GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 29

GEOLOGY OF THE OFFSHORE BONAPARTE BASIN NORTHWESTERN AUSTRALIA

BY
A. J. MORY

DEPARTMENT OF MINES
WESTERN AUSTRALIA

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Perth 1991

MINISTER FOR MINES

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National Library of Australia
Cataloguing-in-publication entry

Mory, A. J. (Arthur John), 1953 —
Geology of the offshore Bonaparte Basin.

Bibliography
ISBN 0 7309 1123 3.

1. Physical geology — Bonaparte Gulf Basin (N.T. and W.A.). 2. Bonaparte Gulf Basin — (N.T. and W.A.) I. Geological Survey of Western Australia. II. Title. (Series: Report (Geological Survey of Western Australia); no. 29).

559.414

ISSN 0508-4741

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Geology of the offshore Bonaparte Basin, northwestern Australia

Abstract

The offshore part of the Bonaparte Basin extends under the Joseph Bonaparte Gulf to Ashmore Reef in the northwest and Flinders Shoal in the north, and covers an approximately triangular area of about 250 000 km^2.

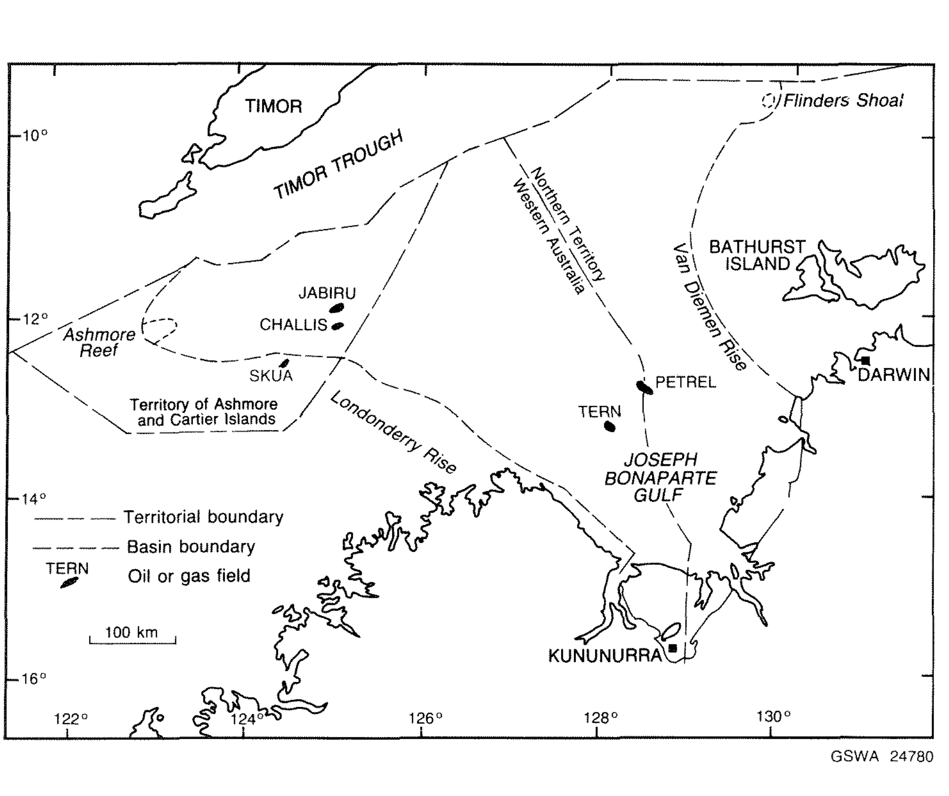
The major part of this report is a review of the stratigraphy; seven groups, 31 formations, five members, and three unnamed units are described.

The oldest rocks that can be positively identified in the offshore Bonaparte Basin are Late Devonian, although Cambrian volcanic and sedimentary rocks are present in the onshore part of the basin. An evaporitic sequence, probably of Silurian age, is evident on seismic sections in the Petrel Sub-basin. Devonian to Carboniferous rocks (Bonaparte Formation, Weaber Group) in the Petrel Sub-basin belong to a phase of mid-Phanerozoic northwest-oriented rifting. The succeeding Permo-Carboniferous sequence (Kulshill and Kinmore Groups) formed during a phase of reactivated rifting and sag in which the Petrel Sub-basin continued to be the principal depocentre. In the Triassic, new depocentres developed along the northwest margin of the basin prior to northeast-oriented rifting and breakup in the Jurassic; the Sahul and Troughton Groups were deposited during this phase. Post-breakup sediments (Flamingo and Bathurst Island Groups) have their depocentres in the major grabens in the northwest and north of the basin, but the Petrel Sub-basin continued as a major site of deposition until the Late Cretaceous. In the Cainozoic, carbonate shelf progradation dominated sedimentation in the northern and northwestern part of the basin.

Keywords: Bonaparte Basin; geology; stratigraphy; palaeogeography; petroleum

Introduction

The Bonaparte Basin extends offshore from near Kununurra in the south, northwest to Ashmore Reef, and north to near Flinders Shoal; it thus covers a triangular area of approximately 270 000 km^2 of which about 20 000 km^2 lies onshore. The offshore part of the basin lies below waters under the jurisdiction of the Commonweath of Australia. At present Western Australia and the Northern Territory each administer approximately half of the area covered by the basin. This area includes much of the Territory of Ashmore and Cartier Islands which is administered by the Northern Territory (Fig. 1). Waters north of 12° S and from 126° E to 128° E, the so-called 'Timor Gap', have been the subject of a dispute with Indonesia since 1979. Under present proposals for a joint zone of cooperation, this area may be administered through an Indonesian - Australian authority and a ministerial council.



GSWA 24780

Figure 1. Locality map showing principal localities and basin outline.

Previous investigations

The first regional work in the basin was concerned largely with the onshore sequence (Matheson and Teichert, 1948; Reeves, 1951; Traves, 1955; Bureau of Mineral Resources (BMR) studies from 1963 to 1971, summarized in Roberts and Veevers, 1973; Guillaume, 1966; Brady et al., 1966). The first wells were drilled onshore (Spirit Hill 1 in 1959 - 60, Bonaparte 1 and 2 in 1963 - 64, Kulshill 1 and 2, and Moyle 1 in 1965 - 66). The most recent accounts of the onshore geology are by Dickins et al. (1972), for the Port Keats area; and Mory and Beere (1988), for the Cambridge Gulf area.

Offshore, early work was largely concerned with sea-floor features (Fairbridge, 1953; Boutakoff, 1963; van Andell and Veevers, 1967). These features included the Bonaparte and Browse depressions — names which also were used for the underlying Bonaparte and Browse Basins. The first offshore wells were drilled by B.O.C. of Australia Limited (BOCAL, later to become Woodside Offshore Petroleum Pty Ltd) in 1967 - 69 in the west of the basin (Ashmore Reef 1 and Sahul Shoals 1) and Arco Australia Ltd (ARCO) in the southeast of the basin (Lacrosse 1 and Petrel 1). ARCO, and its partner Australian Aquitaine Petroleum Pty Ltd (Aquitaine), explored a stratigraphic sequence similar to that onshore, and BOCAL/ Woodside investigated the Mesozoic sequence which has little expression onshore. Summaries of work by ARCO, Aquitaine, BOCAL and Woodside include Caye (1968), Mollan et al. (1969, 1970), Warris (1973), Laws and Kraus (1974), Laws and Brown (1976), and Lee and Gunn (1988). These companies dominated petroleum exploration in the basin until the 1980s, when BHP Petroleum Pty Ltd (BHP), Western Mining Corporation (WMC), and Bond Corporation led new joint ventures. Of these companies, BHP has been extremely active in the offshore part of the basin following the discovery of oil in Jabiru 1A in 1983; since then BHP has drilled 37 out of a total of 54 wells in the basin. Apart from company reports on the basin a number of summaries have been published by the BMR (Williams et al., 1973; Branson, 1978; Brown, 1980).

Present study

The main emphasis of this study is a stratigraphic revision of the offshore Bonaparte Basin. The study was carried out from 1985 to 1988 and incorporates data from wells drilled up to August 1987 in Western Australian waters, and to July 1986 in Northern Territory waters (including the Territory of Ashmore and Cartier Islands). Locations of wells used in this report are given in Appendix 1. A summary of this report was presented by Mory (1988). The stratigraphic subdivision of the Triassic and Late Cretaceous sequences (Sahul and Bathurst Island Groups, respectively) in the Territory of Ashmore and Cartier Islands, which was presented in the summary paper as well as in this report, is based on unpublished correlations by R. P. MacDaniel of BHP Petroleum.

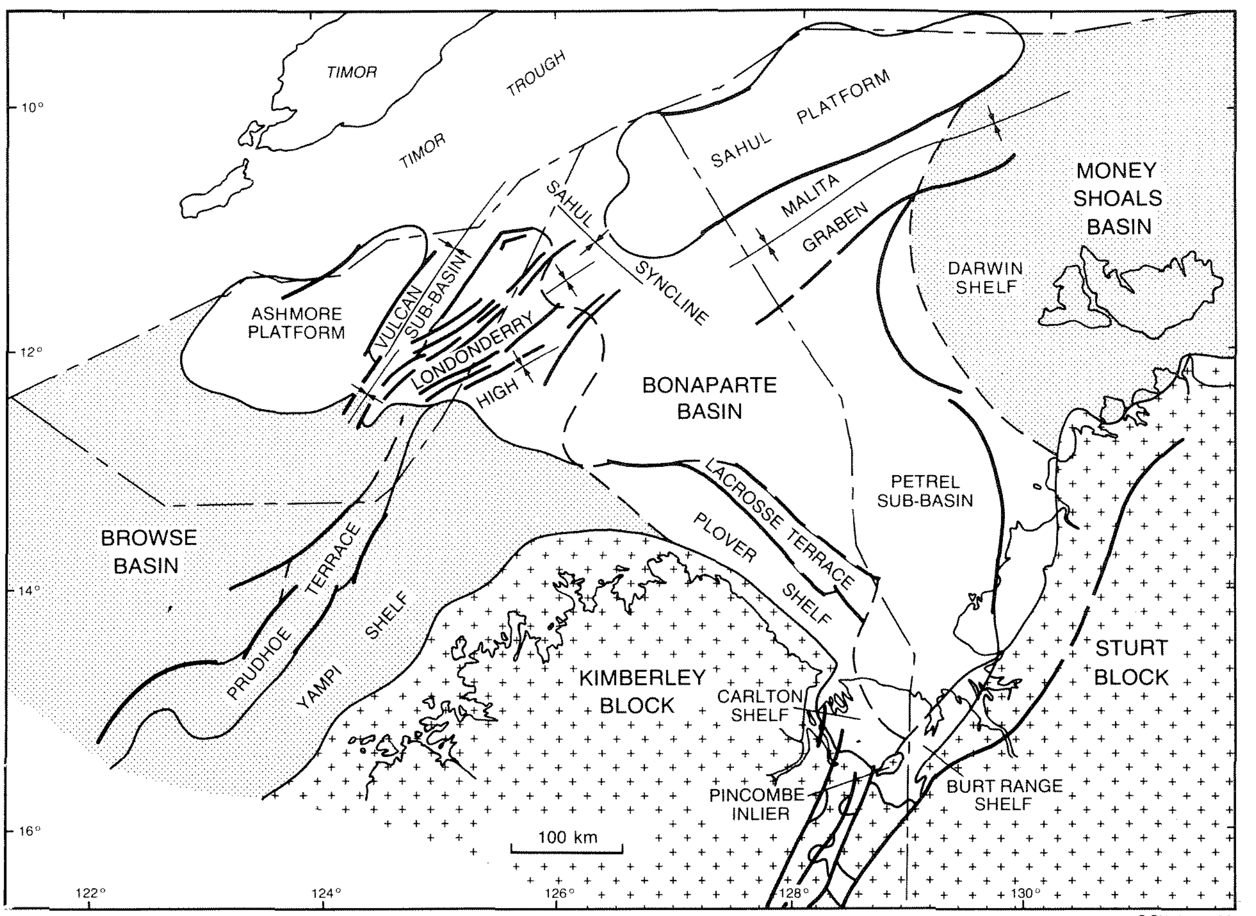


Figure 2. Basin subdivisions for the Bonaparte and adjacent basins (modified after Bhatia et al., 1984).

Structural elements

In the southeast of the basin, the major structural elements trend northwest and define a broad trough which contains a largely Palaeozoic sedimentary fill, possibly up to 17 km thick. These structural elements were formed by middle to late Palaeozoic northwest-trending rift faulting; they include the Plover Shelf, Lacrosse Terrace, Petrel Sub-basin, and Darwin Shelf. In the northwestern and northern parts of the basin, similar structural elements lie almost at right angles to those in the south. The northern set of grabens contain more than 10 km of Mesozoic to Cainozoic sedimentary rocks, compared to less than 4 km over the adjacent highs. This set of grabens and basement highs was formed by Mesozoic northeast-trending rifting related to the breakup of Gondwana. These elements include the Vulcan Sub-basin and Malita Graben, Ashmore and Sahul Platforms, and Londonderry High (Fig. 2).

Vulcan Sub-basin

The Vulcan Sub-basin was defined by Laws and Kraus (1974) as the 'horst and graben province separated from the Londonderry High to the east and the Ashmore Platform to the west by two *en echelon* fault systems'. MacDaniel (1988) expanded the sub-basin to include the 'Eider Trough' and the 'Jabiru Terrace'. The 'Jabiru Terrace' is here considered to be the part of the Londonderry High that separates the Vulcan Sub-basin and Eider Trough. Within the Vulcan Sub-basin are three troughs with a north-northeast orientation: the Cartier and Skua Troughs, and the Swan Graben (MacDaniel, 1988, fig. 3).

