shell's Yowalga 3 was a structural test of Early Palaeozoic and Proterozoic sediments and was drilled on a WNW-ESE trending anticline thought to be salt induced. The earlier wells, Yowalga 1 and 2, had only penetrated part of the section—although the No. 2 well penetrated a short way into the Proterozoic. No hydrocarbon-bearing reservoirs were encountered.

GEOPHYSICAL SURVEYS

Geophysical surveys carried out in 1981 consisted mostly of seismic work. Line-kilometres of seismic surveys increased by 40% on the 1980 figure; onshore seismic work increased by about 144% and offshore seismic work, by about 14%.

Other geophysical activities included marine gravity and marine magnetic surveys carried out in conjunction with marine seismic surveys. A land-based aeromagnetic survey of 2 400 km was completed by Carr Boyd Minerals Ltd in the Eucla Basin (EP192), and Whim Creek Consolidated N.L. completed a 1 350 km land gravity survey in the Canning Basin (EP205).

SEISMIC

During 1981, offshore seismic surveys were conducted in the Perth Basin (1 379 km), Carnarvon Basin (9 005 km), Canning Basin (2 624 km), Bonaparte Gulf Basin (3 356 km), Browse Basin (4 660 km), and on the Exmouth Plateau (699 km). Onshore seismic surveys were conducted in the Perth Basin (1 901 km), Carnarvon Basin (115 km), Canning Basin (7 664 km), and the Officer Basin (2 252 km).

Details are as follows:

SEISMIC SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Perth	WA-135-P	Wainoco International Inc.	768
	WA-113-P	Strata Oil N.L.	116
	WA-115-P	Mesa Australia Ltd	13
	WA-144-P	Mesa Australia Ltd	482
Carnarvon	WA-25-P	West Australian Petroleum Pty Ltd	107
	WA-64-P	West Australian Petroleum Pty Ltd	5
	WA-59-P	Magnet Petroleum Pty Ltd	407
	WA-28-P	Woodside Petroleum Development Pty Ltd	472
Carnarvon	WA-149-P	Mesa Australia Ltd	1 908
	WA-93-P	Hudbay Oil (Australia) Ltd	1 038
	WA-59-P	Hudbay Oil (Australia) Ltd	675
	WA-155-P	Esso Exploration & Production Aust. Inc.	4 393
Bonaparte Gulf	WA-18-P	Mesa Australia Ltd	335
	WA-77-P	Magnet Metals Ltd	906
	WA-128-P	CNW Oil (Australia) Pty Ltd	600
	WA-103-P	The Shell Co. of Australia Ltd	1 515
Canning	WA-62-P	BP Petroleum Development Pty Ltd	515
	WA-137-P	BP Petroleum Development Pty Ltd	280
	WA-142-P	BP Petroleum Development Pty Ltd	850
	WA-114-P	ESP Exploration Pty Ltd	358
	WA-134-P	Wainoco International Inc.	621
Browse	WA-136-P	Conex Oil Exploration Pty Ltd	520
	WA-32-P	Woodside Petroleum Development Pty Ltd	366
	WA-33-P	Woodside Petroleum Development Pty Ltd	1 516
	WA-34-P	Woodside Petroleum Development Pty Ltd	745
	WA-35-P	Woodside Petroleum Development Pty Ltd	1 171
	WA-37-P	Woodside Petroleum Development Pty Ltd	185
	WA-104-P	Brunswick Oil N.L.	157
Exmouth Plateau	WA-96-P	Esso Exploration & Production Aust Inc.	222
	WA-97-P	Esso Exploration & Production Aust. Inc.	472
Total			21 732

SEISMIC SURVEYS—ONSHORE

Basin	Tenement	Company	Line km
Officer	EP186,187	Swan Resources Ltd	106
	EP178-189	The Shell Co. of Australia Ltd	2 146
Perth	EP174	Mesa Australia Ltd	272
	EP224	Phoenix Oil & Gas N.L.	8
	EP204	Phoenix Oil & Gas N.L.	38
	PL-1H	West Australian Petroleum Pty Ltd	188
	EP130	BP Petroleum Development (Aust) Pty Ltd	47
	EP112	Weaver Oil & Gas Corp., Australia	194
	EP201	Lassoc Pty Ltd	67
	EP111	Jervois Sulphates (N.T.) Ltd	384
	EP23	Mesa Australia Ltd	12
	EP105	Mesa Australia Ltd	91
	EP130	Mesa Australia Ltd	388
	EP100	Mesa Australia Ltd	212
Carnarvon	EP41	West Australian Petroleum Pty Ltd	15
	EP110	Otter Exploration N.L.	100
Canning	EP126	Mesa Australia Ltd	211
	EP216	Ranger Oil (Australia) Ltd	1 250
	EP129, 104	Home Oil Australia Ltd	134
	EP239	Weaver Oil & Gas Corp. Australia	50
	EP170	ESP Interior Pty Ltd	407
	EP107	Era South Pacific Pty Ltd	181
	EP142	Wainoco International Inc.	310
	EP97	IEDC	119
	EP101	IEDC	438
	EP102	IEDC	1 328
	EP103	IEDC	804
	EP134	Mobil Oil Australia Ltd	131
	EP219	Mobil Oil Australia Ltd	679
	EP164	Meridian Oil N.L.	45
	EP175	Getty Oil Development Co. Ltd	451
	EP114	Swan Resources Ltd	463
	EP104	Esso Exploration & Production Aust. Inc.	663
Total			11 932

GRAVITY

Several surveys were carried out in conjunction with offshore marine seismic surveys as follows:

GRAVITY SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Canning	WA-62-P	BP Petroleum Development (Aust) Pty Ltd	515
	WA-137-P	BP Petroleum Development (Aust) Pty Ltd	280
	WA-142-P	BP Petroleum Development (Aust) Pty Ltd	850
Total			1 645

MAGNETIC

Magnetic surveys were conducted in conjunction with marine seismic surveys as follows:

MAGNETIC SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Perth	WA-135-P	Wainoco International Inc.	768
Canning	WA-134-P	Wainoco International Inc.	621
Total			1 389

REFERENCE

Janssens, A., 1982, Wells drilled for petroleum exploration in W.A. to the end of 1981: West. Australia Geol. Survey Record 1982/3.

PROTEROZOIC MASS-TRANSPORTED BRECCIAS NEERENO HILL, WESTERN AUSTRALIA

by S. L. Lipple

ABSTRACT

Coarse mass-transported breccias which locally form part of the middle Proterozoic Neereno Sandstone near Neereno Hill are interpreted as the products of rock avalanches and associated debris flows. These fast-moving rock flows, descended from hearby hilly terrain, spread across an alluviated piedmont zone, and entered a quiet-water basin. Their catastrophic impact on the alluvial and basinal sediments generated conglomeratic mud flows and turbidites.

INTRODUCTION

This paper describes an occurrence of Proterozoic breccias and associated mudflows and turbidites discovered near Neereno Hill (lat. 29°25′S, long. 115°58′E) during geological mapping of the Perenjori 1:250 000 Sheet (Baxter and Lipple, 1979).

This occurrence appears to be the first of its type to be documented from the Western Australian Precambrian. It has some importance in that it indicates for this region, the eastern limit of Proterozoic sedimentation on the western Yilgarn Block, and that these deposits must have only travelled a short distance from comparatively hilly terrain.

REGIONAL SETTING

Proterozoic sedimentary rocks occur both in the Irwin Sub-basin of the Perth Basin and eastwards on the adjacent Yilgarn Block (Fig. 1A). A basin sequence, about 2-3 km thick, composed mostly of lithic siltstone and wacke (Yandanooka Group) occupies the Irwin Sub-Basin and overlies the Mullingarra Inlier. Immediately east of the Irwin Sub-basin, a thin platform sequence (Moora Group), divisible into a lower coarse clastic section (Neereno Sandstone of the Billeranga Subgroup) and an upper, clastic-dolomite-chert section (Coomberdale Subgroup), overlies Archaean rocks of the Yilgarn Block with an irregular nonconformity. A stratigraphic scheme, originally proposed by Arriens and Lalor (1959), was published by Low (1975), but following regional mapping and comparison of type sections, a revised stratigraphy was proposed by Baxter and Lipple (1979). The correlation between this and the previous stratigraphic scheme by Low (1975) is summarized in Figures 1A and 2A. The basin sequence is correlated with the lower (Billeranga Subgroup) platform sequence, and the latter is conformably to disconformably overlain by Coomberdale Subgroup, which forms the upper sequence. Although the precise age of these rocks is uncertain, Compston and Arriens (1968) obtained a whole-rock Rb-Sr age of 1400 m.y. from basalt flows (Morawa Lavas) in the lower platform sequence. Several generations of mafic dykes intrude platform sequence rocks.

The basin sequence adjoining the lower platform sequence, consists of laminated, graded lithic siltstone, wackes and minor turbiditic wacke, in which scouring, slump folding and disruption, flame and sedimentary dyke structures are well developed.

The lower platform sequence (Fig. 1A, B) is best exposed at the west of Neereno Hill, where it has been studied in detail. Between the Bateman and Hebiton farms, a section comprising megabreccia, conglomeratic mudstone, shales and wacke attains a thickness of about 200 m (Fig. 2B), but thins rapidly eastwards. Nearby, laterally equivalent fluviatile arkose and breccia (Neereno Sandstone of Low,

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Figure 1. Regional setting, rock distribution and location index. ▶

A. Regional setting of the Proterozoic sedimentary rocks in the Northern Perth Basin. Numerals I—III refer to locations of stratigraphic columns in Figure 2A.

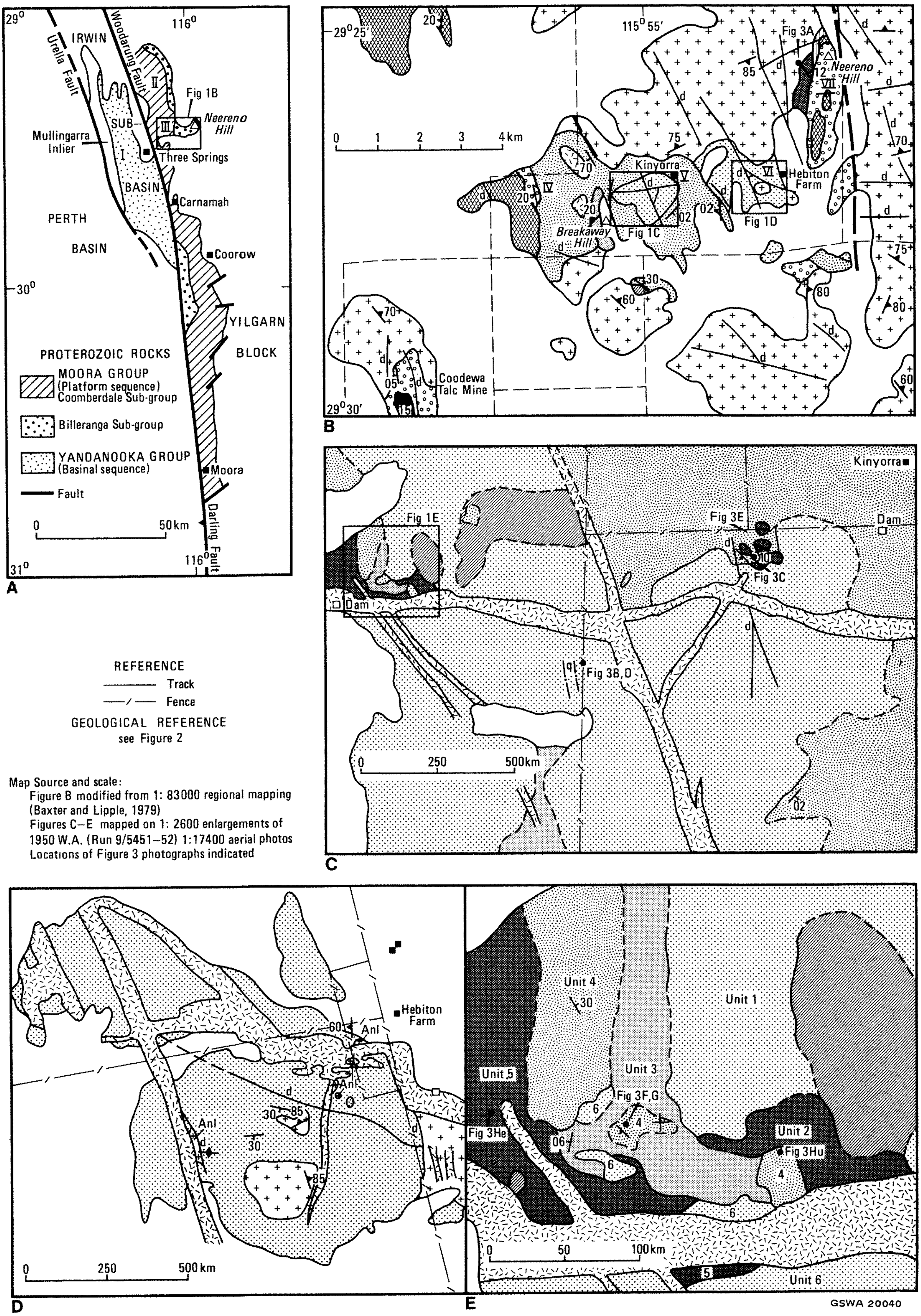
B. Regional geology of the Neereno Hill area. Numerals IV—VII refer to locations in Figure 2b.

C. Rock distribution, Kinyorra; showing locations of Figure 1E and 3B-E.

D. Megabreccia on basement gneiss: Hebiton Farm.

E. Interfingering facies relationships, West of Kinyorra; units are numbered oldest (1) to youngest (6). Locations 3F-H refer to Figure 3.

Lithological reference for Figures 1B-E shown in Figure 2.



29°
116°
IRWIN
Urella Fault
Woodarung Fault
II
Fig 1B
SUB
III
Neereno Hill
Mullingarra Inlier
I
Three Springs
BASIN
Carnamah
PERTH
BASIN
Coorow
30°
YILGARN
BLOCK
PROTEROZOIC ROCKS
MOORA GROUP
(Platform sequence)
Coomberdale Sub-group
Billeranga Sub-group
YANDANOOKA GROUP
(Basinal sequence)
Fault
Moora
0
50km
Darling Fault
116°
31°
A
29°25′
115° 55′
Fig 3A
Neereno Hill
0 1 2 3 4km
Kinyorra
Hebiton Farm
Breakaway Hill
Fig 1C
Fig 1D
Coodewa Talc Mine
29°30′
B
Kinyorra
Fig 1E
Fig 3E
Dam
Fig 3C
Dam
Fig 3B, D
0 250 500km
C
REFERENCE
Track
Fence
GEOLOGICAL REFERENCE
see Figure 2
Map Source and scale:
Figure B modified from 1: 83000 regional mapping (Baxter and Lipple, 1979)
Figures C—E mapped on 1: 2600 enlargements of 1950 W.A. (Run 9/5451—52) 1:17400 aerial photos
Locations of Figure 3 photographs indicated
Hebiton Farm
Anl
0 250 500 km
D
Unit 4
Unit 1
Unit 3
Unit 5
Fig 3F,G
Fig 3He
Unit 2
Fig 3Hu
0 50 100km
Unit 6
E
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1975) are interlayered with purple amygdaloidal basalt flows (Morawa Lavas) capped by lithic siltstone and red chert (Oxley Chert Member) (Fig. 2B). The whole section has a total thickness of about 50 m but includes units which are partly repeated and offset by minor strike and oblique faults.

Equivalence of the lower platform sequence with the basin sequence is indicated by common rock types and comparable environments. A complex alluvial/talus-fan environment merging laterally westwards into a quiet basin intermittently disturbed by slumping and turbidity currents, is envisaged.

A more widespread, upper platform sequence (Mokadine and Campbell Sandstones, Noondine Chert and Jingemia Dolomite) attains a maximum thickness of 250 to 400 m. It consists of cyclically repeated, upward-fining, sequences of conglomeratic sandstone, sandstone, siltstone, chert and dolomite. Stromatolites are common in cherts and dolomites. The upper sequence is much more siliceous than the lower sequence. Feldspathic sandstones are restricted to near the base in contrast to the consistently feldspathic composition of sandstone and wacke in the lower sequence.

The Proterozoic rocks are little deformed, and regional metamorphism is of very low grade. Very open, concentric folding is present northwest of the study area, and some shales contain a weak to moderately spaced cleavage. Dips are generally low (< 10°), although some moderate (30°) to high (70°) dips were recorded immediately adjacent to faults. Some dolerite dykes occupy north-northwest or east-trending faults. The distribution of the units across the mildly undulating topography also indicates a gently dipping sequence. Local syn-sedimentary slump folding next to breccia units is open concentric style (20-30° dips) to isoclinal style (70-90°) and is best seen between Kinyorra and Breakaway Hill.

For the purpose of this paper, two areas of good exposure were studied in detail (Figs 1C and 1D), and further observations were made on related rocks at Neereno Hill itself (Fig. 1B).

GEOLOGY OF BRECCIAS AND ASSOCIATED ROCKS

GENERAL

The spatial distribution of the breccias and associated rocks is shown in Figure 1B. The various rock types exhibit abrupt lateral and vertical facies changes (Figures 1C, D, E, and 2B). It is difficult to unravel the nature of these changes in detail because they represent end members of the range of facies present. There is a change southwestwards from sandy, framework breccia and sandstone (best developed at Neereno Hill), through megabreccia (dominant at Hebiton-Kinyorra farm), and conglomeratic mudstone (Kinyorra), to graded, interbedded breccia, sandstone, wacke and shale (Kinyorra-Breakaway Hill). The variation in rock types and thickening of the sequence southwestwards is schematically illustrated in Figure 2B.

HEBITON-KINYORRA FARM ROCKS

The megabreccias and breccias are unsorted, thick-bedded to massive rocks. Angular clasts of feldspathic gneiss are irregularly distributed and form a very close-packed, anisotropic framework. The sparse matrix consists of lithic sand and/or green to black mudstone. Although individual beds have sharp basal contacts and consist of only one breccia type, a continuous range of breccia types is defined by variation in clast size and matrix-to-clast proportions. For mapping purposes, three types were distinguished: (i) matrix-poor (about 2%) megabreccia with clasts predominantly greater than 5 cm (commonly 50-200 cm) maximum dimension; (ii) matrix-poor (about 2%) breccia; with clasts mostly 2-10 cm maximum dimension and (iii) framework breccia (about 20% sandy matrix) (Figs. 1C-E, 3A, B, D). Megabreccia is the dominant type, and types (ii) and (iii) occur mostly in the area 500-2 000 m west southwest of Kinyorra homestead. Type (iii) breccia is best developed at Neereno Hill.

The three breccia types interfinger with shale, sandstone, and conglomeratic mudstone (Fig. 2B). Northeast of Breakaway Hill (Fig. 1E), megabreccia (here > 1 m thick) is overlain by flat-lying breccia (0.5-1 m); feldspathic pebbly wacke (0.5 m) and lithic siltstone-shale; conglomeratic sandstone and siltstone (0.5-1 m, Fig. 3F, G, H), breccia and megabreccia (> 2 m). About 500 m further west, megabreccia (0.8 m) is bounded by breccia (> 0.5 m) with irregular contacts. West-southwest from Kinyorra, small breccia lenses form a channel in (Figure 1C) slump folded and chaotically mixed conglomeratic mudstone (Fig. 3E). A thin, bedded sandstone is draped over the irregular breccia surface (Fig. 3E). An extensive megabreccia sheet about 20 m thick, abuts the more thinly bedded units at these localities. In detail the margin is sharp and irregular, and appears to partly correspond with the original lateral contact with stratigraphically equivalent conglomeratic sandstone.

In instances where breccia overlies mudstone or siltstone, there there are flame structures along the base, and slump folding in bedded siltstone (Fig. 3E) appears to be most intense adjacent to breccia margins. Megabreccia also directly overlies basement rocks (Fig. 1D) with an irregular nonconformity which has a general dip southwards at up to 3 degrees. Neptunian dykes of breccia fill crevices in the basement. A characteristic red or purple

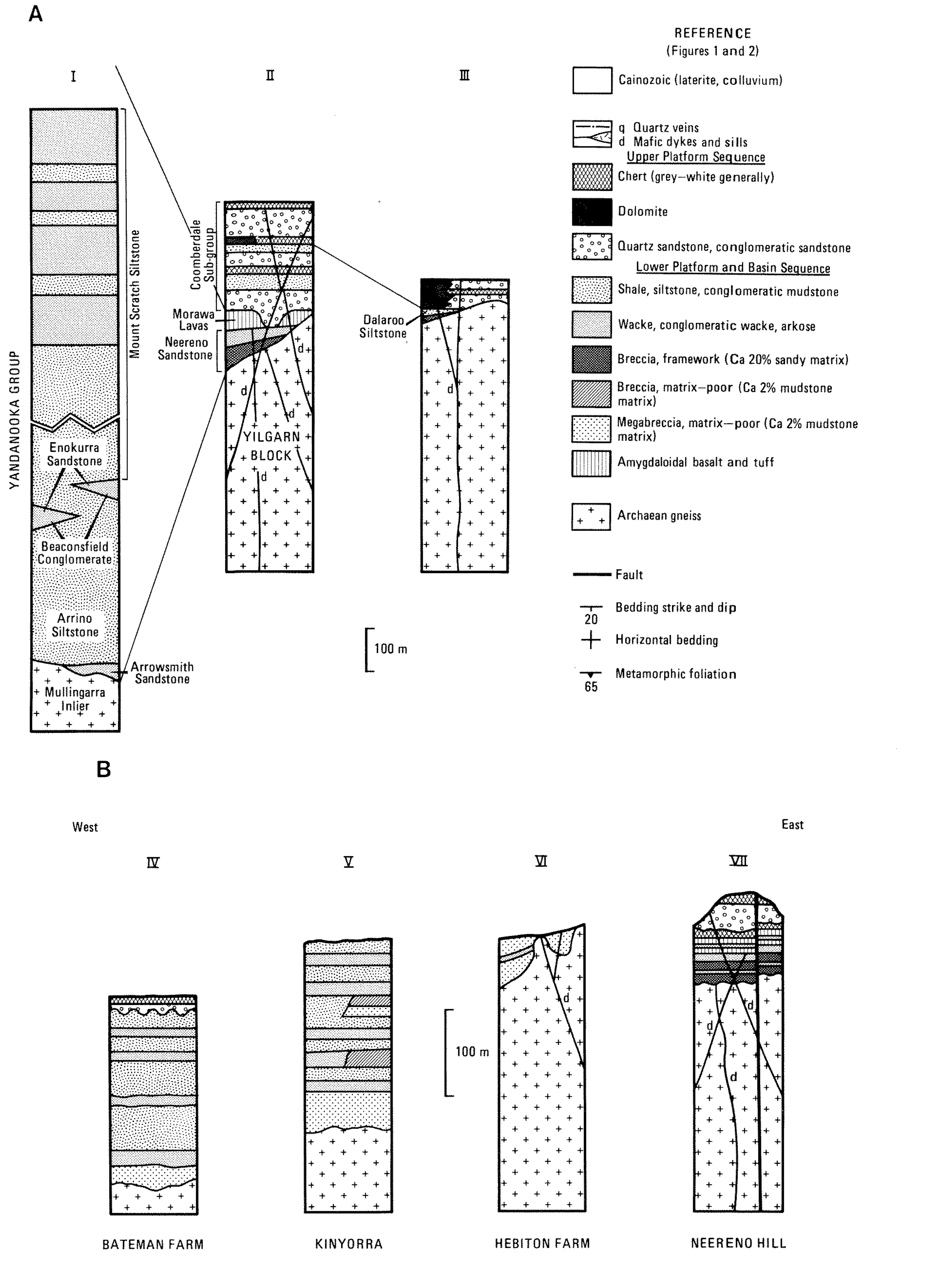


Figure 2. Stratigraphic relationships (Locations of columns shown in Figure 1)
A. Regional stratigraphy.
B. Schematic stratigraphic relationships, Neereno Hill area.

oxidation colour is present in most of the breccia and megabreccia and in basement rock adjacent to joints. Elsewhere, basement rocks are unaffected by this oxidation and thus it can be distinguished from Cainozoic weathering.

Clasts are very angular, with elongate to equant shapes and numerous planar faces derived from joints and foliation in the source rock. Clast types can be directly traced to the adjoining basement. Feldspathic orthogneiss is dominant. A few amphibolite, dolerite, semipelitic paragneiss, ultramafic schist and metaperidotite fragments were noted. Clasts of vein quartz are rare, estimated at one representative locality to be less than 0.01% of the rock volume. Size distribution of clasts appears to be polymodal and skewed towards the coarse end of the range (Fig. 3B). Clasts range from less than 1 mm up to 8 x 3 m and 5 x 7 m dimension in pavement outcrops. In the megabreccia, blocks exceeding 1 x 1 m in size are common. Most clasts have face, rather than point or edge contacts (Figs 3B, D). (Planar to indented contacts (concavo-convex to weakly sutured, Pettijohn, 1975, p. 75) up to 2 m long with little or no intervening groundmass are common).

Some clasts are partially crushed to a mosaic of subgrains in a braided fracture pattern. Mudstone matrix has been introduced along these fractures (Fig. 3D). The very close packing has resulted in a much lower matrix content than is normal for framework deposits (Pettijohn, 1975, p.73). Very rare voids are present, either with quartz rims coarsening inwards to chlorite centres, or with complex quartz-chlorite zoning.

Two types of matrix are recognized. The common matrix in framework breccia is purple, angular, unsorted sand, composed of lithic grains, quartz, feldspar and iron oxides (Fig. 3F). Green to black mudstone including angular mineral and lithic grains forms the second matrix type common in megabreccia and matrix-poor breccia (Figure 3B, D). A squeezed appearance is caused by irregular, sharp, re-entrant contacts between clasts and sandy matrix (Figure 3B, D), and contortion of indistinct bedding. In megabreccia, thin dykes (up to 1 m long and 3 cm wide) of mudstone between clasts, along pre-depositional joints of clasts (Figure 3B, D) also indicate hydroplastic flow. Although the fabric of the megabreccia and breccia is typically massive and disorganized, imbricate fabrics, grading and/or inverse grading are present locally, such as 500 m west-southwest of Kinyorra. These features may be accompanied by an increase in sandstone and/or mudstone matrix. In a few places (e.g. Hebiton Farm, Figure 1D) distinct beds of megabreccia and breccia up to 10 m thick are separated by less than 20 cm of lithic siltstone or immature, weakly bedded, graded sandstone.

Conglomeratic and laminated mudstone and siltstone

These rocks are widely distributed (Fig. 1B) and best developed on Kinyorra Farm (Fig. 1C). Typical

Figure 3. Typical illustrations of facies types. ▶

A. Framework (sandy matrix) breccia containing angular, poorly sorted gneiss clasts (gn) and rare quartz pebbles (q). An imbricate fabric is present. Bedded pebbly sandstone lens (BS) shows indentation of clasts into the top margin. Disoriented, contorted sandstone slab (DS) is included in breccia bed. Hammer head is 18 cm across. Beds dip 12°NE, strike 150°.

B. Coarse blocky breccia with sparse massive pelitic mudstone matrix (S) between angular clasts of gneiss, rare pegmatite (P) and dolerite (V). Clasts have face contacts, are indented (I) and pressure marked (PM). Oxidation has especially affected feldspar (ox fd). Siltstone has been forced along clast joints (SJ).

C. Conglomeratic mudstone has matrix-supported angular gneiss (gn) and minor granitoid (gr) clasts in massive and indistinctly bedded pelitic mudstone.

D. Coarse blocky breccia (polished slabs from 3B), shows indented (I) face contacts. There is selective mosaic (M) crushing (cf. right-hand centre clast). Mudstone matrix has been forced along compaction fractures (SJ). Recent fractures (F) cross rock indiscriminantly.

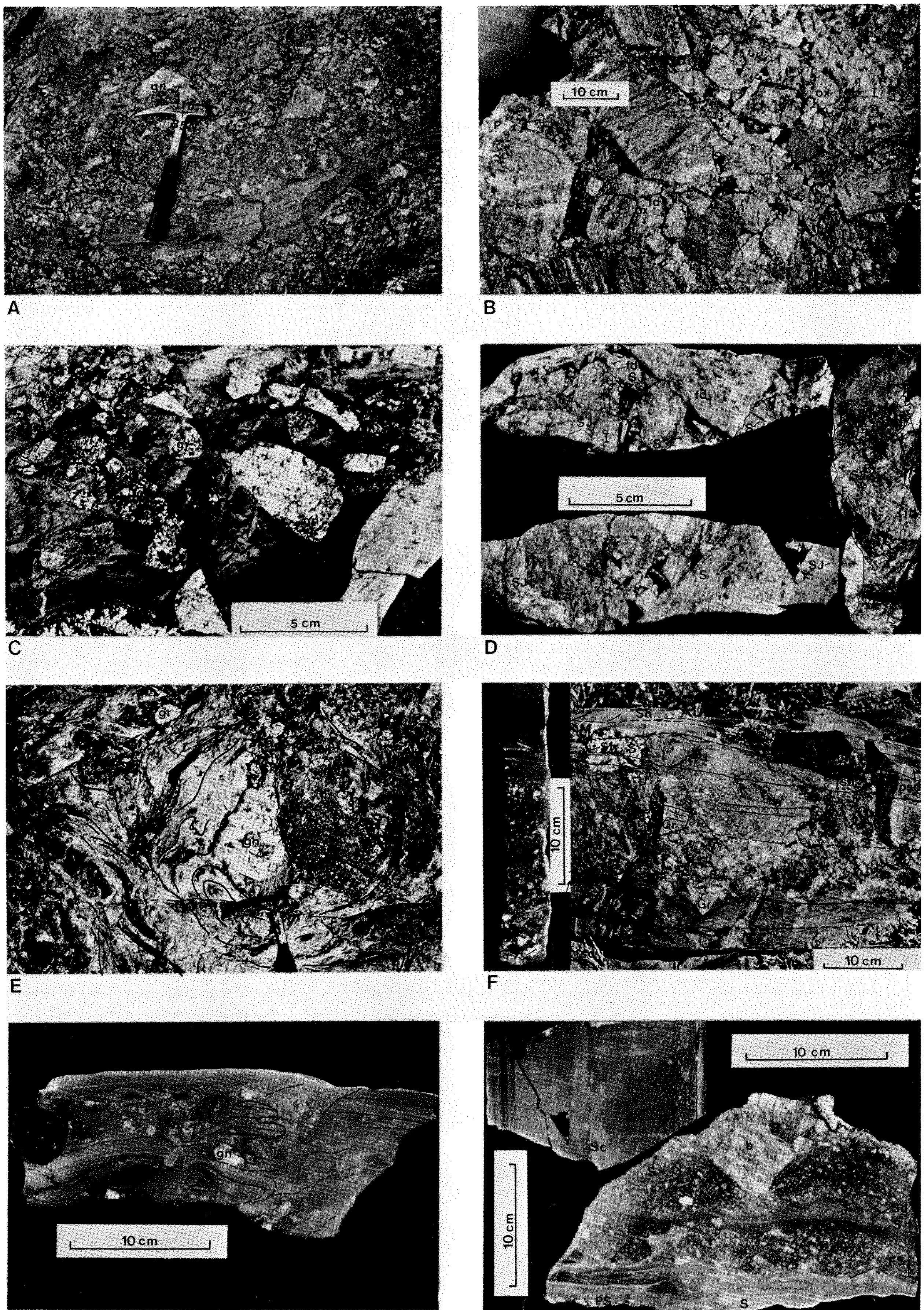
E. Slump-folded, disrupted conglomeratic mudstone contains rafts of conglomeratic mudstone (CM), pebbly sandstone (PS) and gneiss (gn), granitoid (gr) clasts. Hammer head is 18 cm across.

F. Interbedded graded rudites and shales (Left side). Polished slab showing Bouma sequences A-E (Pettijohn, 1975) Graded, imbricate pebbly matrix-rich (sand, mudstone) framework breccia (A) with siltstone clasts (Sc) occurs in 3 cycles. Disrupted laminated siltstone (Ds) is a ?B interval, scoured by overlying (A) interval of pebbly sandstone and showing load features.

Sandstone grades up to laminated, graded siltstone and shale. (Right side) Poorly sorted, laminated siltstone (S), fine sandstone (fsd) exhibit load and flame structures (FS) with matrix-rich framework breccia. Note irregular and tabular, bedded striated (Str) siltstone clasts (Sc). Uppermost shale is cleaved (Cl).

G. Slump-folded chaotic pebbly siltstone, has subrounded red granite (gr), angular gneiss (gn) and disoriented siltstone clasts (sc). Scours and depressed bedding (left side) are featured.

H. (Lower right) Interbedded graded rudites and laminated siltstone. Three cycles of well-laminated, graded, disrupted purple sandstone and grey-green siltstone (S) exhibit flame (FS), attenuation, scour and load structures with overlying graded pebbly sandstone or breccia (b). Density-current-suspended pebbles (dp) were dropped onto siltstone, depressing and truncating laminae, and overlapped by succeeding laminae. (Upper left) Interbedded graded pebbly sandstone, siltstone and shale is interpreted as Bouma sequences A, C-E (Pettijohn, 1975) and features a siltstone clast (SC) and dropped density current-suspended pebble (Dp.)