Ashmore Platform

The Ashmore Platform (Laws and Kraus, 1974; MacDaniel, 1988) is a large elevated block which lies west of the Vulcan Sub-basin and north of the Browse Basin. It consists of a relatively thin sequence of flat-lying Cretaceous sedimentary rocks unconformably overlying Triassic rocks which were faulted and eroded in the Jurassic.

Londonderry High

The Londonderry High is a broad, highly faulted feature that consists of elevated basement rocks with thin, onlapping Late Jurassic and Cretaceous cover. The Londonderry High extends north from the shelf that flanks the Kimberley Block to the south and separates the Vulcan and Petrel Sub-basins. The Jabiru Terrace of MacDaniel (1988) is here considered to be part of the Londonderry High.

Sahul Platform

The Sahul Platform is an elevated area of basement north of the Malita Graben. It is overlain by less than 5000 m of Late Permian to Cainozoic rocks.

Malita Graben

The Malita Graben is a northeast-oriented trough that lies between the Sahul Platform to the north, and the Darwin Shelf and Petrel Sub-basin to the south. The Malita Graben extends into the Money Shoals Basin to the east where it has been referred to as the Calder Graben.

Petrel Sub-basin

The Petrel Sub-basin is a broad, northwest-oriented trough in the southeast of the Bonaparte Basin. It is flanked by the Lacrosse Terrace and Plover Shelf to the southwest, the Darwin Shelf to the northeast, and Mesozoic sub-basins to the northwest. The Petrel Sub-basin also extends onshore to the south, where it is flanked by the Burt Range and Carlton Shelves. The fault systems along the northeast and southwest margins of the Petrel Sub-basin were periodically active in the Palaeozoic and, in the Mesozoic, developed into hinge lines.

Darwin Shelf

The Darwin Shelf is a northwest extension of the Sturt Block and has a thin cover of Jurassic to Cainozoic sedimentary rocks. The northern and western margins of the Darwin Shelf consist of a series of narrow fault blocks which are progressively downfaulted into the the Malita Graben and Petrel Sub-basin, respectively. This part of the Darwin Shelf was referred to as the Bathurst Terrace by Forman et al. (1974).

Lacrosse Terrace

The Lacrosse Terrace is a zone of rotated fault blocks which lies between the southwest margin of the Petrel Sub-basin and the Plover Shelf.

Plover Shelf

The Plover Shelf is part of the Kimberley Block and is overlain by a thin cover of Phanerozoic rocks along the southwest margin of the basin. It is contiguous with the Yampi Shelf in the Browse Basin.

Basin definition

There are few difficulties in defining the Bonaparte Basin onshore: it is flanked by Proterozoic rocks of the Kimberley and Sturt Blocks. There are, however, a number of problems in defining the offshore basin.

Early workers extended the offshore Bonaparte Basin to the edge of the Timor Trough: they used a sea-floor feature (the Londonderry Rise), and the presence of shallow basement (the Sturt Block) to define the northwestern and southeastern limits of the basin, respectively (e.g. Veevers, 1967; Mollan et al., 1970; Williams et al., 1973).

The basin outline as shown by Playford et al. (1975, fig. 64) follows that of the early definition. The southwestern margin of the basin links the northern side of the Kimberley Block with the southern side of the Ashmore Platform. This boundary crosses the shelf adjacent to the Kimberley Block, as well as the Vulcan Sub-basin. Similarly, the eastern margin of the basin crosses the Malita Graben to link the eastern margin of the Sahul Platform with the western limit of Permian and Triassic rocks on the Darwin Shelf (Fig. 2). As a consequence the Triassic to Cainozoic sequence in the Browse Basin, and Jurassic to Cainozoic sequence in the Money Shoals Basin, are much the same as in the Bonaparte Basin.

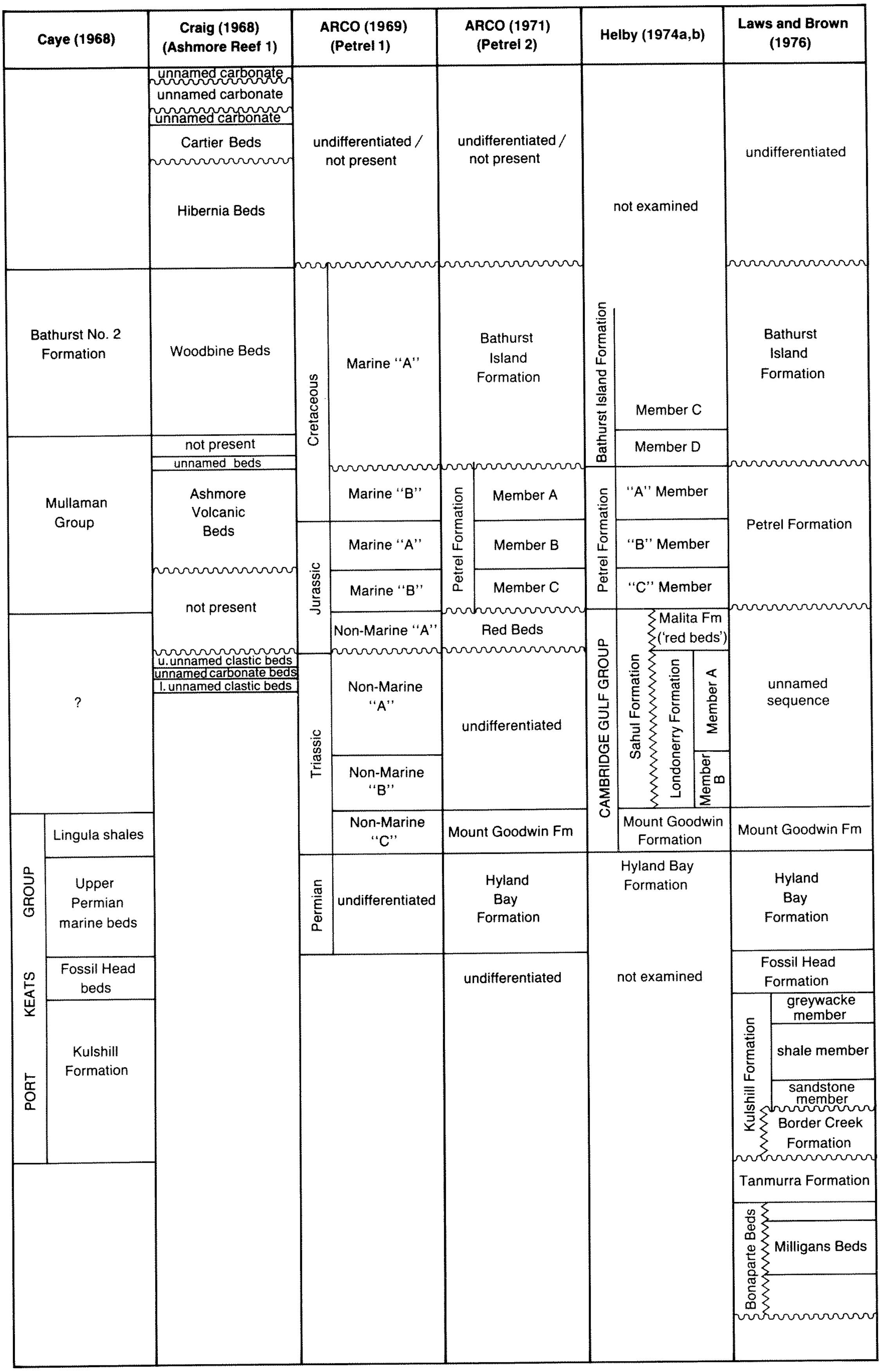
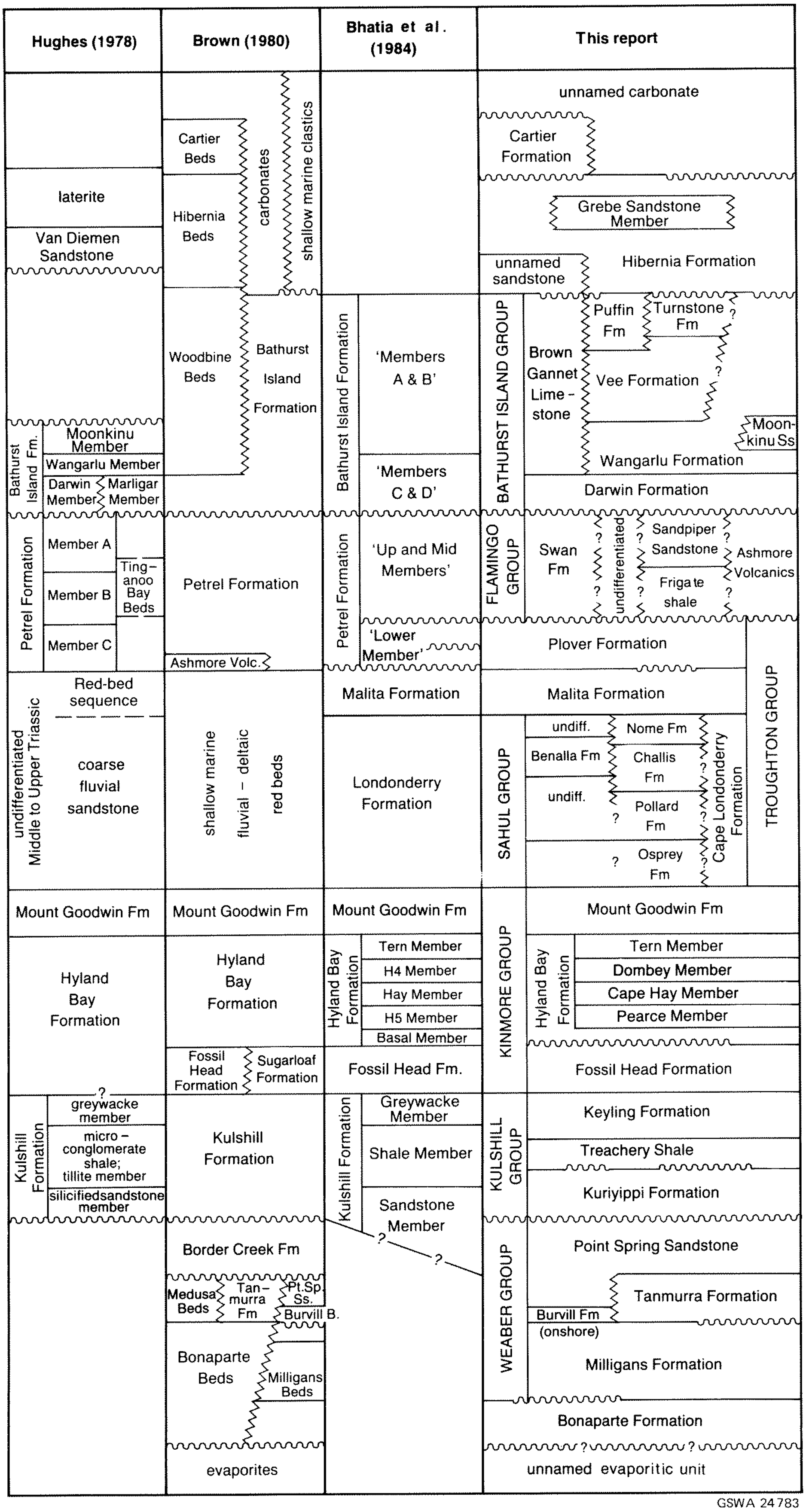


Figure 3. Correlation of previous stratigraphic nomenclature.


Hughes (1978)
Brown (1980)
Bhatia et al. (1984)
This report
laterite
Van Diemen Sandstone
Cartier Beds
Hibernia Beds
carbonates
shallow marine clastics
Woodbine Beds
Bathurst Island Formation
unnamed carbonate
Cartier Formation
Grebe Sandstone Member
unnamed sandstone
Hibernia Formation
Bathurst Island Formation
'Members A & B'
'Members C & D'
BATHURST ISLAND GROUP
Brown Gannet Limestone
Puffin Fm
Turnstone Fm
Vee Formation
Moonkinu Ss
Wangarlu Formation
Darwin Formation
Bathurst Island Fm.
Moonkinu Member
Wangarlu Member
Darwin Member
Marligar Member
Petrel Formation
Member A
Member B
Member C
Tinganoo Bay Beds
Petrel Formation
Ashmore Volc.
'Up and Mid Members'
'Lower Member'
FLAMINGO GROUP
Swan Fm
undifferentiated
Sandpiper Sandstone
Frigate shale
Ashmore Volcanics
Plover Formation
undifferentiated Middle to Upper Triassic
Red-bed sequence
coarse fluvial sandstone
shallow marine
fluvial - deltaic
red beds
Malita Formation
Londonderry Formation
Malita Formation
SAHUL GROUP
undiff.
Nome Fm
Benalla Fm
Challis Fm
undiff.
Pollard Fm
Osprey Fm
Cape Londonderry Formation
TROUGHTON GROUP
Mount Goodwin Fm
Mount Goodwin Fm
Mount Goodwin Fm
Mount Goodwin Fm
Hyland Bay Formation
Hyland Bay Formation
Hyland Bay Formation
Tern Member
H4 Member
Hay Member
H5 Member
Basal Member
KINMORE GROUP
Hyland Bay Formation
Tern Member
Dombey Member
Cape Hay Member
Pearce Member
Fossil Head Formation
Sugarloaf Formation
Fossil Head Fm.
Fossil Head Formation
Kulshill Formation
greywacke member
micro-conglomerate shale; tillite member
silicifiedsandstone member
Kulshill Formation
Kulshill Formation
Greywacke Member
Shale Member
Sandstone Member
KULSHILL GROUP
Keyling Formation
Treachery Shale
Kuriyippi Formation
Border Creek Fm
Medusa Beds
Tanmurra Fm
Pt.Sp. Ss.
Burvill B.
Bonaparte Beds
Milligans Beds
evaporites
WEABER GROUP
Point Spring Sandstone
Tanmurra Formation
Burvill Fm (onshore)
Milligans Formation
Bonaparte Formation
unnamed evaporitic unit
GSWA 24783

The basin definition of Playford et al. (1975), in which the Ashmore Platform and Vulcan Sub-basin are included in the Bonaparte Basin, is followed in this report. However, other definitions have been proposed. MacDaniel (1988) assigned the post-Palaeozoic sequence of the Vulcan Sub-basin and Ashmore Platform to the Browse Basin. In this area he restricted the Bonaparte Basin to the underlying Palaeozoic sequence. His definition follows that of Laws and Kraus (1974, p. 80) who stated that the 'Londonderry High . . . separates the Browse and Bonaparte Basins'; their definition apparently did not exclude the underlying Palaeozoic sequence from the Browse Basin. Bradshaw et al. (1988), however, left both the Ashmore Platform and Vulcan Sub-basin as 'unassigned basinal elements'. By comparison, Lee and Gunn (1988) and Gunn (1988a,b) restricted the Bonaparte Basin to the Palaeozoic sequence south of the Malita Graben and Londonderry High.