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rocks are shown in Figures 3C, E. Subordinate laminated siltstones and mudstones are interbedded with conglomeratic varieties (Fig. 3F, H). The conglomeratic deposits are matrix to framework supported, with various types of clast compositions. Internal stratification is apparently absent or indistinct but some thin to medium bedding is present. Disrupted bedding, slump folding and chaotic mixing are common features (Fig. 3E).

Clasts range from sand to boulder size and comprise red to purple gneiss, equigranular and porphyritic pink granitoid, and lesser amounts of vein quartz, amphibolite, biotite-chlorite schist and numerous kinds of sedimentary rocks. Most clasts are angular, but granitoid types are also subrounded. Sedimentary clasts are less clearly differentiated from the matrix but are typically well rounded and irregularly shaped. These sedimentary clasts can be matched with rock types in the surrounding sediments from which they were probably derived.

Interbedded pebble breccia, sandstone and shale.

This group of rocks is important in the western part of the sequence (Fig. 1C, E), where it interfingers with all the previously described rocks, and becomes finer grained westwards towards the basin centre. Interbedded, sharp-based breccia, laminated sandstone and shale (Fig. 3F, G, H) show features such as inverse or normal grading, parallel laminations, imbricate fabrics, sole marks, scours, slump folding, disruption and disorientation of bedding which are typical of turbidite deposits. Truncation and disturbance of shale bedding by gneiss or granitoid clasts is a feature of these rocks (Fig. 3F, G, H). Several large elongate pebbles which disrupt siltstone lamination are oriented with their long axis perpendicular to bedding. These occur both as isolated clasts and in thin (1-2 cm) pebbly layers within siltstone, and the long axis of the pebble is up to twice the bed thickness. The sandstone is a poorly sorted, purple or green arkosic wacke, with angular quartz, plagioclase, microcline and iron oxide grains and abundant fine fragments of gneiss and shale. Some units contain patches (1-2 cm diameter) of carbonate, epidote and sericite, possibly of diagenetic origin. Detrital and secondary magnetite are abundant in these rocks, but pyrite occurs only very rarely in lithic siltstone.

NEERENO HILL ROCKS

These rocks consist of interlayered sandy framework breccia, purple feldspathic sandstone, thin amygdaloidal basalt, red chert and lithic siltstone (Fig. 2B). The best exposures are southwest of Neereno Hill and form the type section of the Neereno Sandstone (Low, 1975). Total thickness is about 50 m and the rocks dip at an average of about 10° east.

The feldspathic sandstone forms poorly bedded units about 3 m thick, with low-angle, planar cross-bedding, rare undulating bedding, sole marks and festoons, and minor grading. The sole marks are interpreted (R. Hocking pers. comm.) to represent turbulent-flow ripple marking. Sand grains are moderately to well sorted and moderately rounded; the main components are unstrained quartz, plagioclase, microcline, chert, quartzo-feldspathic (?granitoid) rock and minor altered dolerite or mafic volcanic rock.

Purple breccia crops out as small rock humps, in units about 10 m thick. The breccia (Fig. 3A) is framework supported, and contains angular, pebble- to cobble-sized clasts of gneiss and minor vein quartz which define an imbricate fabric. The sandy matrix (about 20%) is similar to the interbedded sandstone beds. The breccia contains thin (2-20 cm), moderately sorted and bedded sandstone lenses, which separate layers of breccia 0.5-1 m thick. The sandstone lenses exhibit grading, low-angle cross-bedding and scours. Some lenses show disruption features (Fig. 3A), including disorientation and contortion of sandstone masses, because of incorporation into breccia, and compaction of breccia clasts into underlying sandstone layers.

A distinct imbricate fabric is shown by elongate clasts sub-parallel to bedding, but with no single prevailing vector in the bedding plane; although in one exposure, clasts have longest axes prevalently oriented in the downcurrent (eastward) direction, and inverse grading in the bed. Here a large boulder of gneiss in the breccia is disrupted by thin (1-2 cm) dykes of pebbly coarse sandstone continuous with the groundmass. The disaggregated components of the gneiss clast show no rotation of the foliation.

The rocks are preserved in the terminal part of a palaeovalley extending at least 30 km north-northwest from Neereno Hill. The palaeovalley has an average southward gradient of 0.4° and is defined by the contours of the unconformity, the restriction of the sedimentary rocks and basalt to the valley and the progressive onlap of younger units onto the basement forming the valley walls.

SEDIMENTARY ENVIRONMENT

Interpretation of Proterozoic climatic, weathering and depositional conditions by direct comparison with modern analogues is prone to be speculative, but many of the features described are consistent with a uniformitarian interpretation. Rare dropstones in laminated siltstone in the basin sequence of the adjoining Irwin Sub-basin (Baxter and Lipple, 1979) because of their Middle Proterozoic age are probably ice-rafted debris rather than plant-rafted. This suggests a cool temperature climate with at least some local ice-formation.

BRECCIAS

Applying a uniformitarian interpretation advocated by Allen (1965) and Dal Cin (1968) (reporting principally on Quaternary deposits) would suggest that the compositional immaturity of the breccias as shown by predominance of feldspathic and mafic clastic material and virtual lack of vein quartz, implies limited transport, rapid deposition and preservation in a cool or cold, possibly semi-arid climate though with episodes of heavy rain which mobilized the considerable quantities of detritus which accumulated during drier periods. However, the important role in weathering since Silurian times of humic acids derived from land plants probably precludes strict application of Cainozoic paleoclimatic data to climatic interpretation of the Neereno Hill deposits. Using modern analogues (Caine and Jennings, 1968, p.100; Dawson, 1977; Ollier, 1975, p.11, 112-113, 188), the coarser, angular unsorted material with abundant planar faces and little matrix in the breccia is consistent with an origin by frost wedging. This talus was weathered *in situ* because breccia clasts show widespread oxidation in contrast with the dark unoxidized siltstone matrix.

The predominance of locally derived angular clasts, and the fabric of the breccias indicate rapid near-source deposition in a high-relief setting, probably by mass transport of talus-slope material. Although a steep initial gradient for the nearby source area is required to generate the kinetic energy necessary for the lateral transport of the boulders, some with calculated masses up to 300 t only a gentle south-sloping relief is indicated by the nonconformity. Krieger (1977) described megabreccias formed by catastrophic landslides and avalances initiated by rockfalls or slides on elevated steep source areas, which travelled at high speeds (100-350 km/h) across gentle piedmont (1-2°) slopes before coming to an abrupt stop. If the megabreccias near Neereno Hill are correctly interpreted as having a similar origin, and applying Kreiger's (1977, Table 1) average coefficient of friction (total vertical fall to horizontal travel) of 0.2, then because the minimum travel distance of the megabreccias is 2 km, a total vertical fall exceeding 400 m is implied.

The absence of clasts of banded iron-formation, which is in fact exposed in nearby basement to the west, south and southeast (Baxter and Lipple, 1979), indicates a northern source. Distinctive Archaean volcanic rocks and banded iron-formation within a large belt exposed 35 km east are not represented as clasts in the breccia.

Sandstone at Neereno Hill, although feldspathic, is moderately rounded and sorted, and is probably derived from more distant granitoid rocks to the north. Pink granitoid cobbles and pebbles occur in equivalent sandstone about 12 km northwest near Oxley Hill. Porphyritic red granitoid cobbles and boulders in sedimentary rocks west and southwest of Kinyorra are probably derived from the same source.

The breccia at Neereno Hill was probably generated by both fluviatile and debris-flow transport. Sandstones interbedded with the breccia are fluviatile as seen from their shape and internal texture, and the presence of cross-beds and festoons. Breccias disrupt and contort thin sandy lenses, contain pebbly sandstone clasts, and have inverse-graded, imbricate fabric, all of which indicate debris-flow transport (Walker, 1975). The sandy lenses represent minor end-stage fluviatile deposition on top of successive debris flows. Disruption was caused by slight remobilization of the unconsolidated flows either by subsequent debris or lava flows. Direction of flow was off the slopes of the palaeovalley and southward along the valley floor. The more rounded sand grains in the matrix contrast with the angular clasts, and were incorporated by reworking the sandstone. The presence of a disintegrated boulder in one layer is interpreted as disaggregation by matrix injection during mass transport.

The megabreccia and breccia at Hebiton-Kinyorra farm have possible origins by several transport mechanisms, including debris flow (Allen, 1965; Bull, 1972; Stephenson, 1972; and Walker, 1975), landslide (Burchfiel, 1966; Kreiger, 1977) or catastropic avalanche (Crandell and Fahnestock, 1965; Shreve, 1966, 1968a, b; Kent, 1966; Plakfer 1977; and Kreiger, 1977). Transport of the breccias by catastropic avalanching is the mechanism consistent with their very coarse, angular, disorganized fabric and other features.

The breccias, which have a sheet-like shape, are uniformly thin but areally extensive (2.5 km^2 on Hebiton farm, and 1.4 km^2 at Kinyorra-Breakaway Hill). There is no lateral sorting within the two main sheets and only little vertical sorting. Fragments lack rounding but may be shattered or pressed together with irregular planar contacts. Clast indentation and mosaic-braided fracture patterns in individual clasts (Fig. 3B, D) indicate failure under impact or compaction rather than selective tectonic deformation. These features were probably produced either during initial collapse of the source material in a rockfall, collision during transport or impact upon the abrupt deposition characteristic of avalanches (Kent, 1966; Kreiger, 1977). Entrapped, compressed air was the probable supporting medium during lateral transport (Kreiger, 1977). Planar clast contacts may have resulted from the collapse of the air support when the avalanche came to rest. Lubrication along the base probably took place by means of a thin mudstone layer which was partially incorporated into the breccias. Compaction, dehydration and hydroplastic squeezing of mudstone between clasts and into fractures occurred during post-depositional consolidation. This probably accounts for the low porosity of the breccias, which is otherwise problematic, although Kreiger (1977) cites examples of avalanche breccias with both high and low porosities.

The low proportion of sandy matrix poses problems in understanding the origin of the breccias. Talus-slope material characteristically has a low sand content. Derivation by avalanching from talus-slope material or rockfall material, with creation of mostly coarse fragments appears the best explanation.

An alternative origin by other forms of debris flow of the type common in an alluvial fan environment is consistent with some of the features present. However, the sheet-like shape of the breccias, the low proportion of sand and mud matrix, and the large number of planar clasts, all pose problems in accepting such an origin.

Other possible mechanisms for the origin of the breccias include formation by sheet ice, a rock glacier, landsliding or as *in situ* talus-slope deposits. These mechanisms are rejected as discussed below. Tillite formed by sheet ice would be expected to contain a uniform distribution of particle sizes with much more fine material (Pettijohn, 1975, p.172) than is seen. A rock glacier, as described by Caine and Jennings, (1968) or Dawson, (1977), could account for many of the features present; however, the resulting breccia would typically lack stratification and graded fabrics, have high porosity, and lack the mudstone matrix. Traces of distorted bedding in the mudstone matrix are more consistent with incorporation of underlying material and hydroplastic squeezing under pressure, rather than later introduction of matrix by fine-sediment infiltration.

Landslides (Kreiger, 1977) are characterized by a widespread crackle brecciation (a feature absent from these breccias), thicken downslope, and are generally nonturbulent with relict preservation of lithological variation in source rocks. Although the basement gneisses show some lithological variation, the breccias have a chaotic mixture of rock types. Talus-slope deposits are typically cone-shaped, of limited areal extent with steep initial dip, exhibit gravity sorting with coarsest material at the lower distal end, and show a marked thickening downslope (Kent, 1966).

CONGLOMERATIC MUDSTONE AND INTERBEDDED RUDITES, SANDSTONE AND SHALE

The impact of advancing megabreccia and breccia avalanche flows probably caused slump folding and disruption of mudstones (Kreiger, 1977) and triggered mudflows (Crandell and Fahnestock, 1965) and turbidity currents in the Neereno Hill area. Debris (mud)-flow transport (Dott, 1963; Fisher and Mattinson, 1968; Fisher, 1971) is indicated by the disruption, slump folding, and chaotic incorporation of multiple-reworked sedimentary clasts in conglomeratic mudstone. Bedding disruption of well-laminated, graded wacke and shales resulted from dropping of pebbles and cobbles transported in high-density currents. Some of these graded sequences (Fig. 3F) are interpreted in terms of the Bouma sequence in turbidites (Pettijohn, 1975, p.561). Shale clasts in breccia occur near bed tops, above denser basement clasts, and are strongly aligned parallel to bedding (Fig. 3F, G, H). These features, together with scouring, inverse grading, and imbricate fabrics (Fig. 3F, G, H) indicate near-source turbidite deposition (Fisher and Mattinson, 1968; Fisher, 1971; Pettijohn, 1975, p. 561-562; Walker, 1977).

SUMMARY

The general sedimentary environment of the breccias, as indicated by the debris mudflows and proximal facies turbidites, seems to have been within the westward transition from an alluvial fan to a quiet-water basin. The range of sedimentary facies over a short stratigraphic interval indicates that the surrounding land had a high topographic relief. Rock avalanches, possibly triggered by nearby volcanic activity, or movement on the Darling Fault plunged into this environment depositing coarse debris on the alluviated piedmont slopes. The foot of the debris mass entered the quiet-water basin causing the normal sequence of muddy sediments to be interrupted by debris flows and which induced slumping and turbidity currents.

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GEOLOGY AND HYDROGEOLOGY OF THE BOYANUP BORE LINE, PERTH BASIN

by R. A. Smith

ABSTRACT

The Boyanup Line of bores across the southern Perth Basin comprises eleven bores at four sites on an east-west line, about 16 km south of Bunbury. The bores were drilled, between February and July 1981 to a maximum depth of 1 000 m and have an aggregate depth of 5 289 m.

The Cockleshell Gully Formation (Early Jurassic) and Yarragadee Formation (Middle to Late Jurassic) dip gently eastward. The Yarragadee Formation is overlain unconformably by the Bunbury Basalt (Early Cretaceous) near Boyanup and the Leederville Formation (Early Cretaceous) except where it is absent beneath the central Swan Coastal Plain. The Leederville Formation appears to fill two synforms resulting from differential subsidence of the underlying formations. The thin and flat-lying "superficial formations" unconformably overlie the pre-existing formations on the Swan Coastal Plain.

The Yarragadee Formation, composed predominantly of sand, contains fresh groundwater in an interval 90-770 m thick extending 570-940 m below-natural-surface. The salinity is about 250 mg/L TDS. Groundwater of similar salinity is present in the overlying Leederville Formation, but the formation is multilayered and has a maximum thickness of 350 m, of which about 70% is sand.

The drilling has confirmed the existence of major, fresh groundwater resources in the southern Perth Basin, mainly beneath the central and eastern coastal plain.

INTRODUCTION

The Boyanup Line consists of eleven bores at four sites 3.5 to 9 km apart along an east-west line across the coastal plain, 16 km south of Bunbury, near Boyanup (Fig. 1).

The bores are part of a long-term drilling programme to evaluate the deep groundwater resources of the Perth Basin. A detailed account of the investigation procedures and bore construction methods is planned to be presented in a later paper. Adjacent lines of deep bores are the Picton Line, 14 km north (Wharton, 1981) and Quindalup Line, 19 km south (Wharton, 1982). In addition several bores drilled to evaluate the shallow groundwater resource are near the Boyanup Line (Commander, 1975 and in prep.).

The climate of the area is temperate. The average annual rainfall varies from about 880 mm near the coast to 1 000 mm at Boyanup. Ninety per cent of the rain falls between April and October. The average annual evaporation is 1 500-1 600 mm and mean daily temperatures range from a maximum of 28°C in February to a minimum of 8°C in July.

PHYSIOGRAPHY AND LAND USE

The Boyanup Line bores are on the Swan Coastal Plain (Saint-Smith, 1912) which is a coastal lowland that extends to the Whicher Scarp (Fig. 1), a late-Tertiary or early-Pleistocene shoreline (Playford, Cockbain and Low, 1976). The coastal plain has been divided by Low (1972) into the Pinjarra Plain, an alluvial plain of clays and loams extending west from the Whicher Scarp; the Bassendean Dunes, comprising low dunes of quartz sand with numerous seasonal-swamps; and the Coastal Belt, comprising calcareous and quartz-sand dunes, with inter-dunal lakes and swamps elongated parallel to the coast.

The Preston River, rising on the Darling Plateau, and Gynudup Brook, a tributary of the Capel River rising on the Whicher Scarp, cross the coastal plain near the Boyanup Line.