Acknowledgements

BHP Petroleum made available Pat MacDaniel's unpublished correlations of the Mesozoic sequence, and digitized well logs from the Territory of the Ashmore and Cartier Islands. Pat MacDaniel and Robin Helby also provided considerable help in writing the summary paper for the North West Shelf Symposium (Mory, 1988) upon which this report is based.

WMC Petroleum provided digitized well logs from the southern part of the basin and gave access to unpublished correlations and palynological reports.

Discussions with Mike Martin, Clinton Foster, and Tom Michelmore (WMC); John Lee and Peter Gunn (Aquitaine); and Graham Bradley (Esso) were particularly helpful.

Stratigraphy

The stratigraphic framework for the offshore Bonaparte Basin presented in this report is based largely on data from petroleum exploration wells, but also includes data from seismic surveys. In the southern offshore area of the basin, the stratigraphy from Geological Survey of Western Australia mapping onshore (Mory and Beere, 1988) can be applied with few modifications. The stratigraphic nomenclature used in this paper is compared with previous nomenclature in Figure 3. The Bonaparte Basin has been the subject of several investigations since the discovery of gas in 1969 by ARCO in Petrel 1. Although discoveries by BHP, especially the Jabiru (1983) and Challis (1984) fields, have renewed interest in the area, and a number of reviews have been published by several exploration companies (ARCO, Aquitaine, BOCAL, Woodside, and BHP) and BMR geologists, few have dealt rigorously with stratigraphic nomenclature. In particular, difficulties have arisen from the use of informal names taken from unpublished well completion reports. These names were, in most cases, published without proper definition or selection of a type section; furthermore, some names had previously been used elsewhere in Australia. Prior to the present study the only formal stratigraphic definitions for units in the offshore Bonaparte Basin appeared in papers primarily concerned with the onshore part of the basin (Traves, 1955; Veevers and Roberts, 1968; Mory and Beere, 1988). In addition, units defined in the Money Shoals Basin by Hughes and Senior (1974) and Hughes (1978) can be applied across the Bonaparte Basin. A number of brief definitions also appeared in Helby (1974b).

Ages given in this chapter are from unpublished palynological work by C. Foster (Kulshill Group), and R. Helby (remainder of the Palaeozoic, Triassic to Early Cretaceous). The correlation of Carboniferous to Permian palynological assemblages with European stages follows that of Cockbain (1985), Foster (1984, 1985, 1986) and Skwarko (in press). The correlation of Triassic to Cretaceous palynological zones with European stages is discussed in Helby et al. (1987). Late Cretaceous dinoflagellate zones are presented by McMinn (1985, 1988). However, Late Cretaceous and Cainozoic ages in well completion reports are largely based on foraminiferal assemblages. Apart from the reports for the small number of wells drilled by Woodside Offshore Petroleum Pty Ltd, and those wells sampled by Rexilius (1987, 1988), few details of these assemblages were given in early wells.

Ungrouped Palaeozoic units

Unnamed evaporitic unit

Definition: The main evaporites in the Bonaparte Basin are known only from seismic data, where structures in which the salt has been remobilized from a much deeper sequence are evident. The unit is not formally named in this report since its original stratigraphic relationships and thickness can only be demonstrated on seismic sections.

Lithology: Intersections of salt diapirs in Kinmore 1, Pelican Island 1, and Sandpiper 1 consist of halite with minor amounts of gypsum and calcite. In areas where seismic data show no evidence of salt remobilization, the unit is assumed to be composed largely of minerals other than halite.

Stratigraphic relationships: This evaporitic sequence can be identified from 'turtle' structures (Lowell, 1985) on seismic sections. These structures are evident in the southernmost part of the basin where they appear to underlie the Bonaparte Formation (e.g. Figs 4 and 5). The strong reflection 830 ms (approximately 2000 m) below the top of the turtle structure is probably a horizon close to the top of Precambrian basement. It is difficult to trace this horizon back to areas where basement is clearly present (e.g. at the edge of the Kimberley Block), because of its discontinuous character on seismic sections.

Distribution and thickness: Salt is known largely from piercement structures and salt swells that intrude Late Devonian and younger rocks in the southern Petrel Sub-basin. The distribution of diapirs appears to be influenced by major faults which bound tilted blocks along the Lacrosse Terrace and along a line of faults which run northeast from Pelican Islet. Near Turtle 1, in the area of the Suzanne Seismic Survey (Fig. 4) the evaporitic sequence appears to be 2000 m thick. Based on seismic velocity effects (up to 0.2 seconds of 'pull-up' within this sequence), approximately 400 m of this consists of salt.

Age: A Silurian to Early Devonian age is deduced by analogy with the the evaporite sequences of the Carribuddy Group in the Canning Basin and the Kalbarri Group in the Carnarvon Basin. Lee and Gunn (1988) suggested that evaporitic sequences may have formed at various times during the Devonian and Carboniferous.

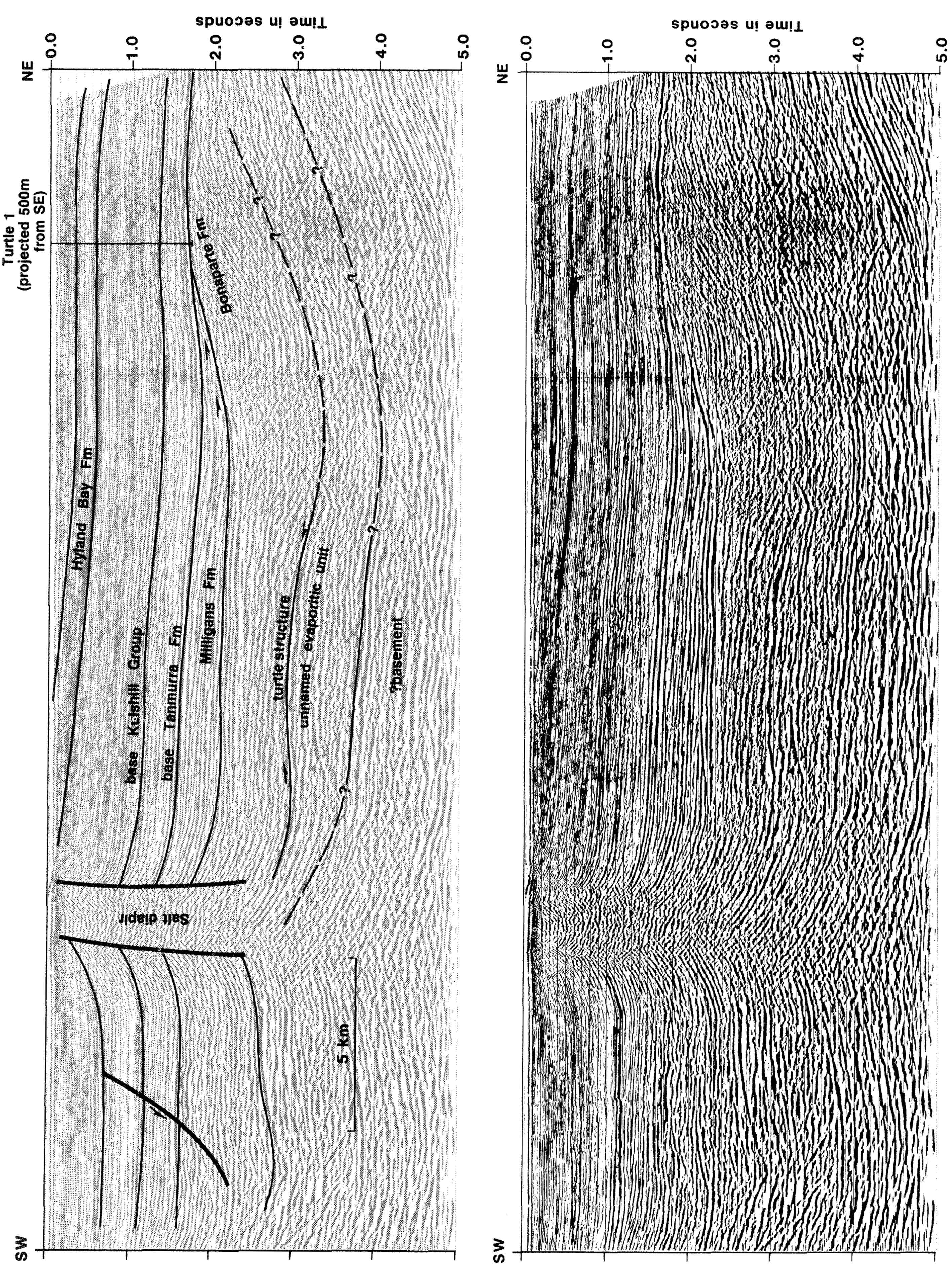


Figure 4. Line 84-48/48A, Suzanne Seismic Survey.

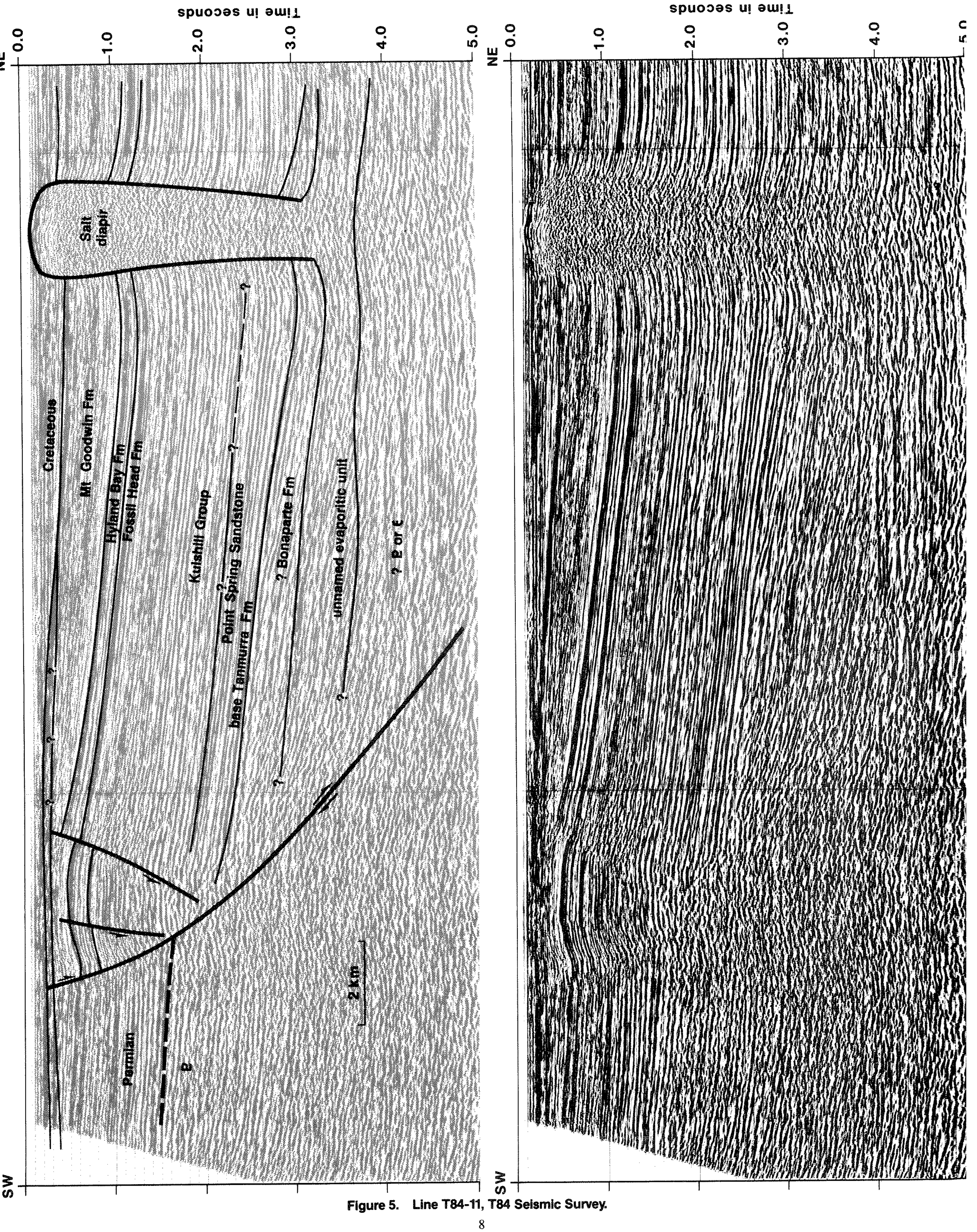


Figure 5. Line T84-11, T84 Seismic Survey.