Most of the Pinjarra Plain has been cleared of native vegetation for dairy and drystock-farming. Small areas of the Bassendean Dunes and the Coastal Belt have also been cleared. A detailed description of the natural vegetation is given in McArthur and Bettenay (1960).

INVESTIGATION PROGRAMME

The bores were drilled between February and July 1981 by the Mines Department Drilling Section with mud rotary rigs. At each site, a 1 000 m deep exploratory-bore (designated A) and a 21-87 m shallow water-bore (C) were drilled. At sites BL1, BL3, and BL4 a 250-402 m intermediate exploratory-bore (B) was also drilled. A summary of the drilling and bore information is given in Table 1.

Sludge samples were taken every 3 m from the four, 1 000 m deep exploratory-bores, split, and stored at the GSWA Core Library. On completion of drilling, natural gamma, long (64 inch), and short (16 inch) normal resistivity logs were run on the deep bores, and various other wireline logs were run

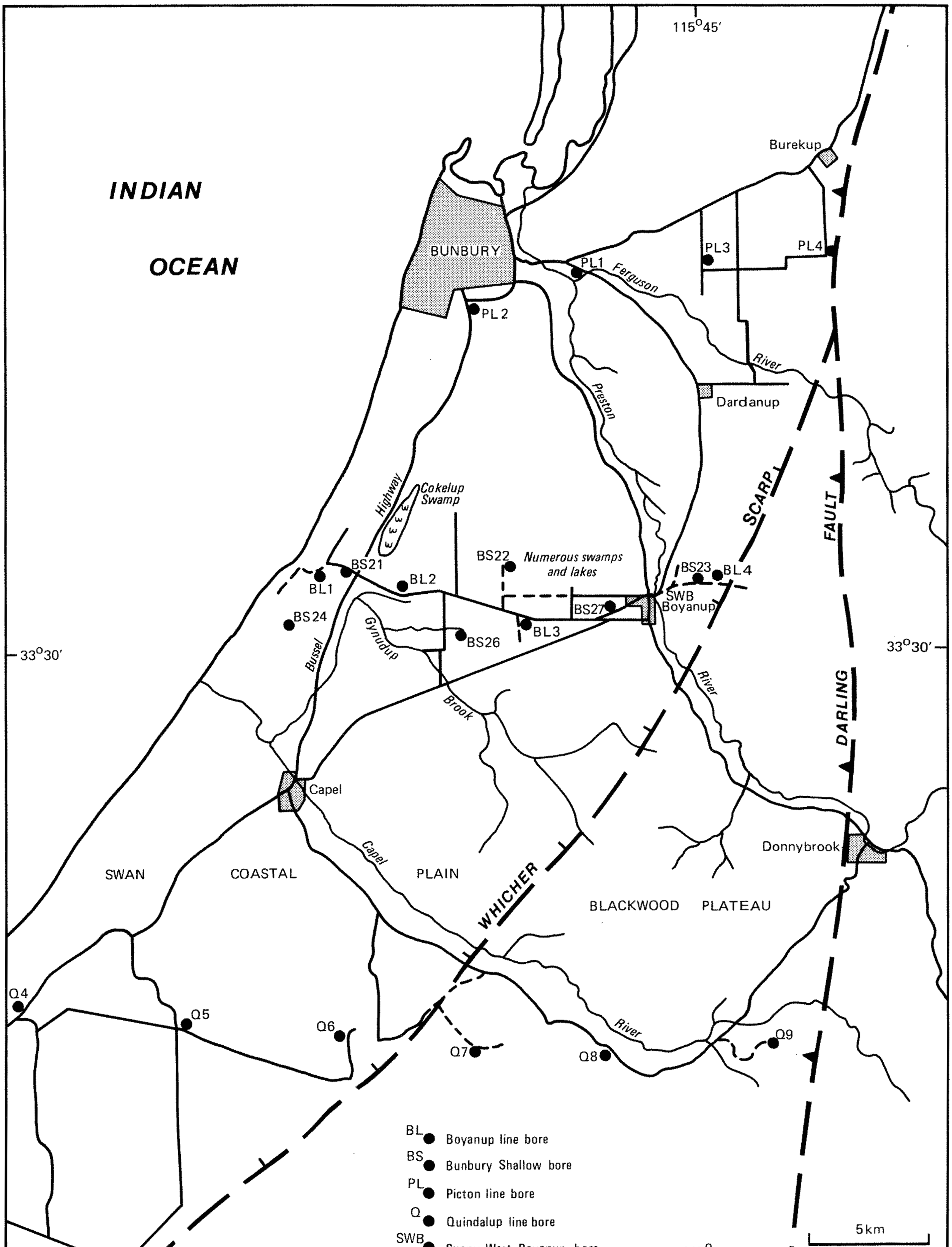

Figure 1. Locality map, Boyanup Line.

TABLE 1. BOYANUP LINE BORE DETAILS

Bore	*Latitude (S)*	*Longitude (E)*	*Elevation (m) bns*			*Depth (m) bns Total cased*	*Observation interval (m) bns*	*Head (m) AHD 11.9.81*	*Salinity (mg/L)*[1]	Formation
			Surface	*Bench mark*	*Casing*					
BL.1A	38°28′13″	115°34′18″	8.160	8.500	8.720	1000 801.5	750-756 (P)	5.31	3260	Cockleshell Gully
"	"	"	"	"	8.630	" "	549-555 (P)	5.86	200	Yarragadee
BL.1B	"	"	8.157	8.497	8.587	402 382	348-354 (P)	5.81	210	"
BL.1C	"	"	7.789	7.919	8.019	87 84.4	78.4-84.4 (S)	5.98	180	"
BL.2A	33°28′29″	115°36′36″	17.867	18.277	18.437	1000 920	788-794 (P)	7.19	240	"
"	"	"	"	"	18.357	" "	489-495 (P)	7.31	450[2]	"
BL.2C	"	"	17.810	18.010	18.010	87 86.2	80-86.2 (S)	8.01	400	"
BL.3A	33°29′21″	115°40′01″	31.809	32.209	32.359	1000 983.5	946-952 (P)	7.83	12 200	Cockleshell Gully
"	"	"	"	"	32.259	" "	642-648 (P)	8.68	250	Yarragadee
BL.3B	"	"	31.898	32.388	32.388	399 397	391-397 (S)	8.96	240	"
BL.3C	"	"	31.543	31.673	31.673	21 20.5	18.5-20.5 (S)	25.98	1610	mainly "superficial"
BL.4A	33°28′36″	115°45′33″	75.695	76.075	76.295	998 899	864-870 (P)	8.56	310	Yarragadee
"	"	"	"	"	76.225	" "	561-567 (P)	9.52	240	"
BL.4B	"	"	75.693	75.953	76.043	250 250	244-250 (S)	31.81	250	Leederville
BL.4C	"	"	74.235	74.395	74.385	40.7[3] 43[3]	40-43(S)	36.58	—	"

AHD—Australian Height Datum bns—below natural surface P—perforated S—screened

1. From Government Chemical Laboratories conductivity using G.S.W.A. Salinity Chart (1979 Revision)
2. Contaminated by cement
3. Washed down 40.7-43 m

as required. For palynological analysis, 71 sidewall cores were obtained from the deep bores. In addition five sidewall cores were obtained from BL1B to test minor coal seams.

In each deep bore, two intervals were selected for observation. Their water levels are measured in an internal pipe and the casing annulus, and are isolated by means of a compressible packer.

There is one observation interval in the other bores. In the deep bores and BL1B, the observation intervals were perforated with shaped charges. In BL3B, BL4B and the shallow bores, the observation intervals are screened.

Each interval was developed by airlifting and surging to obtain a clear uncontaminated sample for chemical analysis. Water from the upper interval in BL2A varied in turbidity and salinity due to cement contamination and is not representative; and a sample was not obtained from BL4C.

GEOLOGY

SETTING

The Boyanup Line bores were drilled in the northern part of the Bunbury Trough, a structural subdivision of the Perth Basin (Playford, Cockbain and Low, 1976). The Bunbury Trough is a deep graben, bounded in the east by the Darling Fault and in the west by the Busselton Fault, and contains about 10 000 m of Phanerozoic sediments.

STRATIGRAPHY

The stratigraphic sequence encountered in the Boyanup Line bores ranged in age from Early Jurassic to Holocene, and is given in Table 2.

Jurassic

Cockleshell Gully Formation: The Cockleshell Gully Formation (Willmott, 1964) is about 2 000 m thick (Playford, Cockbain and Low, 1976) and was intersected at sites 1, 2 and 3. The maximum thickness drilled was 429 m at site 1 (Table 2). It consists of interbedded sandstone and shale with minor siltstone and coal.

In this part of the Perth Basin the Cockleshell Gully Formation is conformably overlain by the Yarragadee Formation. The contact is lithologically, geophysically and palaeontologically difficult to identify, as at site 2, where it may be 130 m shallower than indicated in Figure 2.

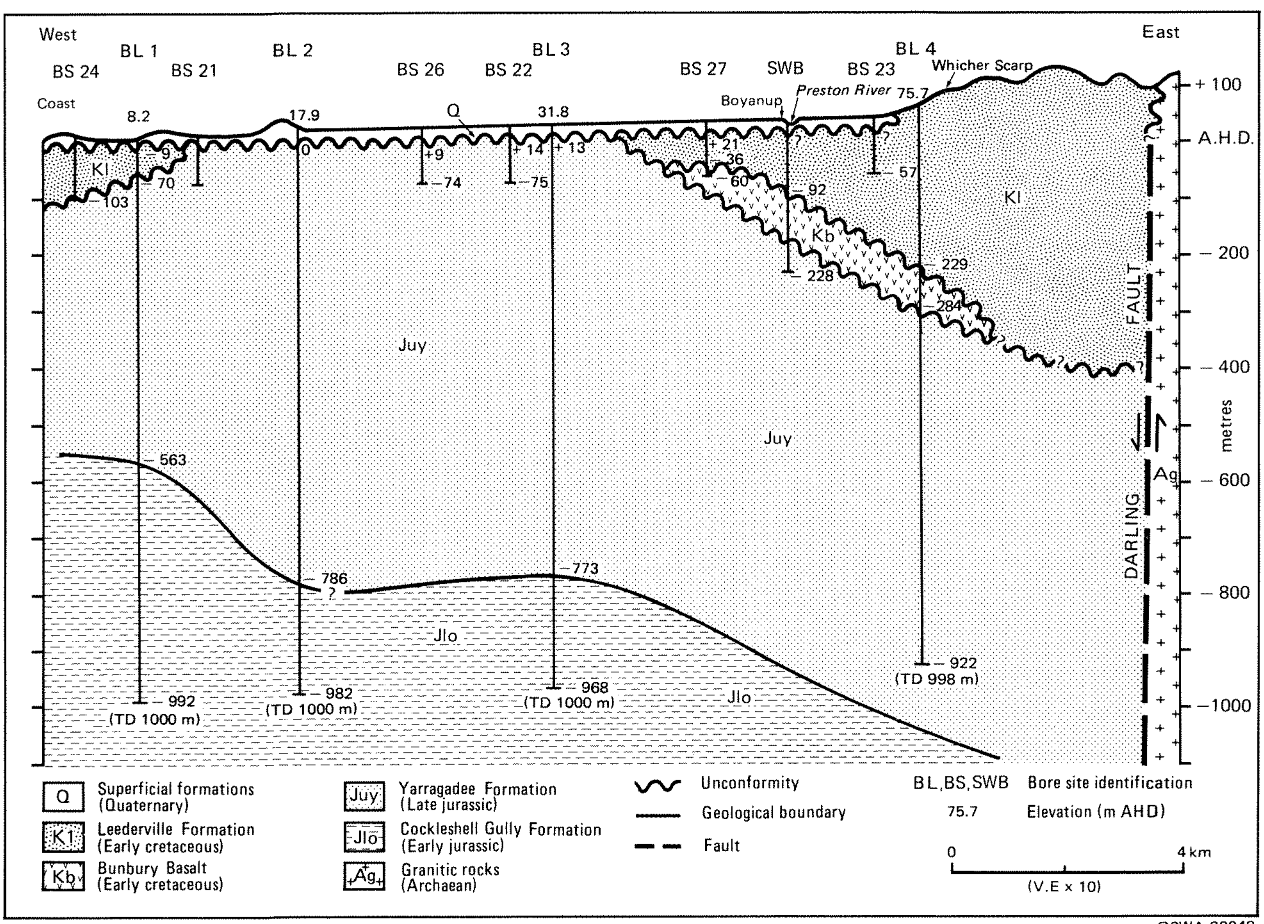

Figure 2. Geological section, Boyanup Line.

The Cockleshell Gully Formation in the Boyanup Line bores has been assigned to *Dictyophyllidites harrisii* assemblage subzone Filatoff (1975) of mid-Jurassic (Bajocian to Aalenian) age and is apparently of non-marine origin (Backhouse, 1981b, c, d). It is probably referable to the Cattamarra Coal Measures of Playford and Low (1972).

Cuttings from the Cockleshell Gully Formation contained minor coal and a sidewall core from 905 m bns in BL1A consisted of finely bedded, brittle coal.

Yarragadee Formation: The Yarragadee Formation (McWhae and others, 1958) was intersected at all sites. The total thickness is not known, but, where intersected, it ranges from 493 to more than 786 m (Table 2). It consists mainly of subangular to subrounded, medium- to very coarse-grained quartz sand, with abundant fine pebbles, minor thin clay and rare, thin coal seams. In the sand are traces of pyrite, accessory garnet, and other heavy minerals. There is about 2% feldspar in the sand at site 3 and thin interbeds of clay are common at site 4.

The Yarragadee Formation conformably overlies the Cockleshell Gully Formation. It is unconformably overlain by the Bunbury Basalt at site 4; the Leederville Formation at site 1; and "superficial formations" at sites 2 and 3.

The palynology of sidewall cores from the Yarragadee Formation indicates a non-marine environment of deposition and a middle- to late-Jurassic age. The youngest palynological assemblages probably belong to the *Contignisporites cooksonae* Oppel-zone (Filatoff, 1975; Backhouse, 1981a, b, c, d). The generally very coarse-grained sand indicated a high-energy (fluviatile) environment.

There are coal traces in the Yarragadee Formation at sites 1, 2, and 4. Coal was most noticeable in sludge samples at site 1 and was recovered in sidewall cores from 367 and 905 m bns at site 1 (Backhouse, 1981e), 87 m at site 2 and 611 at site 4. However, density logging to 389.5 m bns at site 1 did not detect any coal seams.

Cretaceous

Bunbury Basalt: The Bunbury Basalt (McWhae and others, 1958) was intersected from 305-360 m bns in BL4A (Table 2). The basalt showed evidence of alteration or weathering, and the uppermost sample included fragments from the slaggy flow-top (Lewis, 1981).

The Bunbury Basalt unconformably overlies the Yarragadee Formation and is unconformably overlain by the Leederville Formation (Fig. 2).

Palynological assemblages from near the top of the Yarragadee Formation at site 4 belong in the late Jurassic *C. cooksonae* zone. This indicates that the uppermost part of the Yarragadee Formation was either never deposited in this area, or was eroded before the basalt was extruded (Backhouse, 1981a). The Yarragadee Formation 6 m below the basalt had the appearance of being subaerially weathered prior to the extrusion of the basalt which is believed to have spread as flows along valleys eroded into the Yarragadee Formation (Playford, Cockbain and Low, 1976).

Leederville Formation: The Leederville Formation (Cockbain and Playford, 1973) was intersected at sites 1 and 4, where it is 61 and 30 m thick respectively (Table 2). It consists mainly of medium- to very coarse-grained feldspathic quartz sand and gravel with thin interbedded clay and rare carbonaceous shale and coal. At site 1 there are pebbles of siltstone, sandstone, limonite and pyrite-encrusted dolerite at the base and at the top a slightly pyritic black silt.

TABLE 2.
STRATIGRAPHIC SUCCESSION IN THE BOYANUP LINE BORES

Age	*Formation*	*Thickness (m)*				*Summary Lithology*	*Remarks*
		BL1	*BL2*	*BL3*	*BL4*		
Quaternary	Superficial	17	18	19	—	Sand, sandy clay calcarenite	Minor aquifer
		UNCONFORMITY					
Early Cretaceous	Leederville	61	—	—	305	Sand, clayey sand, minor clay	Multilayered aquifer
		DISCONFORMITY					
Early Cretaceous	Bunbury Basalt	—	—	—	55	Weathered basalt	Aquiclude
		UNCONFORMITY					
Late Jurassic	Yarragadee	493	784	786	638	Clay, Clayey sand, sand, coarse sand, minor coal	Major aquifer
Middle to Early Jurassic	Cockleshell Gully	429	198	195	—	Shale, clay, sand	Multilayered aquifer

The Leederville Formation unconformably overlies the Yarragadee Formation at site 1 and the Bunbury Basalt at site 4. East of the Whicher Scarp it crops out and has a deep, weathered lateritic profile. It is unconformably overlain by "superficial formations" on the coastal plain.

Sidewall cores from the Leederville Formation were barren or too sandy for palynological examination (Backhouse. 1981a, d). Sludge samples from site 1 contained several specimens of an undescribed non-marine dinoflagellate cyst (Backhouse, 1981d) which suggests deposition in nearshore non-marine conditions during the Early Cretaceous (Barremian-Early Aptian).

Quaternary

"Superficial formations": The "superficial formations" are about 18 m thick and consist of sand, calcarenite and interbedded sand and clay. Heavy minerals occur at the base of the sequence at site 2, and are mined at Capel.

The "superficial formations" unconformably overlie the Leederville Formation at site 1 and the Yarragadee Formation at sites 2 and 3.

The "superficial formations" are of Quaternary age and extend from the coast to the Whicher Scarp, a late Tertiary or early Pleistocene shoreline. They comprise alluvial, lacustrine, swamp and coastal-dune sediments deposited during variations in sea level and climate in the Quaternary.

STRUCTURE

The inferred geological structure is shown in the section through the Boyanup Line bores (Fig. 2).

The Cockleshell Gully and Yarragadee Formations are conformable and dip east with no evidence of faulting. The Bunbury Basalt infills valleys in the top of the Yarragadee Formation and dips east near Boyanup. The Leederville Formation near the coast thickens to the west and rests unconformably on the Yarragadee Formation, while east of Boyanup, in the Dardanup Syncline (Commander, in prep.), the Leederville Formation thickens to the east and rests unconformably on both the Yarragadee Formation and Bunbury Basalt. The flat-lying "superficial formations" conceal the Yarragadee and Leederville Formations on the coastal plain.

The Mesozoic sediments are downfaulted by the Darling Fault against Archaean granitic rocks in the

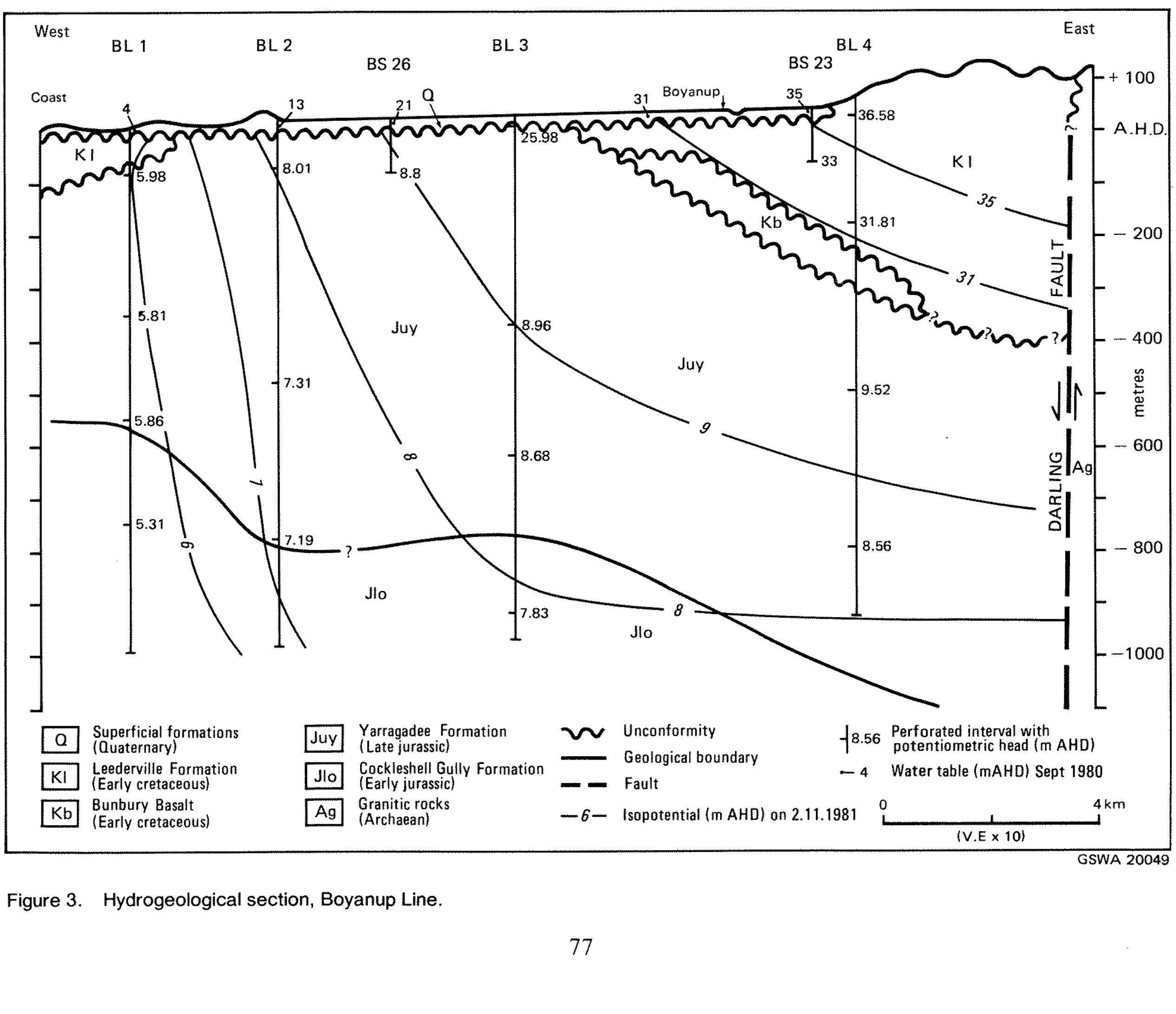

Figure 3. Hydrogeological section, Boyanup Line.

east with local overlapping by the Leederville Formation on to the Archaean rocks. The deposition and distribution of the Leederville Formation possibly results from differential compaction of sediments over the faulted Precambrian basement as described by Cope (1972).

HYDROGEOLOGY

AQUIFER RELATIONSHIPS

A section showing the water levels and apparent isopotentials in the Boyanup Line is given in Figure 3. Water-table values are taken from Commander (in prep.).

Groundwater in the "superficial formations" is recharged by rainfall, and, near the coast, by upward leakage from the Leederville Formation. It flows west and discharges to the sea at a sea-water interface. It is also lost by evapotranspiration and to drains.

In the Dardanup Syncline, the Leederville Formation is recharged by infiltration of rainfall and leakage from the "superficial formations". Groundwater throughflow is to the northwest, and there is downward leakage to the Yarragadee Formation. The Leederville Formation near the coast is recharged by upward leakage from the Yarragadee Formation. Throughflow is to the northwest, and discharge is by upward leakage to the "superficial formations".

Groundwater in the Yarragadee Formation is recharged by leakage from the "superficial formations" and Leederville Formation in the east, and by upward leakage from the Cockleshell Gully Formation near the coast. It flows northwest and discharges downward to the Cockleshell Gully Formation and upward to the Leederville Formation.

Groundwater in the Cockleshell Gully Formation is recharged from the Yarragadee Formation; it is believed to flow northwest and to discharge upward in the Yarragadee Formation near the coast.

AQUIFERS

"Superficial Formations"

The "superficial formations" are less than 20 m thick and consist of sand, calcarenite and interbedded sand and clay. They form an unconfined aquifer with local confined beds in the interbedded sequence.

Groundwater in the "superficial formations" derives from surface infiltration of rainfall and, near the coast, upward leakage from the Leederville Formation. Storage is small and groundwater flows west. Discharge occurs at the sea-water interface at the coast; by evapotranspiration; by flow into drains; and by downward leakage to the Leederville Formation in the Dardanup Syncline and to the Yarragadee Formation in the central coastal plain.

Evapotranspirative losses from the shallow water-table and numerous swamps are high, and, consequently, the groundwater is brackish. Commander (in prep.) reports salinities up to 2 000 mg/L TDS. The only water sample from the "superficial formations" (BL3C) had a salinity of 1 610 mg/L TDS (Table 1).

Leederville Formation

The Leederville Formation is a multilayered aquifer consisting of about 70% medium- to very coarse-grained sand and 30% shale. The extent of the Leederville Formation beneath the "superficial formations" on the western side of the coastal plain is relatively small and better developed in the south (Wharton, 1982). In the east, the formation is preserved in the Dardanup Syncline, and apparent downward and westward hydraulic gradients in the formation indicate recharge to the Leederville Formation by infiltration of rainfall on the Blackwood Plateau and to a lesser extent by downward leakage from the "superficial formations" on the eastern side of the coastal plain. Near the coast there is recharge to the Leederville Formation by upward leakage from the Yarragadee Formation. Groundwater throughflow is northwest from the Blackwood Plateau (Commander, in prep.). Discharge from the Leederville Formation occurs in the Dardanup Syncline by downward leakage to the Yarragadee Formation where the Bunbury Basalt is absent, and along the coast by upward leakage to the "superficial formations".

The only water sample taken from the Leederville Formation (BL4B) had a salinity of 250 mg/L TDS (Table 1) which is representative of groundwater in the formation. The sample was not analyzed for iron but Wharton (1981) reports that iron staining is common with groundwater from the formation.

The Leederville Formation at the eastern end of the Boyanup Line appears to be a substantial multilayered aquifer; it contains low-salinity groundwater and a high proportion of coarse sands. It is virtually unexploited and has considerable scope for development.

Yarragadee Formation

The Yarragadee Formation comprises weakly consolidated, very coarse-grained sandstone with minor beds of shale and coal. It is 490-770 m thick (Fig. 3).

Recharge to the aquifer is by downward leakage from the Leederville Formation in the Dardanup Syncline and the "superficial formations" in the central coastal plain, and upward leakage from the Cockleshell Gully Formation at the coast. Groundwater flow is northwest and discharge is via the overlying sediments to the sea near Bunbury (Commander, in prep.). There is also some discharge by downward leakage to the Cockleshell Gully Formation except at the coast.

Groundwater salinity estimated from long-normal resistivity logs in the Boyanup Line bores, ranges from about 80 to 1 500 mg/L TDS and averages 250 mg/L TDS. It exceeds 500 mg/L TDS over a short interval in the upper part of the aquifer at site 3 and in the lower part at site 4 (Fig. 4).

Three aerated samples of groundwater from the Yarragadee Formation at site 1 were analyzed for total iron, which ranged from 3.8 to 9.6 mg/L (these are high values).

Near the Boyanup Line of bores, groundwater from the Yarragadee Formation is used for Boyanup town-water-supply, dairy processing and sand mining. The extent and thickness of sands in the Yarragadee Formation which contain fresh groundwater indicate that this formation forms a major aquifer capable of considerable further exploitation.

Cockleshell Gully Formation

The Cockleshell Gully Formation was intersected at sites 1-3 and was penetrated for a maximum of 429 m at site 1 (Fig. 2). It comprises interbedded sandstone and shale. Shales up to 20 m thick in the upper part of the formation coincide with the base of the freshwater aquifer in the Yarragadee Formation at sites 2 and 3. At site 1 where the formation is 563 m bns, about 50 m of sandy beds at the top of the formation contain fresh water (Fig. 4) and in hydraulic continuity with overlying Yarragadee Formation (Fig. 3). The aquifer is recharged by downward leakage from the Yarragadee Formation and groundwater flow is probably to the northwest. Discharge is by upward leakage to the Yarragadee Formation at the coast. The estimated groundwater salinity in the Cockleshell Gully Formation increases rapidly with depth from 210 to 42 000 mg/L TDS (Fig. 4).

This aquifer is not exploited because it is nearly 600 m bns and large resources are available in the overlying Yarragadee Formation.

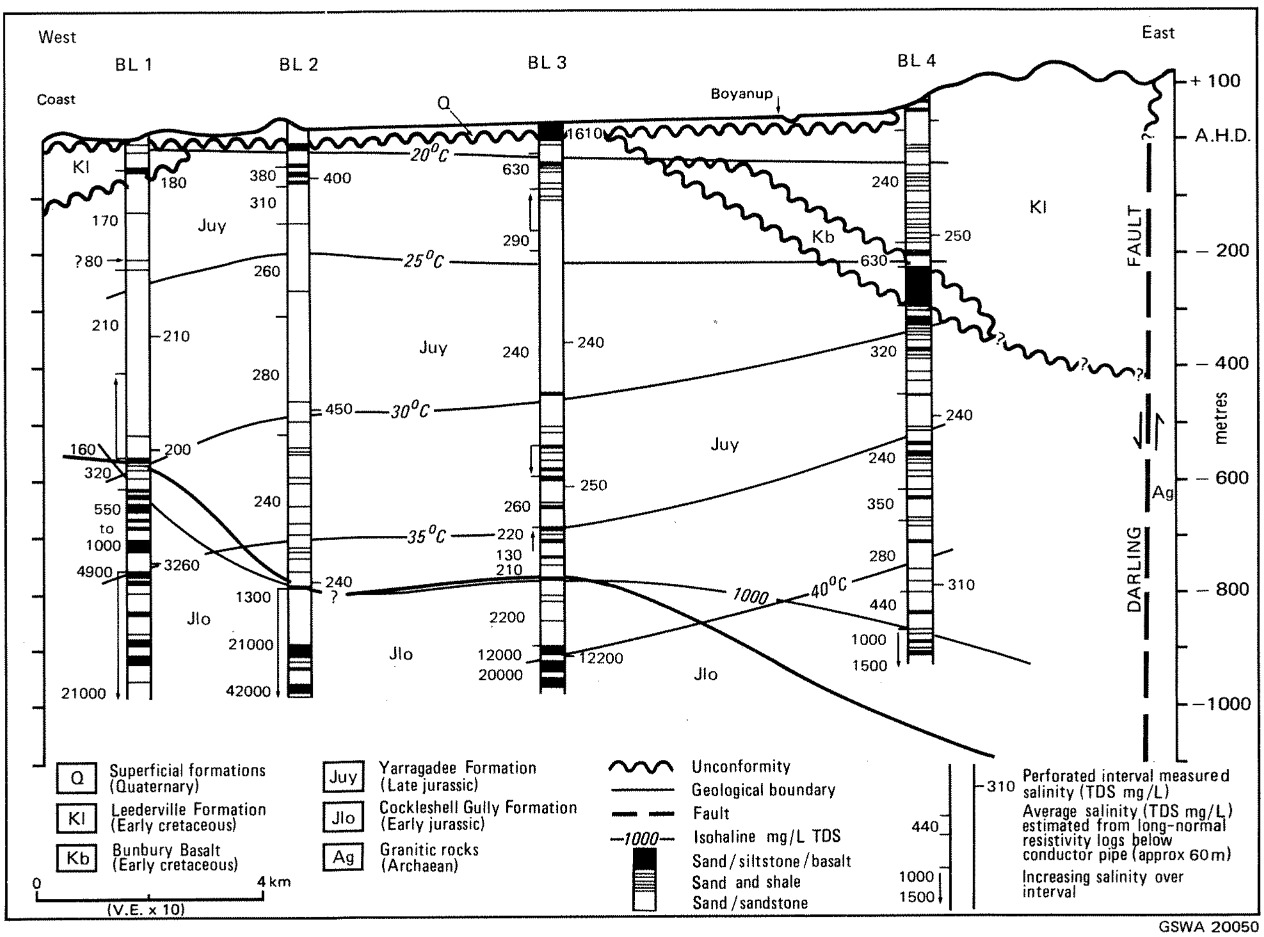

Figure 4. Lithology, groundwater, salinity and temperature, Boyanup Line.

HYDROCHEMISTRY

Water samples were recovered from each observation interval except from BL4C and analyzed by the Government Chemical Laboratories. Formation factors were calculated for the observation intervals and used to estimate salinities (Fig. 4) from the long-normal resistivity logs.

The major ions plotted as a percentage of their total milli-equivalent per litre on a trilinear diagram (Piper, 1944), indicate two distinctive ionic compositions (Fig. 5). In all the samples sodium is the principal anion but the relative concentration of the cations HCO_3^- and Cl^- varies. Most of the Yarragadee Formation water samples contain as much bicarbonate as chloride; in the other samples chloride is the predominant cation.

GROUNDWATER TEMPERATURE

Differential temperature-logs were run in the deep bore at each site, to the completed depth (Fig. 4). The logs were run 6-8 weeks after completion of each bore and the temperature gradients are taken to represent the geothermal gradient at each site. The average geothermal gradient at each site is low and increases west to east from 20 to 27°C/1000 m. The highest gradient occurs in BL4A, across the Bunbury Basalt, which has a low thermal conductivity.