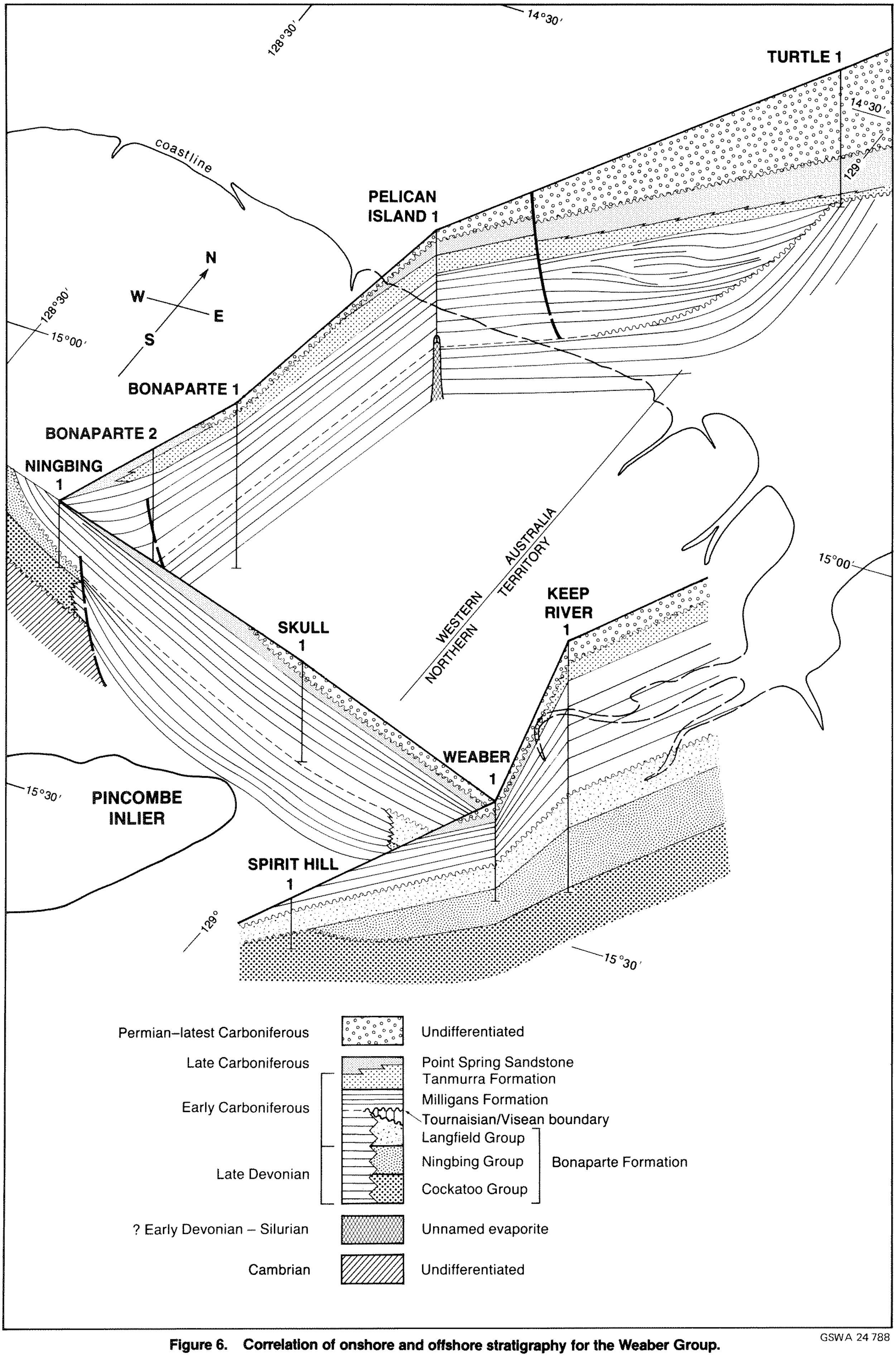


Figure 6. Correlation of onshore and offshore stratigraphy for the Weaber Group.

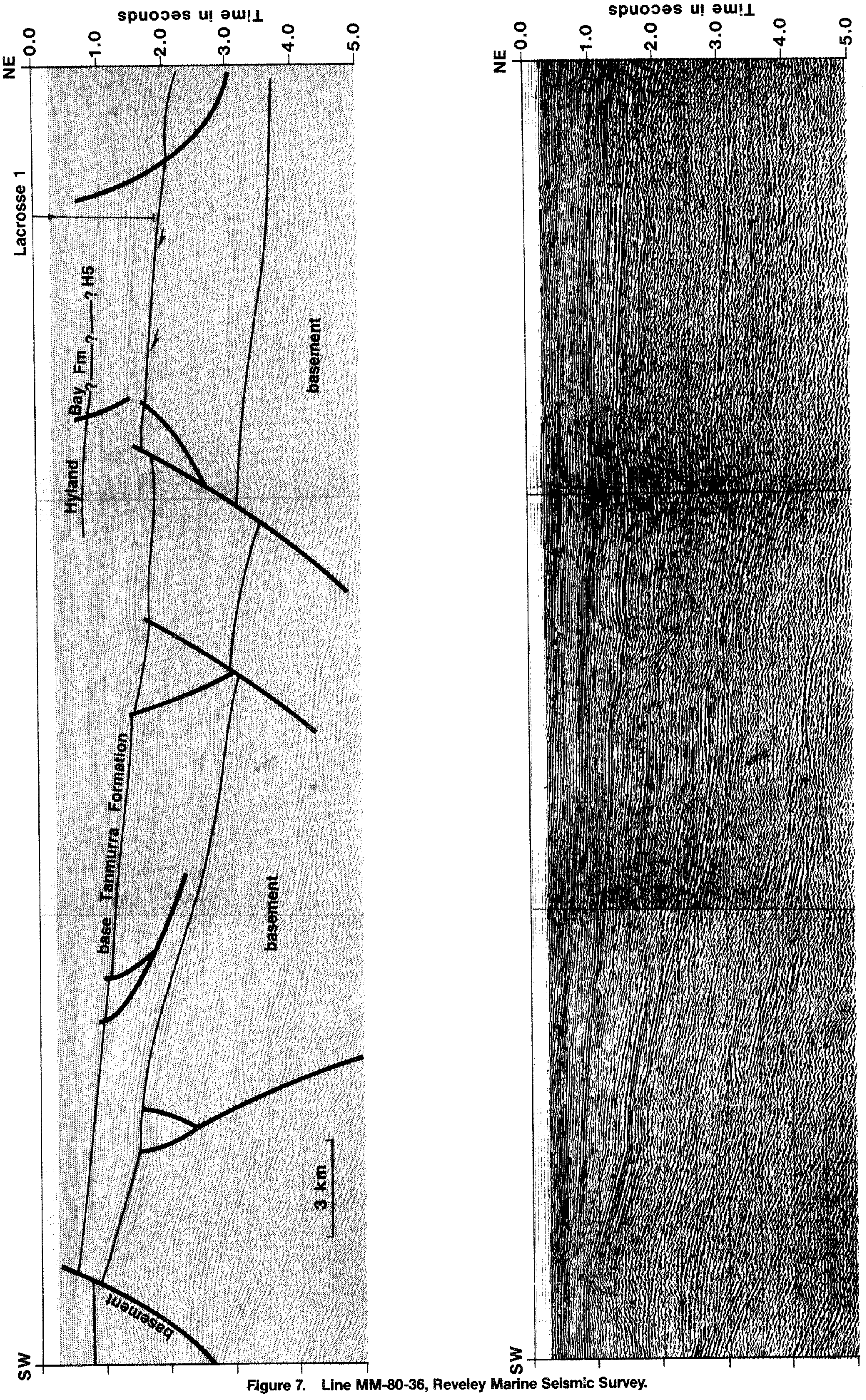


Figure 7. Line MM-80-36, Reveley Marine Seismic Survey.

Depositional environment: The large quantity of evaporites present in the basin clearly indicates that hypersaline waters accumulated in the Petrel Sub-basin in the Silurian to Early Devonian. From the distribution of salt structures seen on seismic sections, Edgerley and Crist (1974) suggested that the evaporite sequence accumulated in the southern Petrel Sub-basin between the Lacrosse Terrace and Darwin Shelf. They further suggested that during deposition the salt-bearing sequence was separated from deeper marine environments to the northwest by a tilted fault block or terrace. Such a structure would form a sill and, assuming an arid climate, would trap hypersaline waters at moderate water depths.

Bonaparte Formation

Definition: The 'Bonaparte Beds' were originally defined as a subsurface unit that consists of shale, siltstone, and sandstone of Late Devonian to Visean age (Veevers and Roberts, 1968). Veevers and Roberts (1968) designated the type section as the interval 497 - 3210 m in Bonaparte 1. Beere and Mory (1986) recognized an unconformity at 2280 m in this well and restricted the name 'Bonaparte Formation' to the sequence of shale, siltstone, sandstone, and minor sandy limestone between 2280 and 3210 m (TD) in Bonaparte 1. So defined, the Bonaparte Formation is restricted to the Late Devonian to Early Carboniferous (Tournaisian) sequence, whereas the Visean sequence (497 to 2280 m in Bonaparte 1) which was previously included in this unit was distinguished as the 'Milligans Formation'. In the type section, the boundary between the two units is marked by a distinct change on the gamma-ray log and the presence of a dipmeter unconformity. In the offshore Petrel Sub-basin the unit has been confused with the lithologically similar Milligans Formation. The Milligans Formation is distinguished form the Bonaparte Formation because an unconformity oftern separates the two units. The Milligans Formation is interpreted as missing from the Petrel Sub-basin where the Tanmurra Formation has an uncomfortable lower contact as shown in Turtle 1, and below Lacrosse 1 on seismic sections (Figs 4 - 7). Although the 'Lower Milligans Formation' of Lee and Gunn (1988) has been assigned a Visean age it is probably equivalent to the Bonaparte Formation since it disconformably underlies 'Upper Milligans Formation.'

Lithology: The type section consists of shale and siltstone, interbedded with sandstone and minor amounts of sandy limestone. It differs from the Milligans Formation in that it is sandier and contains chlorite and carbonate. In Keep river 1, two fining-up sequences are present (3222 - 3446 m and 3446 - 3571 m). Each sequence consists of basal sandstone or sandy limestone overlain by calcareous siltsone and silty shale (More and Beere, 1988).

Stratigraphic relationships: The Bonaparte Formation is unconformably to conformably overlain by the Milligans Formation. In the onshore part of the basin it is laterally equivalent to the Langfield, Ningbing, and Cockatoo Groups (Fig. 6). Offshore, the unit is unconformably overlain by the Tanmurra Formation. In Keep River 1 and Weaber 1, the Bonaparte Formation lies conformably between the Enga Sandstone and Ningbing Group.

Distribution and thickness: The Bonaparte Formation is known only in the southern Petrel Sub-basin, primarily from seismic sections and exploration wells. The most northerly intersections are in Sandpiper 1, Matilda 1, Turtle 1, and Barnett 1. Up to 930 m has been intersected, but the base of the unit has not been penetrated. Seismic data indicate that the unit is locally more than 3000 m thick.

Fossils and age: A diverse fauna and flora has been identified in the Bonaparte Formation from Bonaparte 1 (Le Blanc, 1964), Kulshill 1 (Duchemin and Creevey, 1966) and Keep River 1 (Caye, 1969). A Late Devonian to Early Carboniferous (Late Tournaisian) age is indicated by the fauna, and by stratigraphic relationships with the Ningbing and Langfield Groups. The only palynological zone identified from this unit is the *Anapiculatisporites largus* Assemblage of the *Granulatisporites frustulentus* Microflora in Turtle 1 and Barnett 1. On stratigraphic grounds this assemblage probably ranges throughout the Tournaisian as well as the Visean with which it was originally correlated (Kemp et al., 1977). Such an age suggests that the *Anapiculatisporites largus* Assemblage is coeval with the supposedly underlying *Grandispora spiculifera* Assemblage (Fig. 8).

Depositional environment: The Bonaparte Formation was probably deposited under low-energy shelf to open-marine conditions. Sandstones in the unit were probably deposited by mass flow or turbidity currents; the fining-up sequences in Keep River 1 are probably due to fan abandonment.

Weaber Group

The Weaber Group (Traves, 1955; Mory and Beere, 1988) consists of the Milligans Formation, Tanmurra Formation, and Point Spring Sandstone in the offshore part of the basin. Other units present in the group, but not represented offshore, include the Waggon Creek Formation, Utting Calcarenite, Burvill Formation, and Border Creek Member of the Point Spring Sandstone (Mory and Beere, 1988). The group conformably to unconformably overlies the Bonaparte Formation (Figs 7 and 8). The angular unconformity often visible on seismic data at the base of the Tanmurra Formation (Figs 4 and 7) is here interpreted to indicate that the Milligans Formation (at the base of the group) is missing in these sections.

The group may be up to 3500 m thick. On seismic sections, the basal unit (Milligans Formation) may be difficult to distinguish from the underlying Bonaparte Formation where a conformable relationship is evident. Between Pelican Island 1 and Turtle 1, however, there is a disconformable relationship between the two units (Fig. 6) and the group is over 2000 m thick.