CONCLUSIONS

The Boyanup Line bores have defined the extension of the structure and stratigraphy as found in the eastern Quindalup Line and the Picton Line bores.

The drilling has confirmed the thickness (550-880 m), depth and quality of very large, fresh groundwater resources in the Yarragadee Formation (as indicated by the Picton and Quindalup Line bores) and smaller resources in the Leederville Formation.

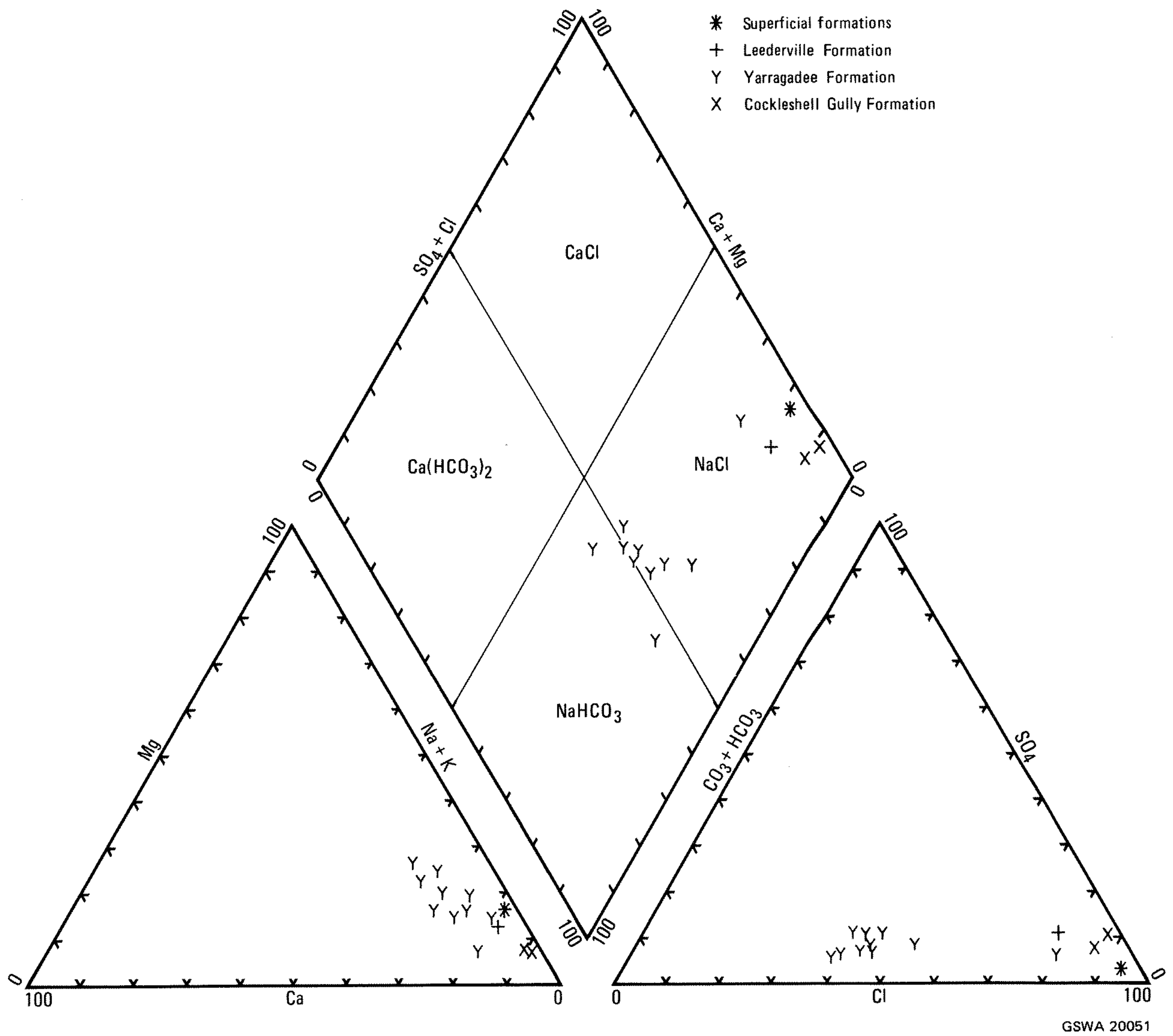

Figure 5. Trilinear diagram of water analyses, Boyanup Line.

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A 2557 m.y. BANDED GNEISS AT BARRET WELL NEAR EDJUDINA, EASTERN GOLDFIELDS PROVINCE

by J. C. Roddick and W. G. Libby

ABSTRACT

Rubidium-strontium whole-rock analysis of thirteen samples of migmatitic gneiss near Barret Well, about 170 km northeast of Kalgoorlie in Western Australia, yields a date of 2 557 ± 35 m.y. with an R_I of 0.7025 ± 0.0002. This date is similar to that of non-gneissic granitic rocks of the Eastern Goldfields, but younger than that of other gneisses. The relatively young date of the Barret Well gneiss supports earlier suggestions, based on geological evidence, that migmatization was associated with magmatic emplacement of late Archaean granitic rock.

INTRODUCTION

Well-foliated granitic gneiss is exposed over an area of about one square kilometre at Barret Well (lat. 29°39′ S., long. 122°43′ E.) in the central part of the Eastern Goldfields Province, about 170 kilometres northeast of Kalgoorlie and 40 kilometres east-north-east of Edjudina homestead. Thirteen whole-rock determinations from six samples and splits of some heterogeneous samples give a Rb-Sr isochron date of 2557 ± 35 m.y. This date is similar to that of many granitoids in the Eastern Goldfields but significantly younger than other gneisses, for example, 2723 ± 41 m.y. at Menangina (de Laeter and others, 1973) and 2625 ± 34 m.y. at Perseverance (Cooper and others, 1978).

PURPOSE AND HISTORY

In recent years it has become fashionable to consider gneissic terrains in the Archaean cratons to be remnants of ancient basement into which surrounding, less deformed, granitoid rocks have been intruded and upon which nearby supracrustal rocks have accumulated. A principal objective of the present study was to test this assumption in an area where local geological opinion differed from the above hypothesis. The study demonstrates, first that there is no reason to believe the gneisses at Barret Well to be substantially older than adjacent granitoids and, second, that the degree of gneissic foliation is an unreliable criterion on which to base an estimate of the age of a body of rock.

The gneiss, mapped by Williams and others (1976), is part of a migmatite complex which straddles the broad Elora anticline in the eastern quarter of the Edjudina 1:250 000 sheet. These authors interpret the migmatite terrain to be "... the result of continued emplacement of granitic material into an older layered succession." Contact metamorphism in adjacent supracrustal rocks of the Mulgabbie and Gindalbie Formations up to 5 km west of the migmatite is cited. The body of gneiss is intruded by homogeneous granites and granitic dykes.

Similar gneisses, associated with greenstone belts farther south in the Eastern Goldfields, have been interpreted to be have been present prior to accumulation of much, at least, of the adjacent volcanic and sedimentary rocks of the greenstone belt (Archibald and Bettenay, 1977) and are considered to have been present prior to the intrusion into the area of major post-orogenic batholiths. They may therefore be considered to be the basement of both the local supracrustal sequences and batholithic granitic rocks. The purpose of the current investigation has been to test the model in a specific area where a rather different history has been suggested.

LOCATION AND PETROGRAPHY

The regional location of the Barret Well geochronological samples is shown in Figure 1 and details of the location of individual samples are shown in Figure 2.

Field and petrographic characteristics of individual samples are summarized in Table 1. In general the samples, which are all gneissic, range in texture from seriate to even grained allotriomorphic granular. They range in composition from biotite adamellite, with about equal proportions of oligoclase and microcline, to biotite granodiorite (near adamellite). Several samples contain muscovite but this is missing from others, most notably from the more finely crystalline, less altered phases. Blebby quartz is characteristic of the unit, and most samples are myrmekitic. Gneissic foliation is evident in some thin sections, and is marked by orientation of biotite and quartz. Feldspar, especially the coarser phases, is patchily dusted with submicroscopic secondary material. Other secondary products—sericite, chlorite, epidote and carbonate—are rare.

EXPERIMENTAL PROCEDURES

The experimental procedures used are similar to those described by Chappell and others (1969) with a few minor changes. All samples were analysed for Rb and Sr by X-ray fluorescence spectrometry using background measurements for mass absorption corrections. Analyses of the standard NBS stoichiometric $SrCO_3$ salt SRM 987 on the mass spectrometer (MSF with Cary 31 electrometer) during this study gave a $^{87}Sr/^{86}Sr$ value of 0.71023 ± 5 (standard deviation of population). NBS 70A potassium feldspar analysed during the course of the work had values of 522 ppm of Rb and 65.4 ppm

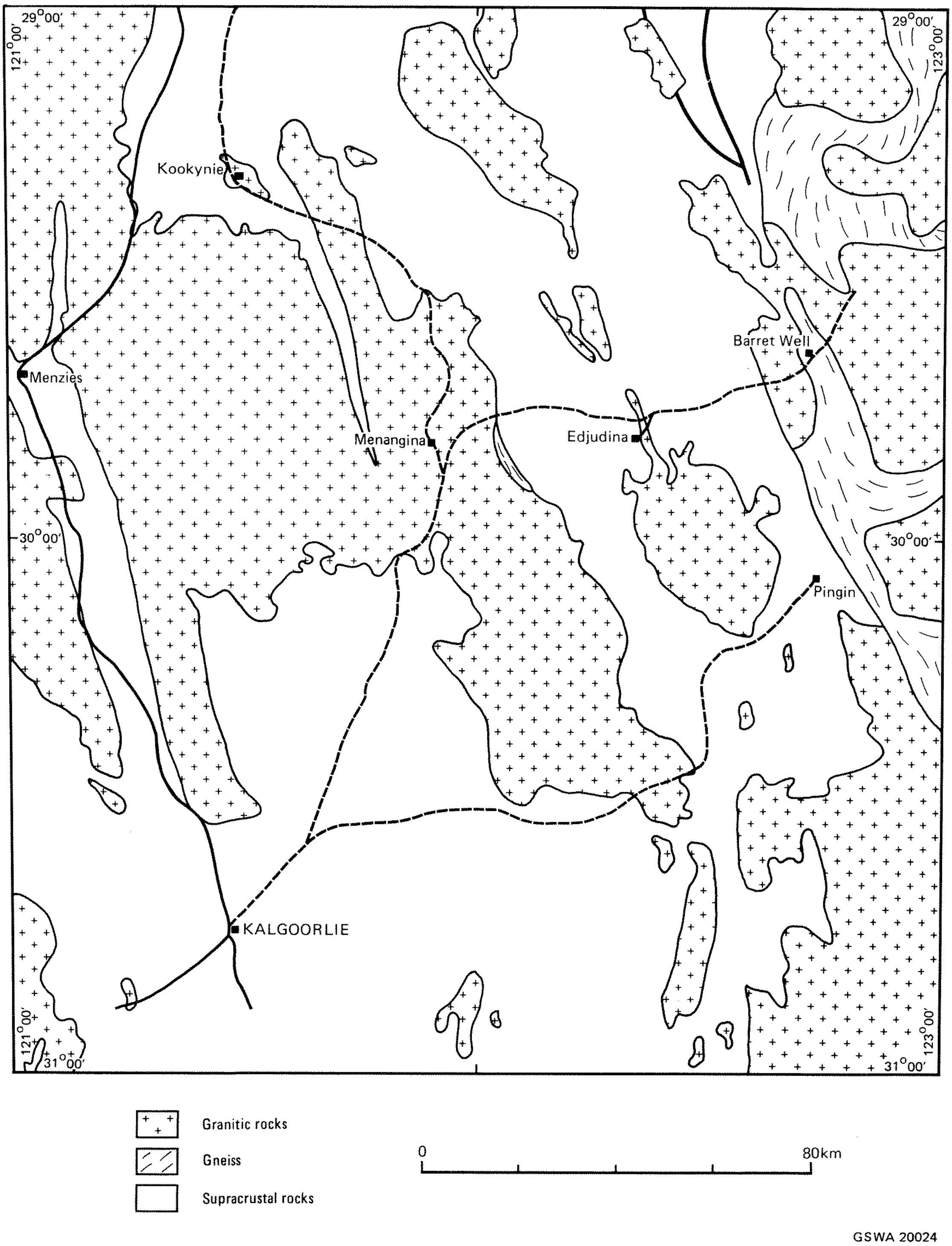

Figure 1. Location and regional geology.

total Sr by isotope dilution. All XRF results were compared and adjusted to these values. Blanks were sufficiently low (Rb 1.0 nanograms (ng); Sr 3.0 ng) to provide negligible correction in most cases. The ^{87}Rb decay constant used was 1.42 x $10^{-11}y^{-1}$ (Steiger and Jäger, 1977). The regression technique of McIntyre and others (1966) was used and tests of significance associated with the isochron interpretation were made at the 95 percent level of confidence. The T-multiplier was applied to the estimated errors in X and Y, as suggested by Brooks and others (1972), rather than on the basis of the number of samples regressed. In assigning errors to the regression points, the coefficient of variation for the $^{87}Rb/^{86}Sr$ ratio was taken as 0.5 percent (McIntyre and others, 1966) and for the $^{87}Sr/^{86}Sr$ ratio, as 0.01 percent.

TABLE 1

A.N.U. Sample No.	*G.S.W.A. Sample No. and Description*
72-928	(GSWA 56422 A): Fresh samples of biotite adamellite gneiss from thick exfoliation (about 1 foot) on flat outcrop. First outcrop along road from Yarri as Barret Well is approached.
72-929	(GSWA 56422 B): Fresh biotite-oligoclase grandodiorite gneiss from exfoliation.
72-930	(GSWA 56422 C): Fresh banded biotite adamellite to granodiorite gneiss located about 30 metres from 929 and about 200 metres northwest of well. Less muscovite and dusting of feldspar in finer, adamellitic bands than in the coarse, granodioritic phase.
72-931	(GSWA 56422 D): Fresh two-mica granodiorite gneiss northwest of 929 and 930, along fence. Coarse quartz-feldspar veins cut the gneiss discordantly. Appears to have distorted flow banding in gneiss in some locations.
72-932	(GSWA 56422 E): Two-mica granodiorite gneiss with a friable biotite band. West of 929 and 930 but in the same outcrop. Here again, the finer phase, rich in apatite, is characterized by less dusting of oligoclase and has less muscovite than the coarser phase.
72-933	(GSWA 56422 F): Fresh biotite adamellite gneiss 100 metres west of 932, near corner of fence.

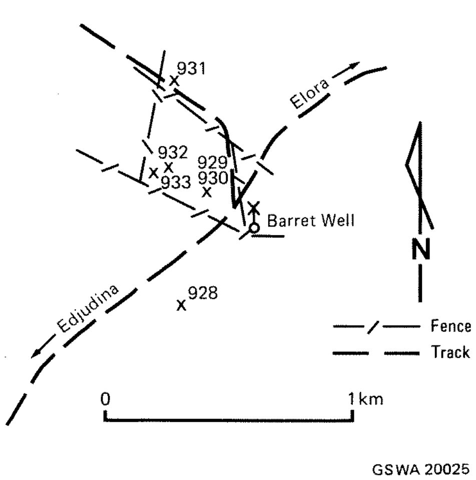

Figure 2. Sample locations.

ANALYTICAL RESULTS

Six whole-rock samples of both homogeneous gneiss and well-banded gneiss were collected. Two of the samples were each sliced into four sub-samples along their compositional bands (1″ to 3″ thick) in order to assess the degree of Sr isotopic homogenization as well as to determine the age of the gneiss. Table 2 presents the data and Figure 3 indicates that the data for most samples define a good isochron. Only one point (932-B) is significantly off line. This particular sample is of a biotite-rich zone which appears to be more friable than the other fresh samples and has probably been affected by resent surface weathering. Regression of all analyses except 932-B (a total of 13 points) defines an age of 2557 ± 34 m.y. and an initial $^{87}Sr/^{86}Sr$ of 0.7025 ± 0.0002 (M.S.W.D. = 1.5). Regression on the separate sliced specimens (928, 930) yields ages that agree within error with the 13-point isochron.

TABLE 2
BARRET WELL GNEISS

Sample No.	*Rb (ppm)*	*Sr (ppm)*	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
72-928	109	393	.8058	.73220
928-A	75	417	.5175	.72161
928-B	99	439	.6542	.72680
928-C	104	429	.7000	.72861
928-D	83	423	.5630	.72333
929	56	443	.3639	.71615
930-A	98	482	.5850	.72399
930-B	65	504	.3745	.71653
930-C	79	503	.4558	.71949
930-D	69	502	.3965	.71722
981	71	534	.3857	.71660
932-A	53	469	.3292	.71458
932-B	135	567	.6869	.72871
933	84	487	.4988	.72094

The precise isochron defined both by whole-rock samples and thin slices indicates complete Sr isotopic homogenization was attained during the formation of the genissic bands at 2557 ± 34 m.y. The initial Sr ratio is only slightly above the presumed upper mantle ratio at that time. Coupling these data with the bulk earth Sr isotopic composition (Cameron and others, 1981) indicates that the source material for the gneiss was probably derived from the upper mantle no earlier than 2750 m.y. ago.

The isochron date from Barret Well is younger than dates of other gneisses from the Eastern Goldfields but is similar to non-gneisses granitoids.

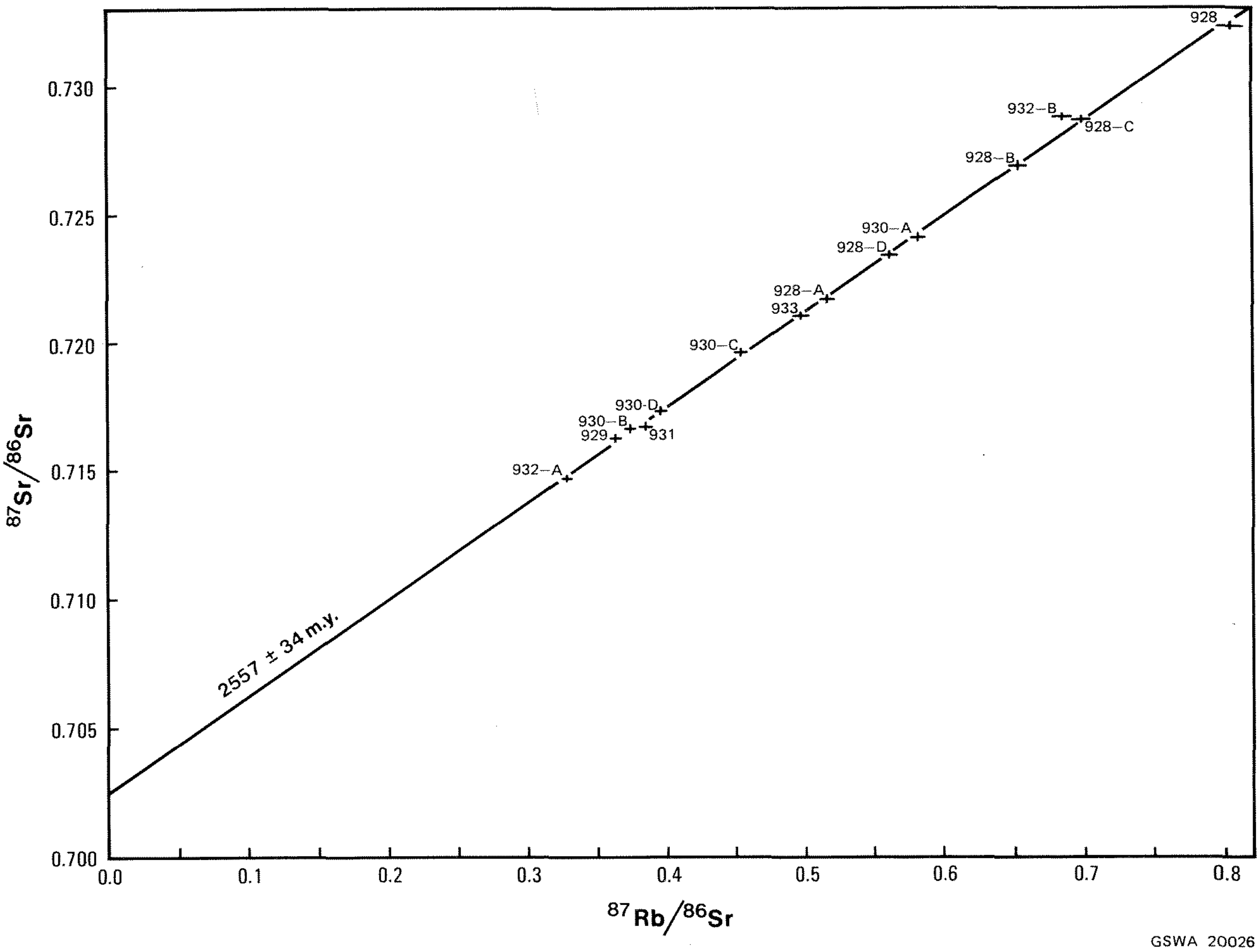

Figure 3. Rb-Sr whole-rock isochron.

Rb-Sr whole rock dates from the Eastern Goldfields (de Laeter and others, 1981) are shown in the histogram in Figure 4.

The results do not eliminate the possibility of generation of the Barret Well gneisses early in the Archaean Tectonic Cycle (i.e. 2600 m.y. to 2800 m.y.) However, they do indicate that an event disturbed the system near the end of the cycle (about 2550 m.y.), thus supporting the concept of late Archaean migmatization and accompanying intrusion by dykes as proposed by Williams and others (1976).

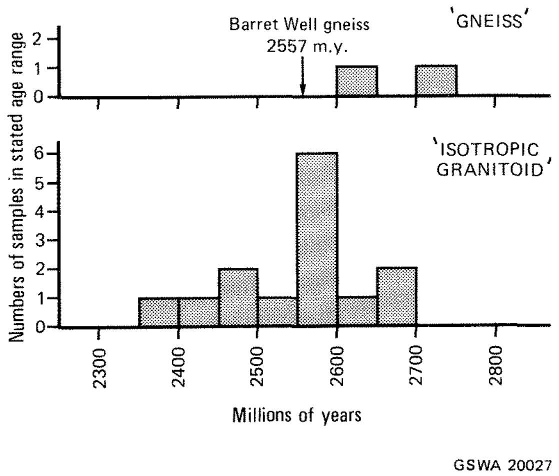

Figure 4. Ages of isotropic granitoid and gneiss in the Eastern Goldfields Province.

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GROUNDWATER IN THE BLACKSTONE REGION

by P. H. Wharton

ABSTRACT

The Blackstone Region is located in the east of Western Australia and borders the Northern Territory and South Australia. It includes the Warburton Aboriginal Reserve and part of the Central Australian Reserve.

The area was intensively drilled during 1980 to obtain water supplies for Aboriginal settlements and outstations.

The region is dominated by the Proterozoic rocks of the Musgrave Block which is bounded to the west and south by Phanerozoic sediments of the Officer Basin and to the north by the Proterozoic Amadeus Basin.

From the drilling results the most important Proterozoic aquifers in the Musgrave Block are the weathered mafic and ultramafic rocks which have yielded supplies of up to 100 m^3/day, with salinities of 600 to 1 000 mg/L TDS. The Permian sandstones of the Officer Basin are the most important aquifer in the region with yields of up to 1 470 m^3/day and salinities from 400-2 000 mg/L TDS.

The overlying Cainozoic sediments contain some useful, shallow supplies of groundwater. In particular, calcrete, which fills an ancient drainage system, yields supplies of up to 70 m^3/day with salinities of 700 to 3 000 mg/L. However it is susceptible to pollution and has a high nitrate concentration which may limit its exploitation.

INTRODUCTION

LOCATION

The Blackstone Region of Western Australia was defined by Daniels (1974) as encompassing the Bentley, Scott, Talbot and Cooper 1:250 000 map sheet areas, and is bounded by latitudes 25° and 27° south and longitudes 126° and 129° east (Fig. 1).

The region adjoins the South Australian and Northern Territory borders, and includes the Warburton Aboriginal Reserve, and part of the Central Australian Aboriginal Reserve.

Settlements in the area include aboriginal communities at Warburton, Blackstone, Wingelinna, Jameson and Giles (Warakurna), and a meteorological station at Giles. Warburton is 574 km northeast of Laverton, and 1 530 km from Perth. A graded road connects Warburton and Laverton.

OBJECTIVES

This report describes the results of drilling by the Mines Department of Western Australia in the Blackstone Region and at Kalka in South Australia, during 1980, and discusses the occurrence of groundwater in the region based on the results of this drilling and previous investigations.

PHYSIOGRAPHY

The main physiographic feature of the region is a belt of prominent hills and ranges which extends from Warburton through Jameson, Blackstone and Wingelinna into South Australia. A small part of the Rawlinson, Kathleen and Dean Ranges extends across the northeastern corner of the region.

The ranges are flanked by undulating plains of the Gibson and Great Victoria deserts. The desert areas consist mainly of sand dunes, with some low laterite-surfaced ridges, occasional rocky hills, and scattered salt lakes. The major physiographic units are shown in Figure 2.

The region drains mostly to the south and southwest, towards the Eucla Basin, along poorly developed calcrete drainages. The drainages are only well defined in, or near, the main ranges.

CLIMATE

The climate is arid with highly irregular rainfall. The annual rainfall at Warburton between 1941 and 1972 ranged from 35 mm to 691 mm, with an average of 220 mm. The potential evaporation is more than 3 000 mm. Watercourses flow only after prolonged periods of heavy rainfall.

VEGETATION

The vegetation consists mainly of spinifex and stunted mulga scrub, with stands of desert oak on areas of calcrete, and some dense thickets of mulga in low areas. Eucalypts, including white gum, and a variety of trees and shrubs grow along the watercourses.

PREVIOUS INVESTIGATIONS

Water supplies and the occurrence of groundwater in the region have previously been investigated by Sofoulis (1962), Farbridge (1968), Barnett (1980), Wharton (1981), and by the South Australian Department of Mines and Energy.

The results of drilling for water at Giles are given by O'Driscoll (1956). Farbridge (1967) reports on the drilling of three bores by Southwestern Mining in the Cobb Depression, and Buck (1980) gives details of exploratory water-bores drilled for Shell Development (Australia) Pty Ltd, for Yowalga 3 drill site. Two of the Shell bores and the Cobb Depression bores are shown in Figure 1, and details of the bores are given in Table 1.

MINES DEPARTMENT DRILLING, 1980

The Geological Survey was requested by the Public Works Department to investigate the groundwater prospects, and to select bore sites, in a number of specific areas in the Blackstone Region. The bores were planned to provide water for small aboriginal out-camps, and to supplement water supplies at Warburton, Jameson, Blackstone and Kalka. Bore sites were selected in these areas by Barnett (1980) and Wharton (1980).

The Mines Department Drilling Section Drilled bores at 17 sites; 16 in Western Australia, and 1 in South Australia (Fig. 1), using a Jacro rotary rig with air-circulation and equipped with a down-hole hammer.

Ten bores were successful, and will be equipped for production. Three of the remaining seven bores were not drilled deep enough to fully investigate potential aquifers (sites 19A, 28 and 29), two were dry (sites 17 and 18), and two yielded water with a salinity too high for human consumption (sites 15 and 20).

The successful bores were completed with 168 mm steel-casing, either slotted over the production

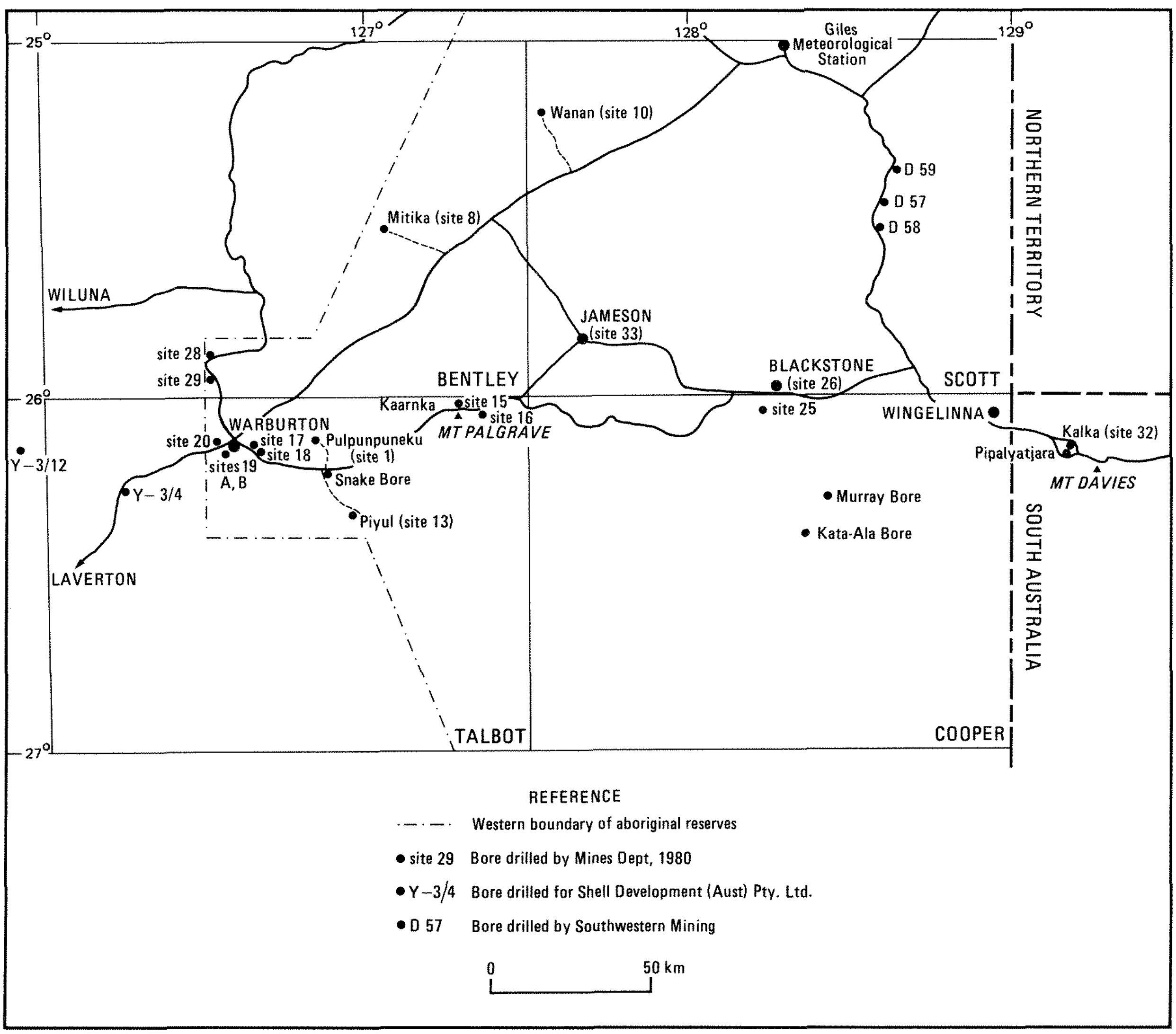

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Figure 1. Locality map.

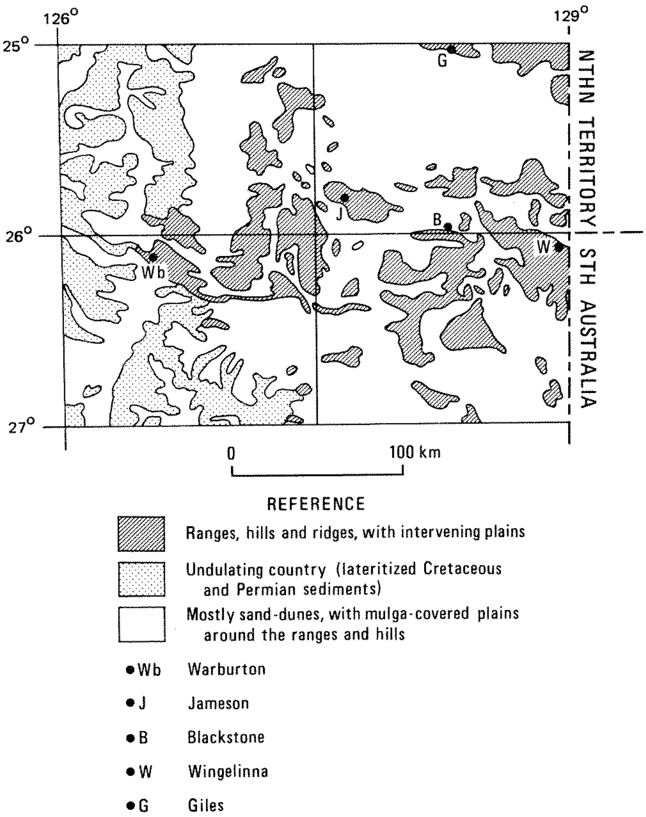

Figure 2. Major physiographic units.

interval, or with a continuous-slot stainless-steel screen run on the end of the casing. The slotted casing and screens were packed with fine gravel which was collected locally.