The Weaber Group forms a thick, coarsening and shallowing-up sequence which formed by delta progradation into the basin.

Milligans Formation

Definition: The Milligans Formation is the basal unit of the Weaber Group and consists predominantly of fossiliferous shale and siltstone. The name was first used as 'Milligans Beds' by Utting (1958) for Carboniferous shales which underlie the Keep River plain, and by Hare and Thomas (1961) for Visean shale and siltstone in Spirit Hill 1. The type section is the interval 44 - 155 m in Milligans No. 1 Bore (Veevers and Roberts, 1968). Veevers and Roberts (1968) restricted this unit to the Burt Range and Carlton Shelves. Mory and Beere (1988) extended the unit into the Petrel

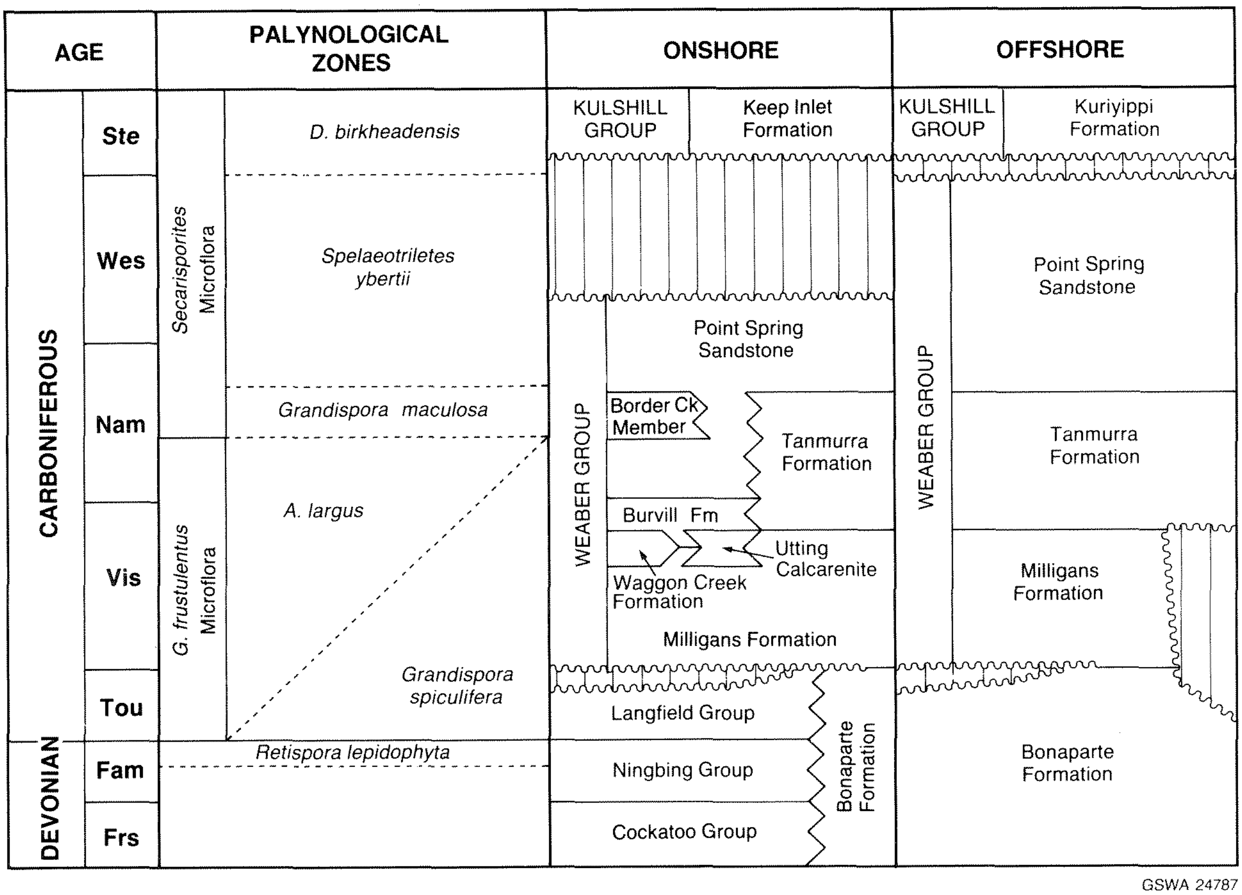


Figure 8. Palynological correlation of the onshore and offshore Devonian and Carboniferous stratigraphy.

Sub-basin to include the latest Tournaisian to Visean shale, which Veevers and Roberts (1968) had included in their 'Bonaparte Beds'. The interval 497 - 2280 m in Bonaparte 1, previously part of the type 'Bonaparte Beds', is designated a reference section for the Milligans Formation since the type section represents only a small part of the unit. Lee and Gunn's (1988) attempt to divide the unit into an 'Upper' and 'Lower' sequence is considered suspect, as this subdivision is based on log correlations of onshore wells (Lee, *in* Barnes and Lee, 1984) in which the monotonous siltstone and mudstone succession has a correspondingly indistinct log signature. Although Lee and Gunn (1988) assigned a Visean age to the 'Lower Milligans Formation', their unit appears to be equivalent to the Bonaparte Formation, at least in offshore wells, based on its stratigraphic position disconformably below the 'Upper Milligans Formation'. The difficulty of distinguishing Tournaisian from Visean microfloras suggests that upper and lower Visean units can not be confirmed on palaeontological evidence.

Lithology: The Milligans Formation consists predominantly of grey to black silty shale which is locally calcareous, gypsiferous, or pyritic. Interbedded sandstone, siltstone, limestone, pebbly sandstone, and conglomerate are also present in the onshore intersections of this unit. In Kulshill 1 the Milligans Formation (2831 - 3216 m) is considerably more sandy than the reference section, which probably reflects a position closer to the basin margin during deposition. Northeasterly prograding wedges up to 100 m thick, visible on seismic sections between Pelican Island 1 and Turtle 1 (Fig. 6), probably consist of sandstone similar to that in the Waggon Creek Formation in the onshore part of the basin.

Stratigraphic relationships: The Milligans Formation unconformably overlies older units, except in deeper parts of the Petrel Sub-basin where the unit is conformable on the Bonaparte Formation (Fig. 4).

Distribution and thickness: The Milligans Formation is known primarily from deep exploration wells in the onshore part of the basin, and from seismic data. It reaches a maximum thickness of 2142 m in Keep River 1. The only offshore well intersections of the unit to date are in Lesueur 1 and Cambridge 1, and are incomplete.

Fossils and age: The Milligans Formation contains a diverse and abundant macrofauna in Bonaparte 1 and 2, and Keep River 1 (Le Blanc, 1964, 1965; Caye, 1969). Foraminifers described by Mamet and Belford (1968) from Bonaparte 1 indicate an age of latest Tournaisian (Tn3c) to late Visean (V3b-c). By comparison, Veevers and Roberts (1968) and Grey (1983) determined an early to late Visean age for the unit. Based on the stratigraphic interpretation of the Milligans and Bonaparte Formations in this report, the *Anapiculatisporites largus* Assemblage, which has been identified from this unit (Kemp et al., 1977), probably ranges throughout the Tournaisian and Visean.

Depositional environment: The presence of several submarine fans (Waggon Creek Formation) and shelf carbonates (Utting Calcarenite) within the Milligans Formation in the onshore part of the basin indicates an outer-shelf environment of deposition. Sandstones deposited as prograding wedges south of Turtle 1 probably represent submarine fans similar to those described by Mory and Beere (1988) from the Waggon Creek Formation in the onshore part of the basin.

Tanmurra Formation

Definition: The Tanmurra Formation was defined in an unpublished report by Le Blanc (1964) as the interval of sandstone with minor amounts of limestone, siltstone, and dolomite, from 194 to 497 m in Bonaparte 1 (Veevers and Roberts, 1968). The name has since been applied to the predominantly carbonate interval of the same age in the offshore Petrel Sub-basin. ARCO geologists originally named the Formation 'Medusa Beds' in the Lacrosse 1 well completion report.

Stratigraphic relationships: The Tanmurra Formation disconformably to unconformably overlies the Bonaparte Formation and conformably overlies the Milligans Formation. It is laterally equivalent, in part, to the Point Spring Sandstone, as well as the Burvill Formation and Utting Calcarenite. The latter two units are confined to the Carlton Shelf in the onshore part of the basin (Mory and Beere, 1988). Towards the centre of the Petrel Sub-basin, a similar facies change from carbonate to siliciclastic lithologies is evident from the change in the seismic character of the Tanmurra Formation.

Distribution and thickness: Unlike the other formations in this group the Tanmurra Formation is known only from the subsurface. The unit is restricted to the southern Petrel Sub-basin where it ranges from 100 to 465 m in thickness.

Fossils and age: Foraminifers in Bonaparte 1 indicate a late Visean to early Namurian age for the Tanmurra Formation (Mamet and Belford, 1968). In Bonaparte 1 and 2, and Pelican Island 1, palynomorphs of the *Anapiculatisporites largus* Assemblage have been identified in this unit. In Lacrosse 1, by comparison, the *Grandispora maculosa* Assemblage is present. In all other offshore wells, the unit contains few palynomorphs, and lies between occurrences of the *Anapiculatisporites largus* Assemblage (below) and the *Grandispora maculosa* Assemblage (above).

Depositional environment: The Tanmurra Formation consists primarily of shelf carbonates, but in onshore wells a large clastic input, presumably from deltas of the Point Spring Sandstone, is evident.

Point Spring Sandstone

Definition: The Point Spring Sandstone (Traves, 1949, 1955) consists of sandstone and pebbly sandstone with minor amounts of conglomerate and siltstone (Mory and Beere, 1988). Veevers and Roberts (1968) designated the type section 6 km east-northeast of Point Spring, below conglomerate of the 'Border Creek Formation'. Mory and Beere (1988) recognized the lenticular, interfingering relationship of the conglomerate, and assigned it member status in the Point Spring Sandstone. The member is restricted to onshore sections and is not described here.

In the subsurface, the top of the Point Spring Sandstone corresponds to an abrupt change in lithology from shale to sandstone which appears to coincide with the top of the *Spelaeotriletes ybertii* Assemblage. So defined, the lower part of the 'Kulshill Formation' of Duchemin and Creevey (1966) and Hughes (1978) belongs within the Point Spring Sandstone. In Kulshill 1, the interval here identified as the Point Spring Sandstone also includes a section which Duchemin and Creevey (1966) assigned to the Tanmurra Formation and 'Milligans Beds' (Fig. 9). Correlation of the Point Spring Sandstone in Kulshill 1 with other wells is hindered by the lack of good onshore seismic data, and by the electric-log response in this well, which appears to have been affected by radioactive elements.

Lithology: In outcrop, the Point Spring Sandstone consists of sandstone, pebbly sandstone, and minor amounts of siltstone, arranged in fining- and coarsening-up cycles generally less than 20 m thick. In the subsurface, the unit contains considerably more shale and includes minor amounts of calcareous sandstone and limestone, in fining-up cycles up to 70 m thick. Correlation of these cycles between wells is difficult, presumably due to relatively rapid facies changes.

Stratigraphic relationships: The Point Spring Sandstone conformably overlies the Tanmurra Formation in the subsurface and the Burvill Formation in outcrop. Laterally the unit is equivalent, in part, to the Burvill Formation and Tanmurra Formation.

Distribution and thickness: The Point Spring Sandstone is exposed in an arcuate belt between Weaber Range and Utting. In this belt the unit is 180 to 380 m thick (Mory and Beere, 1988). In the subsurface the unit has been intersected as far north as Lesueur 1 and generally ranges in thickness from 187 to 385 m; in Kulshill 1, however, the unit is 876 m thick.

Fossils and age: In outcrop, the Point Spring Sandstone contains a diverse fauna and flora of which only the brachiopods have been fully described (Thomas, 1962; Roberts, 1971). Two distinct brachiopod faunas, from the base and top of the formation, indicate a late Visean to Namurian age. In Kulshill 1, brachiopods, ostracods, conodonts, and foraminifers from the interval between cores 21 and 23 (1880 - 2044 m) also indicate a late Visean to Namurian age for the unit. In other petroleum exploration wells, the palynomorph assemblages *Grandispora maculosa* and *Spelaeotriletes ybertii* have been identified in this unit. The ages of these assemblages are based on faunal determinations in Kulshill 1.

Depositional environment: In the onshore sections the Point Spring Sandstone was deposited in shoreface, fluvial, distributary mouth, and crevasse environments on a delta plain. Consequently the thick shale sections present in the offshore sections probably represent prodeltaic to distal distributary deposits.