Details of the bores are given in Table 2.

HYDROGEOLOGY

SETTING

The Blackstone Region is dominated by the Proterozoic Musgrave Block (Daniels, 1974), which is bounded to the west and south by the Phanerozoic Officer Basin and to the north by the Proterozoic Amadeus Basin, and which extends into the Northern Territory and South Australia (Fig. 3).

The Cobb Depression is probably a broad downwarping of the Musgrave Block (Daniels, 1974) which is filled with Permian sediments; a thickness of at least 122 m was intersected in a bore drilled by Southwestern Mining (Farbridge, 1967).

The Musgrave Block is generally a favourable area for the occurrence of low-salinity groundwater as it is up to 200 metres higher than the surrounding salt-lakes and saline drainages. Groundwater in the block moves relatively rapidly under high hydraulic-gradients, and is close to, or within, recharge areas,

(a) TABLE 1. DETAILS OF OTHER BORES SHOWN IN FIGURE 1

Bore	*Drilled by (or for)*	*Year*	*Depth (m)*	*Yield (m^3/d)*	*SWL (mbns)*	*Salinity (mg/L TDS)*	*NO_3 (mg/L)*	*F (mg/L)*	*Aquifer*
Y-2/12	Shell Development Pty Ltd	1980	141	500	57.8	620	17	0.1	Permian sandstone
Y-3/4	Shell Development Pty Ltd	1980	75	38	50.4	1 890	—	—	Permian sediments
Snake	—	—	—	—	—	750	130	1.0	Calcrete
Murray	?SA Dept Mines & Energy	—	—	—	—	—	—	—	?Vesicular basalt
Kata-Ala	SA Dept Mines & Energy	1978	70	5	9.5	1 000	—	—	Fractured granite
D57	Southwestern Mining	1967	107	1 090	22.4	1 075	65	1.4	Permian sandstone
D58	Southwestern Mining	1967	28	"soak"	16.9	—	—	—	Weathered gneiss
D59	Southwestern Mining	1967	122	1 473	38.9	2 013	43	1.5	Permian sandstone

(a) Bores not drilled by the W.A. Mines Department in 1980

TABLE 2. BORES DRILLED IN THE BLACKSTONE REGION, 1980

GSWA Site No.	Location	Latitude ° ′ ″	Longitude ° ′ ″	Commenced	Completed	Total depth (m)	Interval screened (or slotted casing) mbns	"Aquifer"	Test-rate (m^3/d)	Drawdown (m)	After time (hrs)	SWL (mbns)	Salinity (mg/L TDS by summation)	NO_3 (mg/L)	F (mg/L)	Status (P.P.B. = Potential production bore)
1	Pulpunpuneku	26 07 54	126 51 35	28/10/80	28/10/80	16	Screen 12.1-15.2	Calcrete	Airlift 157 Pumping Test	—	—	6.48	931	115	1.0	P.P.B.
8	Mitika	25 32 35	127 05 36	23/09/80	25/09/80	86	Slots 65.0-82.8	Weathered Permian Siltstone	96							
10	Wanan	25 15 00	127 33 50	30/09/80	04/10/80	49	Slots 34.9-47.8	Weathered and jointed gneiss	61	7.9	2	37.23	394	36	0.4	P.P.B.
13	Piyul	26 19 02	126 55 37	30/10/80	31/10/80	16	Screen 10.1-13.2	Sand, minor calcrete	8.1 91	6 17.4	2 0.17	26.50	1 855	115	3.2	Equipped with hand pump
15	Kaarnka (W)	26 02 34	127 16 39	03/11/80	04/11/80	19	—	Calcrete	72	1.4	2	5.28	1 825	208	1.2	P.P.B.
16	Kaarnka (E)	26 03 53	127 20 51	06/11/80	11/11/80	40	Slots 19.8-38.8	Weathered ?acid volcanic	Air-lifting 26-79	—	—	—	2 279	97	3.0	Abandoned
17	Warburton Range (N)	26 09 05	126 38 32	18/10/80	18/10/80	49	—	?Proterozoic sediments	12	8.4	2	15.9	1 024	75	2.0	P.P.B.
18	Warburton Range (S)	26 09 34	126 39 07	20/10/80	22/10/80	52	—	Dolerite	Dry	—	—	—	—	—	—	Hole bridged on completion 8 m, abandoned
19A	Brown Range	26 09 58	126 33 26	10/10/80	17/10/80	28.4	—	Quartzite	No supply	—	—	16.2	—	—	—	Sealed and abandoned
19B	Brown Range	26 09 57	126 33 13	01/12/80	03/12/80	31.7	Screen 26.6-29.6	Quartzite, minor shale	1	—	—	13.27	—	—	—	Sealed and abandoned
20	Brown Range (N)	26 08 22	126 32 27	06/10/80	08/10/80	38	Slots 16.1-35.4	Weathered quartzite, sandstone & siltstone	18	6.8	2	13.7	1 029	13	0.6	P.P.B.
25	Blackstone (SW)	26 02 53	128 14 00	18/11/80	20/11/80	55.2	Screen 51.4-54.5	Weathered gabbro	17	2.8	1.5	12.53	3 825	102	2.7	Abandoned
26	Blackstone Camp	25 59 45	128 16 58	21/11/80	22/11/80	42.2	Screen 38.7-41.8	?Gabbro (very deeply weathered)	67	3.5	2	21.81	741	44	0.2	P.P.B.
28	Kunbul (N)	25 53 50	126 30 05	22/10/80	24/10/80	17.6	—	Quartzite	96	1.9	2	33.55	765	35	0.2	P.P.B.
29	Kunbul (S)	25 56 20	126 30 51	24/10/80	25/10/80	8.8	—	Quartzite	Dry	—	—	—	—	—	—	Sealed and abandoned
32	Kalka	26 07 05	129 09 20	25/11/80	27/11/80	60	Slots 32.6-57.2	?Very deeply weathered ?gabbro	Dry 17	— 0.9	— 2	— 30.63	— 726	— 22	— 0.8	Sealed and abandoned Equipped for production
33	(approx.) Jameson (approx.)	(approx.) 25 52 00 (approx.)	127 42 00	13/11/80	16/11/80	61	Slots 23.2-47.2	Weathered gabbro	93	6.1	2	25.6	947	170	0.4	P.P.B.

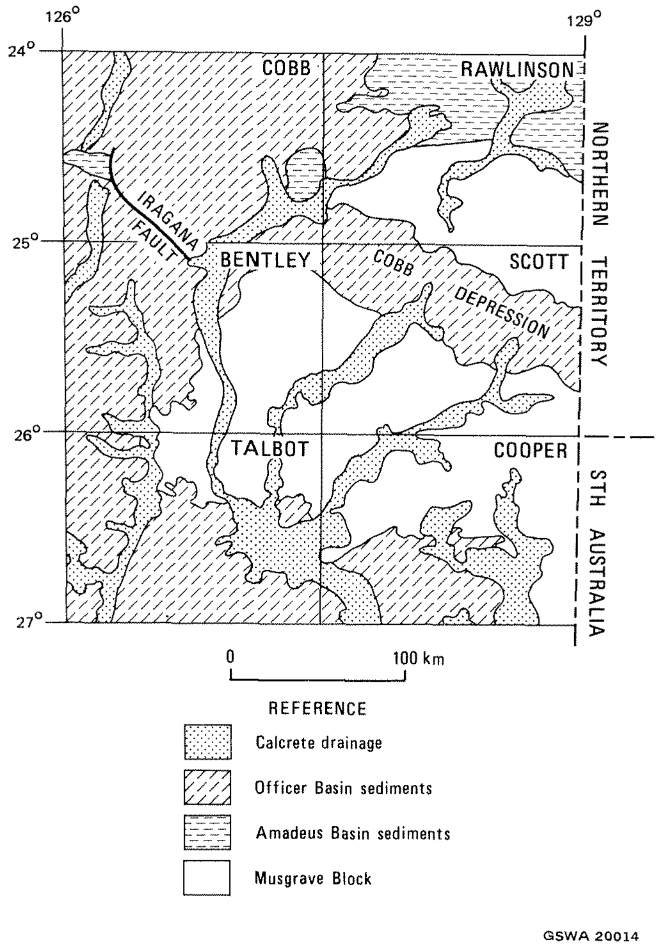

Figure 3. Structural subdivisions.

resulting in minimal salt accumulation. The quantity and quality of groundwater available is also dependent on the nature of the aquifer.

PROTEROZOIC AQUIFERS (MUSGRAVE BLOCK)

The Musgrave Block is composed of Proterozoic granitic rocks, granulite and gneiss, volcanic rocks, mafic and ultramafic intrusives, and sediments. The geology of the Musgrave Block is complex, and is described in detail by Daniels (1974).

Mafic and ultramafic intrusive rocks

Gabbro, and associated ultramafic and acid differentiates, form the Giles Complex (Sprigg and Wilson, 1959), which extends from north of Mount Palgrave in Western Australia to 160 km east of Mount Davies in South Australia (Daniels, 1974).

Weathered and fractured rocks of this complex (mainly gabbro) are intersected in bores at Jameson, Blackstone, Wingelinna and Kalka (Fig. 1), and form the most important Proterozoic aquifer in the region. The bores yield up to 100 m³/day of water, and some may be capable of considerably higher yields. Groundwater salinity is generally between 600 and 1 000 mg/L TDS, although it exceeds 1 000 mg/L TDS in some bores at Wingelinna.

In successful bores the gabbro is weathered to depths of between 25 and 80 metres, and transmissive zones include gabbro grit (remnants of fresh gabbro), clay with secondary porosity, calcified clay and grit, and fractures within fresh gabbro.

Granite, gneiss and granulite

Few bores have been drilled into granite, gneiss or granulite as most settlements in the region have developed from abandoned mining-company camps, and these rocks are not usually a target for mineral exploration.

The only known successful bores in granite or gneiss intersect weathered and jointed gneiss at Wanan (site 10) and at Wingelinna. At Kata-Ala, 4 bores have been drilled, but only one yields a poor supply from fractured granite. Other unsuccessful bores have been drilled in granite at Giles, and in gneiss at site D58 (Farbridge, 1967).

Extrusive igneous rocks

Extrusive igneous rocks have been intersected in bores drilled at Warburton and Kaarnka (site 16), and were probably intersected in Murray Bore.

Water for the Western Mining Corporation camp at Warburton was pumped from two bores and Sim's Shaft, all of which intersect basalt and sediments of the Milesia Formation. Sim's shaft yields a large supply (650 m^3/day) of slightly brackish water (1 700-2 300 mg/L TDS).

The bore at Kaarnka (site 16) intersects weathered acid volcanics which are overlain by sand and clacrete. It yields at least 12 m^3/day, with a salinity of 1 00 mg/L TDS.

Details of Murray Bore are not known; however, water from the bore supports a small aboriginal community. The bore probably intersects vesicular basalt.

Sediments

The Townsend Quartzite forms a dominant ridge along the southern margin of the Musgrave Block. The Department of Aboriginal Affairs reports that an abandoned army bore drilled into the formation west of Warburton yielded about 480 m^3/day. Two bores, 19A and 19B, were drilled near the abandoned army bore by the Mines Department, with limited success. Bore 19B yields about 20 m^3/day of water with a salinity of 1 000 mg/L TDS, but bore 10A was unsuccessful and was abandoned.

Large supplies of groundwater may be available from the formation if extensive joint systems exist. Recharge to the formation is by direct infiltration, and by downward movement from sand and calcrete which overlie the formation and which provide temporary water storage. Recharge is also likely from the water-courses, when flowing, which parallel the quartzite ridge on the upslope side.

The prospects for obtaining supplies of fresh groundwater from other Proterozoic sediments are poor. Bores intersecting these sediments near Warburton were either dry, had low yields or intersected saline groundwater.

OFFICER BASIN SEDIMENTS

Permian sandstones in marginal areas of the Officer Basin are capable of yielding large supplies of fresh or brackish groundwater. Water bores which have intersected Permian sediments in the region include a number of bores drilled for Shell Development (Australia) Pty Ltd (Buck, 1980), two bores drilled in the Cobb Depression by Southwestern Mining (Farbridge, 1967) and the bore at Mitika (site 8). The bores yield up to 1 470 m^3/day of water with salinities ranging from 400 mg/L TDS to 2 000 mg/L TDS.

Groundwater in the Permian sediments is recharged by the downward infiltration of rainwater, which is temporarily stored in the overlying sand, and from water which discharges into the sand from creeks draining the Musgrave Block.

CAINOZOIC SEDIMENTS

Calcrete and alluvium

Calcrete partly fills an ancient drainage system which channels runoff from most of the region southwards. Thicknesses of 6 m to 18 m have been intersected in bores drilled by the Mines Department, and up to 20 m in the Warburton water-supply bores. The calcrete has a high secondary porosity, and is capable of yielding large supplies; for example the bore at Piyul (site 13) yields 72 m^3/day, with a drawdown of only 1.4 m after 2 hours of pumping.

The salinity of water in the calcrete ranges from about 700 mg/L TDS (Snake Bore, and two Warburton bores) to greater than 3 000 mg/L TDS, and is brackish or saline in the centre of large drainages, and away from the ranges.

Groundwater in calcrete is susceptible to pollution, because the calcrete is very permeable and water moves through it in discrete channels. At Warburton two bores within 500 metres of the sewage settling ponds have probably yielded polluted groundwater in the past (Wharton, 1981), but are not being used at present.

All known analyses of groundwater from calcrete in the region show unacceptably high nitrate concentrations.

Calcrete is the most important shallow aquifer in the Blackstone region, although the high nitrate concentrations and the potential for groundwater pollution will hinder its further development. Groundwater in the calcrete is probably a major source of recharge to underlying Proterozoic aquifers (e.g. at Wanan, Kaarnka east, Kalka and Blackstone).

Alluvium other than calcrete is generally too thin to maintain permanent water supplies. Any contained groundwater in the alluvium may dry up, or become excessively saline during drought periods (Farbridge, 1968).

Colluvium

The meteorological station Giles and the Warakurna aboriginal community obtain groundwater supplies from colluvium overlying Proterozoic acid volcanic rocks. Exploratory bores drilled at Giles are up to 55 m deep, and yield up to 120 m^3/day of water with salinities ranging from 620 to 4 900 mg/L TDS.

The colluvium in other areas is generally too thin or too clayey to yield more than very small groundwater supplies.

Eolian Sand

Eolian sand in interdunal areas is probably less than 6 m thick, and of insufficient thickness to maintain a permanent body of groundwater. However, the sand allows the rapid infiltration of rainwater and provides temporary storage for recharge water to underlying aquifers, e.g. calcrete and Permian sandstone.

GROUNDWATER QUALITY

The salinity of groundwater in the bores shown in Figure 1 ranges from 390 mg/L TDS (Mitika, site 8) to 3 800 mg/L TDS (Brown Range, site 20). It is expected that more saline groundwater occurs away from the ranges in the larger calcrete drainages.

Much of the potable groundwater in the Blackstone Region has a nitrate concentration which exceeds the limit recommended by the World Health Organisation (45 mg/L). High nitrate concentrations can cause methaemoglobinaemia in infants.

Groundwater in the Permian sediments of the Officer Basin may generally have acceptable nitrate concentrations. The water from bores D59, Y-3/12 and Mitika (site 8) has nitrate concentrations ranging from 17 mg/L, and only the water from D57 has a high concentration of 65 mg/L.

All bores in other aquifers in the region yield water with excessively high nitrate concentrations, except bores at Kalka and Blackstone (in weathered gabbro), and bore 19B near Warburton (in quartzite). Some bores, including those at Giles, Kaarnka and Wanan, have fluoride concentrations which exceed the W. H. O. limit of 1.5 mg/L.

CONCLUSIONS

Calcrete is presently the most important aquifer in the Blackstone Region. Moderate to large supplies of fresh groundwater are available from the aquifer near to elevated recharge areas, however water in the calcrete has unacceptabley high nitrate concentrations, and is susceptible to pollution.

The Mines Department drilling in 1980 showed that thick sections of weathered and jointed gabbro are prospective aquifers. Bores in weathered gabbro yield moderated supplies of generally fresh groundwater, paricularly in areas where the gabbro is overlain by permeable surface sediments, such as calcrete.

Sandstones of the Officer Basin and the Cobb Depression are potentially the most important aquifers in the region. Drilling by mining and oil exploration companies, and the Mines Department, has shown that bores in these sediments are capable of yields of at least 1 500 m^3/day, with salinities ranging from 400 mg/L TDS to 2 000 mg/L TDS. Groundwater in these sediments generally have acceptable nitrate and fluoride concentrations.

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25336/12/83—1M—L/3427

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