Kulshill Group

The Kulshill Group ('Kulshill Formation' of Duchemin and Creevey, 1966; amended by Mory, 1988) consists of a dominantly coarse-grained siliciclastic sequence which contains sandstone, siltstone, mudstone, tillite, conglomerate, and minor amounts of limestone and coal. In the offshore part of the basin, and in the subsurface in the Northern Territory, the group is divided into three formations: Kuriyippi Formation, Treachery Shale, and Keyling Formation (in ascending order). The Keep Inlet Formation (Glover et al., 1955; Mory and Beere, 1988), which outcrops along the Western Australian - Northern Territory border, is coeval with part of the group and should be included in it. In Flat Top 1, the Kulshill Group is condensed and the formations cannot be differentiated. The informal threefold subdivision of the unit

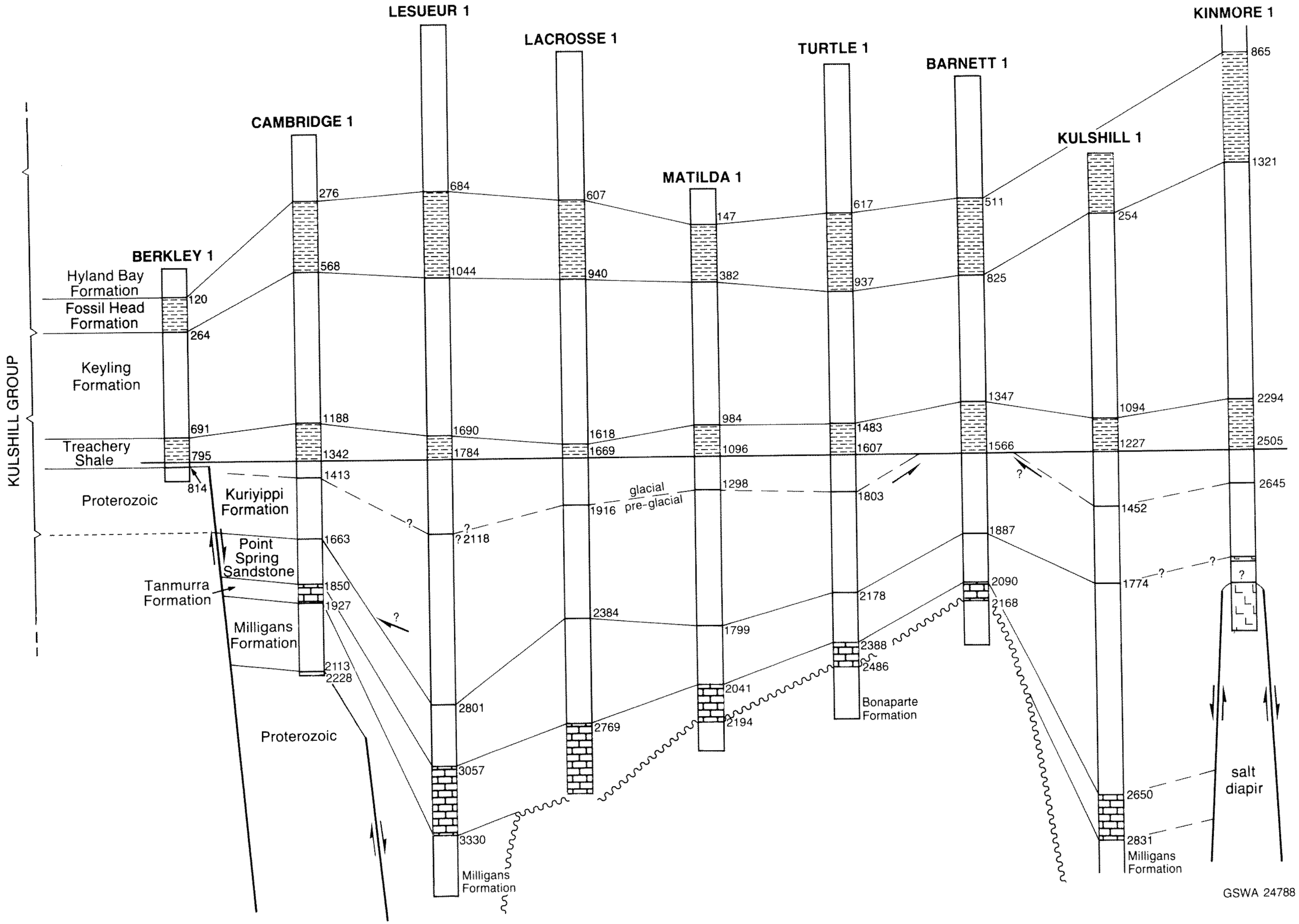


Figure 9. Summary of well correlations for the Kulshill and upper Weaber Groups. See Plate 1 for detailed log correlation.

into 'sandstone', 'shale', and 'greywacke' members (in ascending order; Duchemin and Creevey, 1966; Hughes, 1978) has not been applied consistently across the basin and is abandoned here. The relationship with the underlying Weaber Group is possibly disconformable, based on thinning of the Kuriyippi Formation towards Cambridge 1 (Fig. 9). Such a relationship is not, however, obvious on seismic sections. With the elevation of the 'Kulshill Formation' to group status, the 'Port Keats Group' (Noakes, 1949; Caye, 1968) is abandoned; the remaining units from this group are assigned to the Kinmore Group.

The 'Kulshill Formation' was originally defined as the interval 596 - 1813 m in Kulshill 1 (Duchemin and Creevey, 1966; Hughes, 1978). Palynology (from unpublished work by C.B. Foster for Western Mining Corporation) and log correlations indicate that the name 'Kulshill', now raised to group status, should be applied to the interval 254 - 1774 m in that well (Plate 1). Ages given for individual formations are based on C.B. Foster's unpublished reports. These ages are considerably younger than those indicated by Lee and Gunn (1988, fig. 3); this is probably because they incorporated part of the Weaber Group in the Kulshill Group, but may also reflect their lack of access to Foster's revised ages.

The Kulshill Group is 550 to 1757 m thick in wells along the southern margin of the basin, but reaches approximately 7000 m on seismic sections near the Petrel gasfield (Lee and Gunn, 1988); individual formations cannot be identified on these seismic sections. The name as used by Lee and Gunn (1988) includes Namurian to Westphalian siliciclastics, above the Tanmurra Formation, that disconformably underlie the Kulshill Group as defined herein. These siliciclastics are here regarded as part of the Weaber Group (Fig. 9).

The Kulshill Group was deposited in an overall transgressive cycle. Overprinted on this transgression is the onset of glaciation high in the Kuriyippi Formation. The glacial intervals within the group have not been used to define formation boundaries because glacial features can be recognized clearly only from cores.

Kuriyippi Formation

Definition: The Kuriyippi Formation is the basal unit of the Kulshill Group; it consists of upward-fining cycles of clean sandstone and lesser amounts of siltstone. The unit is named after Kuriyippi Hills, east of Kulshill 2. The type section is the interval 1784 - 2801 m in Lesueur 1. So defined, the unit contains the informal 'Sandstone Member' and part of the 'Shale Member' of Hughes (1978). A 10 - 40 m thick sandstone at the top of the formation forms a persistent marker across the basin. This sandstone may in fact belong at the base of the overlying unit, but is included in the Kuriyippi Formation, because of the gross lithology of this formation.

Lithology: The Kuriyippi Formation consists of a sequence of upward-fining siliciclastic cycles overlain by glacial siliciclastics. Generally the cycles are 30 to 90 m thick and comprise clean, argillaceous and calcareous sandstone overlain by carbonaceous shale, siltstone, and minor amounts of coal. The glacial sequence at the top of the unit consists of sandstone, pebbly sandstone, conglomerate, tillite, and siltstone.

Stratigraphic relationships: The Kuriyippi Formation appears to conformably overlie the Point Spring Sandstone in most wells. However, thinning of the unit towards Cambridge 1 suggests onlap, and hence a disconformable relationship, in that area (Plate 1). It is difficult to resolve the nature of this contact from seismic sections because of numerous faults between Cambridge 1 and the nearest wells (Lesueur 1 and Lacrosse 1), and the weak seismic reflections at the level of the Kuriyippi Formation. An alternative correlation of these well sections assumes that the Kuriyippi Formation becomes condensed towards Cambridge 1, and conformably overlies the Point Spring Sandstone. In Berkley 1, only the glacial part of the unit is represented; it appears likely that the formation onlaps onto Proterozoic basement as the lower, pre-glacial part of the unit is missing in this well. Consequently, a disconformable relationship with the underlying Point Spring Sandstone is favoured in the Cambridge 1 area (Plate 1).

Distribution and thickness: The Kuriyippi Formation is present in the southern Petrel Sub-basin and Lacrosse Terrace where it ranges in thickness from 321 to 1017 m. The unit is also present on the Plover Shelf where it thins to 19 m in Berkley 1. It is not present on the Darwin Shelf on the northeastern side of the basin.

Fossils and age: The Kuriyippi Formation contains palynomorphs of the *Diatomozonotriletes birkheadensis* and *Granulatisporites confluens* Assemblages as well as rare acritarchs. The *D. birkheadensis* Assemblage includes palynofloras previously assigned to Helby's (1969) *Potoniesporites* Assemblage. Although this assemblage contains no faunal evidence of its age, it has been assigned a late Carboniferous (Stephanian) age from its stratigraphic position below the *G. confluens* Assemblage of earliest Permian (Stage 2) age (Cockbain, 1985; Foster, 1986).

Depositional environment: The Laterally persistent fining-up cycles in the lower part of the Kuriyippi Formation suggest deposition in a fluvial environment with the individual cycles representing coalesced braided floodplains. The cycles are similar to those described by Mory and Beere (1988, fig. 120) from the Keep Inlet Formation and also may be the result of tectonic movements in the hinterland. The upper part of the formation consists predominantly of sandstone and tillite, and represents deposition on a glacial floodplain.

Treachery Shale

Definition: The Treachery Shale consists of carbonaceous shale with tillite. The unit is named after Treachery Bay southwest of Port Keats. The type section is the interval 1094 - 1227 m in Kulshill 1. The unit is equivalent to the middle part of the informal 'Shale Member' of Hughes (1978).

Lithology: The Treachery Shale consists predominantly of carbonaceous, argillaceous, tillitic and varved siltstone. Claystone and minor amounts of sandstone are also present.

Stratigraphic relationships: The Treachery Shale conformably overlies the Kuriyippi Formation, except in the vicinity of Barnett 1 where seismic data indicate that it disconformably overlies the Kuriyippi Formation.

Distribution and thickness: The formation ranges from 51 to 219 m thick and is present in the southern Petrel Sub-basin, and on the Lacrosse Terrace and Plover Shelf.

Fossils and age: Microfloras of the *Granulatisporites confluens* Oppel-zone (Foster and Waterhouse, 1988) are present throughout the Treachery Shale, but also range into the enclosing formations. Marine macrofaunas associated with this zone in the Canning Basin are of early Permian (Asselian) age (Foster and Waterhouse, 1988).

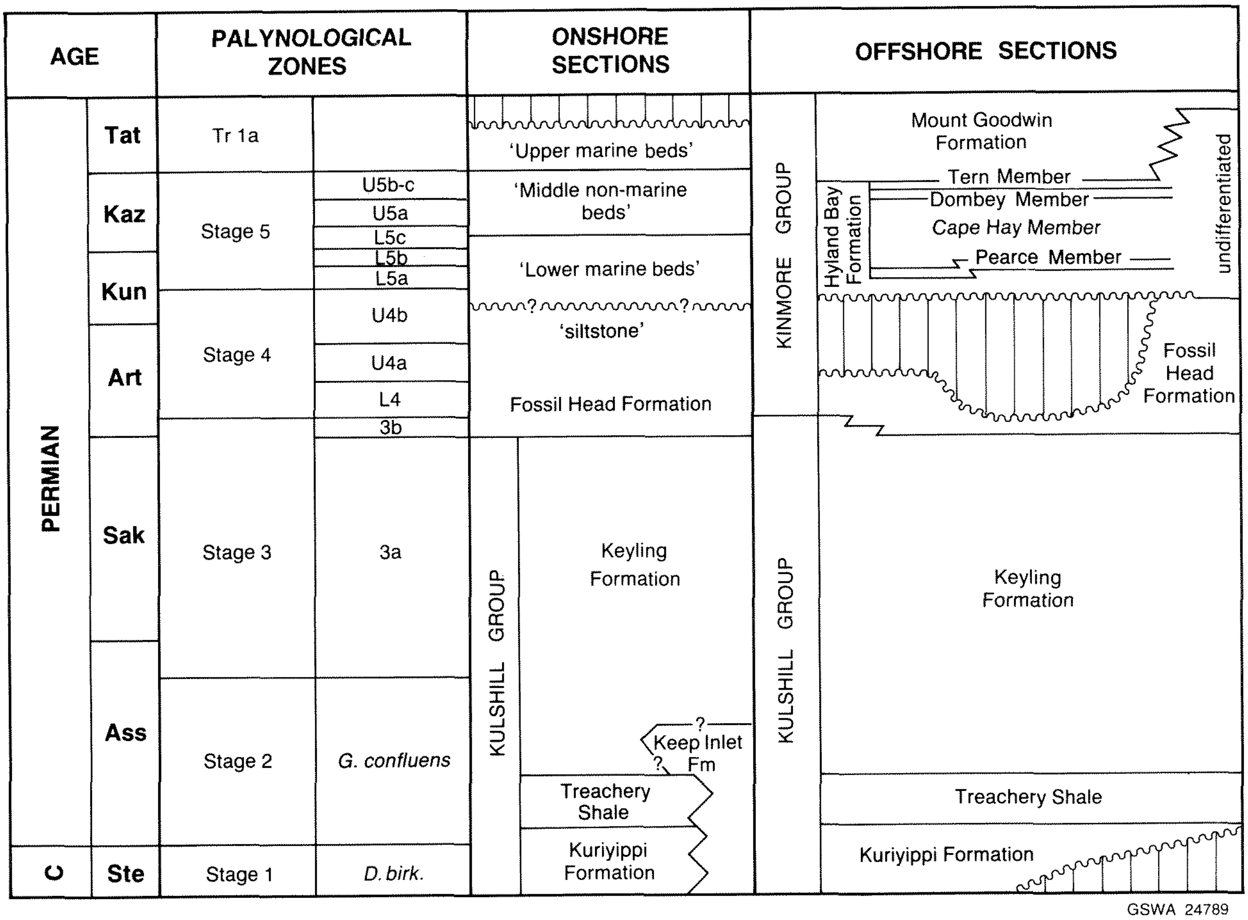


Figure 10. Correlation of units within the Kulshill and Kinmore Groups.

Depositional environment: The lack of marine faunas and the presence of well-developed palynomorph assemblages in this tillitic unit suggest intermittent glacial outwash into a lacustrine environment.

Keyling Formation

Definition: The Keyling Formation consists of a predominantly siliciclastic sequence with minor amounts of coal and limestone at the top of the Kulshill Group. The name is from Keyling Inlet in southeastern Joseph Bonaparte Gulf. The type section is the interval from 254 to 1094 m in Kulshill 1. The formation is approximately equivalent to the 'Greywacke Member' of Duchemin and Creevey (1966) and Hughes (1978). In Kulshill 1 the 'Sandstone member' of Duchemin and Creevey's (1966) informal 'Sugarloaf Formation' is included in the Keyling Formation (Fig. 9). The presence of Stage 3 palynomorphs suggests that the 'Kulshill Formation' in drillhole NTGS 82/47 at Anson Bay (Fahey and Edgoose, 1986) probably belongs to the Keyling Formation.

Lithology: The Keyling Formation conists largely of interbedded sandstone and siltstone with upward-fining, and lesser upward-coarsening, cycles in the lower half of the formation. Minor amounts of coal and limestone are also present.

Stratigraphic relationships: The Keyling Formation conformably overlies the Treachery Shale. Onshore, coeval rocks in drillhole NTGS 82/47 disconformably overlie granitic basement. Palynological evidence suggests that the unit is equivalent, in part, to the Fossil Head Formation (Fig. 10).

Distribution and thickness: The Keyling Formation is known in the southern Petrel Sub-basin south from Tern 1, and on the Lacrosse Terrace and Plover Shelf. It ranges in thickness from 19 to 1017 m; the thinnest sections are in Berkley 1 and Moyle 1 (both 19 m).

Fossils and age: The Keyling Formation contains microfloras of the *Granulatisporites confluens* Oppel-zone and Stage 3a that indicate an Asselian to Sakmarian age. In Cambridge 1, Stage 3b palynomorphs are also present in the top two metres of this unit. In Lesueur 1 the entire Stage 3b appears to be represented in the Keyling Formation based on the Lower *Granulatisporites trisinus* Zone of Helby (*in* Lane, 1981). The fauna present in this formation appears to be impoverished. However, appraisals of the microfauna have been made only in the early wells drilled in the basin, such as Kulshill 1 and Lacrosse 1.

Depositional environment: The presence of minor amounts of limestone throughout this unit (especially in Barnett 1), and coaly horizons, suggests the Keyling Formation was deposited in fluvial to deltaic environments. An upward increase in fauna in both Kulshill 1 and Lesueur 1 indicates increasing marine influence towards the top of the formation. Regional correlations within the upper part of the Keyling Formation are difficult to make (Plate 1) as regional seismic events appear to have been masked by facies changes as deltaic environments replace fluvial environments.

Kinmore Group

The Kinmore Group comprises (in ascending order) the Fossil Head, Hyland Bay, and Mount Goodwin Formations (Fig. 10). It is named after Kinmore Point south of Port Keats. The group lies conformably between the Kulshill Group (below) and the Sahul and Troughton Groups (above); it is up to 1800 m thick.

The group is equivalent to the 'Port Keats Group' of Noakes (1949). This name is best abandoned because the upper and lower limits were poorly defined, and because subsequent workers (Duchemin and Creevey, 1966; Guillaume, 1966; Caye, 1968) also included the 'Kulshill Formation' in the group.

Fossil Head Formation

Definition: Although the name of this formation comes from Fossil Head, the contained macrofauna (Skwarko, in press) suggests that the sequence at that locality ('Fossil Head Sandstones' of Brown, 1895) is probably equivalent to the lower part of the Hyland Bay Formation. The Fossil Head Formation, as here defined, is equivalent to the 'Shale member' of Duchemin and Creevey's (1966) informal 'Sugarloaf Formation'. That name had a prior use in New South Wales; the name 'Fossil Head beds' of Caye (1968), published as a citation in a table, was probably intended to replace it. Subsequent workers have associated the name Fossil Head Formation with the sequence of carbonaceous siltstone and mudstone with sandstone and minor limestone which underlies the Hyland Bay Formation in the subsurface (e.g. Laws and Brown, 1976). This definition has since gained wide acceptance, and is adhered to in this report. The type section is the interval from 2993 to 3569 m in Tern 1 (Mory, 1988). Although Hughes (1978) described the enclosing formations, he did not mention this unit. This omission was probably due to his miscorrelation of the basal limestone in Flat Top 1 (the only well from his study in which the Fossil Head Formation is present) with the Pearce Member of the Hyland Bay Formation. Although the basal shales of the Hyland Bay Formation are similar to those of the Fossil Head Formation, the top of the formation is generally marked by a small disconformity, or a 10 to 15 m thick limestone, at the base of the overlying Hyland Bay Formation.

Lithology: The Fossil Head Formation consists of grey to black siltstone and sandstone with some fossiliferous limestone. Trace quantities of shell fragments, pyrite, chert, and anhydrite occur in the finer grained lithologies.

Stratigraphic relationships: The Fossil Head Formation conformably overlies the Keyling Formation. Palynological evidence suggests that the Fossil Head Formation is equivalent, in part, to the upper part of the Keyling Formation (Fig. 10).

Distribution and thickness: Most occurrences of the Fossil Head Formation are in the southern Petrel Sub-basin, south of Petrel 1, where it varies in thickness from 116 to 590 m. The unit is also questionably identified in Osprey 1 on the Londonderry High.

Fossils and age: Abundant fossil fragments (including bryozoans, brachiopods, echinoderms, corals, gastropods, and ostracods) have been observed from cuttings, but only the microflora has received systematic attention. In nearly all wells, Stage 3b palynomorphs characterized by the presence of *Granulatisporites trisinus* have been identified throughout the formation. In Lesueur 1, by comparison, Helby (*in* Lane, 1981) identified the *Praecolpatites sinuosus* and Upper *Granulatisporites trisinus* Zones in this unit. He correlated these zones with upper Stage 4a and lower Stage 4 of Kemp et al. (1977). Similarly Helby (*in* Chan, 1982a) identified the *Microbaculispora villosa* and *Praecolpatites sinuosus* Zones (upper Stage 4a and 4b) in Tern 2 from the top of the Fossil Head Formation.

Depositional environment: Marine fossils throughout the Fossil Head Formation, and its predominantly shaly character, suggest that deposition took place in marine-shelf conditions away from major clastic input. The lower part of the Fossil Head Formation was probably deposited as prodeltaic muds, as the lower part of the unit is coeval with the deltaic Keyling Formation.

Hyland Bay Formation

Definition: The Hyland Bay Formation was named in the Petrel 2 well completion report (ARCO, 1971b) for the sequence of sandstone, siltstone, shale, and limestone between 3461 and 4028 m. Hughes (1978), however, gave the type section as the interval 3464 - 3980 m (T.D.) in Petrel 1. Petrel 2 is here designated as a reference section since Petrel 1 did not penetrate the base of the Hyland Bay Formation. Four members are identified in this formation: Pearce, Cape Hay, Dombey, and Tern Members.

In the onshore part of the basin, the informal 'Upper Permian marine beds', 'plant-bearing beds' and 'marine horizon of Fossil Head' of Dickins et al. (1972) are lithologically equivalent to the Hyland Bay Formation. Based on depositional environment, these three informal units parallel the offshore subdivision of the formation. The Tern and Dombey Members are equivalent to the 'Upper Permian marine beds'; the Cape Hay Member is equivalent to the 'plant-bearing beds'; and the Pearce Member and basal undifferentiated Hyland Bay Formation are equivalent to the 'marine horizon of Fossil Head'. The 'Upper Permian marine beds', however, are early Tatarian in age compared to a Kungurian to Kazanian age for the Hyland Bay Formation in the southeastern, offshore part of the Petrel Sub-basin (Fig. 11). Drummond (1963) divided the sequence drilled in the coal bores (1904 - 1908) between Port Keats and Cliff Head into five informal units ('Formations I to V'). However, these units have not been used by other workers. The correlations of Dickins et al. (1972) suggest that in the Port Keats bores the lower half of 'Formation I', 'Formation II', and the base of 'Formation III' (Drummond, 1963, fig. 6) are equivalent to the Hyland Bay Formation. Their correlations also suggest that the sedimentary sequence in the rest of these bores should be included in this formation.

In the northwestern Bonaparte Basin, the Hyland Bay Formation contains a basal shale and two thick carbonate units which are overlain and separated by two thin siliciclastic units (e.g. Osprey 1, Dillon Shoals 1, and Anderdon 1). These northwestern well sections are analogous to those in the southeastern Petrel Sub-basin in that they contain two distinct carbonate horizons. The carbonate horizons in the northwest have been correlated with the two in the southeast of the basin by seismic mapping, although palynological

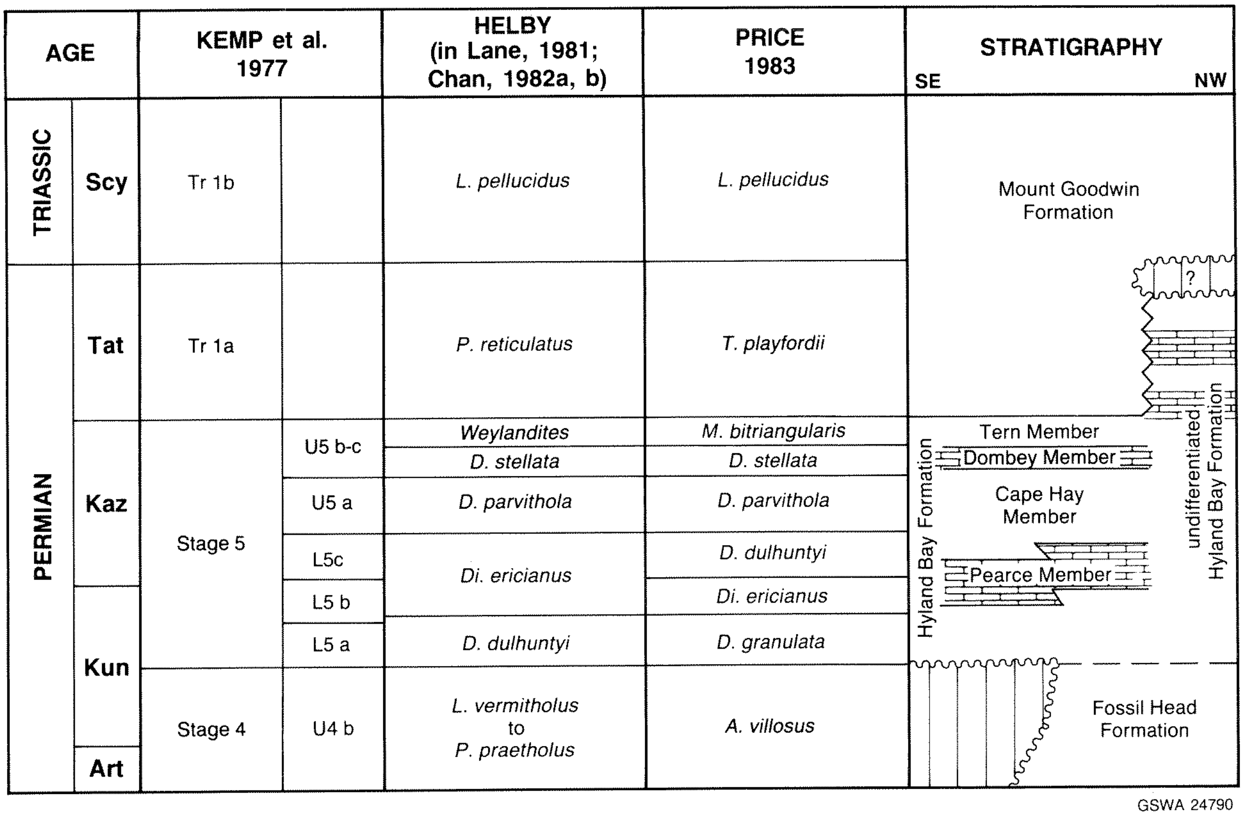


Figure 11. Palynological correlation of the Hyland Bay Formation.

evidence suggests that the northwestern carbonates are much younger (Fig. 11). Consequently, members have not been differentiated in the northwestern sections. In Osprey 1, the 363 m of shale and minor sandstone below the basal limestone is difficult to distinguish from the underlying Fossil Head Formation on lithological grounds alone. Although the presence of the *Dulhuntyispora* Assemblage in the upper 75 m of this section suggests that this interval is the Hyland Bay Formation, part of the underlying section may belong to the Fossil Head Formation. In Flat Top 1 on the Darwin Shelf, the formation consists largely of carbonate and cannot be subdivided into members.

Lithology: The Hyland Bay Formation consists of a basal unit, overlain by fossiliferous limestone (Pearce Member), sandstone, mudstone and siltstone with minor amounts of coal (Cape Hay Member), a second fossiliferous limestone (Dombey Member), and uppermost sandstone and mudstone (Tern Member). On the Londonderry High the formation contains two thick carbonates enclosed by a siliciclastic sequence.

Stratigraphic relationships: Although the Hyland Bay Formation appears to conformably overlie the Fossil Head Formation, the absence of Stage 4b at this level in many of the offshore sections suggests a disconformable relationship. Only in Tern 2 has Stage 4b been preserved. The unit also disconformably overlies granitic basement onshore in the Cliff Head No. 1 coal bore, and offshore in Troubadour 1.

Distribution and thickness: Most intersections of the Hyland Bay Formation are in the southern Petrel Sub-basin where the unit ranges from 176 to 520 m in thickness. It is also known from the west of the sub-basin (Plover 1 and 2) and on the Londonderry High (Osprey 1, Whimbrel 1, Dillon Shoals 1, and Anderdon 1). The thickest intersections in that area are from Osprey 1 (428 m) and Anderdon 1 (489 m). In Osprey 1, the lower limit of the formation is difficult to distinguish from the underlying Fossil Head Formation, and it may be thicker than 428 m in that well. In Anderdon 1, the formation has not been fully penetrated. Thin intersections of late Permian carbonates in Sahul Shoals 1 (53 m) and Troubadour 1 (21 m), on the Ashmore and Sahul Platforms respectively, are questionably assigned to the Hyland Bay Formation. The only complete section in the onshore part of the basin is in the Port Keats No. 4 coal bore (approximately 101 - 402 m).

Fossils and age: In the southeastern Petrel Sub-basin, the Hyland Bay Formation contains a prolific Stage 5 microflora (Kungurian to Kazanian — late Early to Late Permian). Helby (*in* Lane, 1981; *in* Chan, 1982a,b) proposed five assemblage zones from this formation. These were named the *Dulhuntyispora dulhuntyi, Didecitriletes ericianus, Dulhuntyispora parvithola, Dulhuntyispora stellata,* and *Weylandites* Zones (in ascending order). In more recent work, Helby (*in* Holten, 1985b) has adopted Price's (1983) zonation for the Permian of Queensland. In Price's (1983) scheme, the *D. granulata* Zone is equivalent to Helby's *D. dulhuntyi* Zone, the *Di. ericianus* Zone plus the overlying *D. dulhuntyi* Zone is equivalent to Helby's *Di. ericianus* Zone, and the *Microreticulatisporites bitriangularis* Zone is probably equivalent to the *Weylandites* Zone (Fig. 11). Foster (1984, 1985) recognized only upper and lower Stage 5 palynofloras in the Bonaparte Basin since he could not find a consistent stratigraphic distribution of species of *Dulhuntyispora.* In the northeast of the basin, the Hyland Bay Formation contains microfloras equivalent to the Tatarian *Protohaploxypinus Microcorpus* Zone of Helby et al. (1987), as well as *Dulhuntyispora* Microfloras. In Osprey 1, Helby (*in* ARCO,1972a) identified microfloras from the *Protohaploxypinus reticulatus* or *Lunatisporites pellucidus* Assemblages in the upper limestone of the Hyland Bay Formation; this is the only well to date in which palynological evidence suggests that the unit may extend into the earliest Triassic.

The diverse fauna present in this formation in offshore wells has been little documented, apart from well completion reports which note the presence of foraminifers, ostracods, gastropods, and bryozoans. By comparison, considerable work has been completed on brachiopod, mollusc, and bryozoan faunas collected from the outcrops in the Port Keats area (Etheridge, 1897, 1907; Thomas, 1957; Dickins, 1963; Skwarko, in press).

Depositional environment: In the southeast of the basin, deposition of the Hyland Bay Formation commenced in an open-marine environment (basal shale and limestone, plus Pearce Member). This was followed by deltaic progradation (Cape Hay Member), due to uplift along the Halls Creek Orogen. The regressive deltaic sedimentation was followed by a marine transgression and the deposition of marine carbonates. The following clastic sequence (Tern Member) was deposited by a prograding barrier-island complex, in offshore to shoreface and lagoonal environments (Bhatia et al., 1984; Grenfell, 1985). In the northwest of the basin, open-marine conditions prevailed with deposition of fine siliciclastics and carbonates.

Pearce Member

Definition: The name 'Pearce Member' replaced the informal 'H5 Member' for the fossiliferous limestone low in the Hyland Bay Formation (Mory, 1988). The name is from Pearce Point, south-southwest of Port Keats. The informal name arose from the association of ARCO seismic horizon 'H5' with the limestone. The type section is the interval 3952 - 3983 m in Petrel 2.

Lithology: The Pearce Member consists of biomicritic to biosparitic limestone, which contains abundant shell fragments, bryozoans and crinoids (Bhatia et al., 1984).

Stratigraphic relationships: The Pearce Member lies conformably between undifferentiated Hyland Bay Formation (below) and the Cape Hay Member (above).

Distribution and thickness: In spite of its thickness (5 - 57 m), the Pearce Member has been recognized on seismic sections over a wide area in the southern half of the basin, from the Darwin Shelf across to the Londonderry High.

Fossils and age: Apart from the presence of an abundant marine fauna, which is largely undescribed, acritarchs and palynomorphs have been identified from the Pearce Member. Helby (*in* Lane, 1981, and Chan, 1982a) identified his *Dulhuntyispora ericianus* Zone from this member in Lesueur 1. In Tern 2, the member lies between occurrences of the *Didecitriletes ericianus* and *Dulhuntyispora parvithola* Zones. These zones range from lower Stage 5a to upper Stage 5a (Kungurian to Kazanian), and suggest that the member may be diachronous (Fig. 11).

Depositional environment: The Pearce Member was deposited on an open-marine shelf.

Cape Hay Member

Definition: The Cape Hay Member ('Hay Member' of Bhatia et al., 1984) is the interval of sandstone, mudstone, and siltstone which lies between the two limestone members of the Hyland Bay Formation. The name has been used previously for the Hay River Formation in the Georgina Basin and so the full geographic name should be used to avoid confusion. The type section is the interval 3549 - 3918 m in Petrel 1. The Petrel gasfield reservoir lies within this unit. The member is here considered to be lithologically equivalent to the 'Middle non-marine beds' of Dickins et al. (1972) which are exposed in coastal sections in the Northern Territory.

Lithology: The Cape Hay member is a predominantly siliciclastic unit in which two main coarsening-upward cycles are present. Bhatia et al. (1984) recognized five lithological units in the member. The lower cycle consists of dark mudstone and siltstone, overlain by bioturbated, interbedded sandstone and mudstone. The sandstone in this interval is commonly lenticular, and contains flasers, cross-beds, and ripple cross-laminations. The upper cycle consists of carbonaceous mudstone and siltstone with sandstone interbeds, at the base, overlain by sandstone with mudstone and minor amounts of coal, overlain in turn by uppermost medium- to coarse-grained, cross-bedded sandstone with minor argillaceous, coaly beds.

Stratigraphic relationships: The Cape Hay Member lies conformably between the Pearce Member (below) and the Dombey Member (above). It is probably equivalent, in part, to the Pearce Member, as the Dombey Member appears to be time transgressive.

Distribution and thickness: The Cape Hay Member has a similar distribution to the overlying Dombey Member and underlying Pearce Member, in that it occurs in the southern half of the Petrel Sub-basin. Based on well intersections, it varies in thickness from 200 to 450 m.

Fossils and age: Helby (*in* Lane, 1981) identified palynomorphs of the *Didecitriletes ericianus* and *Dulhuntyispora parvithola* Zones in the Cape Hay Member in Lesueur 1, whereas in Tern 2 he recognized the *Dulhuntyispora stellata* Zone in addition to the former two zones (*in* Chan, 1982a). These zones range from lower Stage 5b to upper Stage 5b-c (latest Kungurian to Kazanian, Fig. 11).

Depositional environment: The Cape Hay Member was deposited in a deltaic environment. The lower coarsening-up cycle results from progradation from a prodeltaic to delta-front environment. The upper cycle represents a continuation of that progradation from estuarine deposits of the delta-front and lower delta-plain, to upper delta-plain alluvial point-bar deposits (Bhatia et al., 1984).

Dombey Member

Definition: The name 'Dombey Member' replaced the informal 'H4 Member' for the limestone horizon high in the Hyland Bay Formation (Mory, 1988). The name is from Cape Dombey at the northern end of Hyland Bay. The informal name comes from the association of ARCO's 'H4' seismic horizon with the limestone. The interval 3523 - 3549 m in Petrel 1 is the type section.

Lithology: The Dombey Member is similar to the Pearce Member. It consists of biomicritic to biosparitic limestone with abundant shell fragments, bryozoans, and crinoids (Bhatia et al., 1984).

Stratigraphic relationships: The Dombey Member is conformable between the Cape Hay Member (below) and the Tern Member (above).

Distribution and thickness: As with the Pearce Member, the Dombey Member has been recognized on seismic sections over a wide area in the southern half of the basin between the Darwin Shelf and Londonderry High. It ranges in thickness from 5 to 30 m across the Petrel Sub-basin and Darwin Shelf.

Fossils and age: In the southern Petrel Sub-basin the Dombey Member contains microfloras of the *Dulhuntyispora stellata* Zone (Helby, *in* Lane, 1981; Chan, 1982a) which indicate an upper Stage 5b-c (Late Kazanian) age. The abundant fauna in this unit has not been studied in detail.

Depositional environment: The Dombey Member was deposited in an open marine-shelf environment.

Tern Member

Definition: The Tern Member (Bhatia et al., 1984) is the sandstone and mudstone sequence at the top of the Hyland Bay Formation. The type section is the interval 2521 to 2585 m in Tern 1. Sandstone in the member is the Tern gasfield reservoir.

Lithology: The Tern Member generally consists of a fossiliferous coarsening-up sequence of mudstone and sandstone, although the sequence is, in some areas, composed entirely of mudstone (e.g. in Lacrosse 1 and Lesueur 1) or sandstone (e.g. in Bougainville 1).

Stratigraphic relationships: The Tern Member conformably overlies the Dombey Member at the top of the Hyland Bay Formation.

Distribution and thickness: The Tern Member is present throughout the southern Petrel Sub-basin. It has been intersected as far north as the Petrel wells. The unit is 30 to 70 m thick.

Fossils and age: The Tern Member contains unidentified shelly material and trace fossils from the *Cruziana* Association (Bhatia et al., 1984). Helby (*in* Lane, 1981; and *in* Chan 1982a,b) identified palynomorphs of the *Dulhuntyispora stellata* and *Weylandites* Zones from this unit. These zones indicate and upper Stage 5b-c (late Kazanian) age.

Depositional environment: The coursening-up, regressive marine cycle of the Tern Member was interpreted as a barrier-bar sequence by Bhatia et al. (1984). Within this environment, the shelly, cross-bedded and laminated sandstones represent upper shoreface or foreshore deposits, and interbedded bioturbated sandstone and mudstone represent lower shoreface deposits. Siltstone- and mudstone-dominated sections of this member, such as at Lacrosse 1 and Lesueur 1, were deposited landwards of the barrier island in a lagoonal environment (Bhatia et al., 1984).

Mount Goodwin Formation

Definition: The Mount Goodwin Formation consists predominantly of siltstone and shale; it was named after Mount Goodwin, near Port Keats (ARCO, 1971b). The formation is equivalent to the 'Lingula shales' of Caye (1968). The type section was first defined in an unpublished report by Helby (1974b) as the interval from 2887 to 3464 m in Petrel 1. Hughes (1978) cited the interval 2892 - 3464 m for the type section; the 2892 m level is incorrect as it is from Petrel 1A (ARCO, 1971a).

Lithology: The Mount Goodwin Formation consists of dark to light grey shale with minor amounts of siltstone and thin interbeds of fine-grained sandstone. Glauconite is often present in the siltstone. In Sahul Shoals 1, traces of dolomite, marl, and coal are also present. In Dillon Shoals 1, the low gamma-ray log values in the upper three hundred metres of this unit are anomalous. However, the high sonic log values and the lack of sandstone in cuttings in this interval indicates that the gamma-ray log response is a result of severe caving rather than the presence of sandstone. Similarly, the gamma-ray log response over the interval 2329 to 2364 m in Osprey 1 is anomalous and may indicate caving or a small fault.

Stratigraphic relationships: Offshore, the Mount Goodwin Formation generally conformably overlies the Hyland Bay Formation. Spore-pollen zones present in both units (Fig. 11) indicate that this contact is diachronous. In the Londonderry High area, vitrinite reflectance data suggest that the Mount Goodwin Formation may be locally disconformable on the underlying formation. Onshore, there is no evidence for a latest Permian age for the Mount Goodwin Formation, which suggests that it disconformably overlies the Hyland Bay Formation.

Distribution and thickness: The Mount Goodwin Formation is present over most of the basin. A maximum thickness of almost 670 m was intersected in Dillon Shoals 1. The formation extends onshore in the Port Keats area, but is less than 20 m thick. It thins over the Sahul Platform to 89 m in Troubadour 1. The unit has been removed by erosion south of Turtle 1 and has not been penetrated west of 124° E.

Fossils and age: The Mount Goodwin Formation contains palynofloras equivalent to the *Protohaploxypinus microcorpus*, *Lunatisporites pellucidus* and *Protohaploxypinus samoilovichii* spore-pollen Zones of Helby et al. (1987). These zones indicate a Tatarian (latest Permian) to Smithian (Early Triassic) age. Dickins et al. (1972) recorded that lingulid brachiopods, vertebrate remains, branchiopods (identified as estheriids) and unidentifiable plants were collected from outcrops in the Port Keats area. Apart from the work of Tasch and Jones (1979) on the conchostracan branchiopods from the Port Keats area and Petrel 1, no further work on this material is known. In Sahul Shoals 1, bivalves, pyritized ammonites, and worm burrows were recorded from core at the top of this unit. From this material, Skwarko and Kummel (1974) identified Halobidae bivalves and the ammonite *Nicomedites* sp. This genus indicates an early Anisian (Middle Triassic) age which is anomalous when compared to the older ages indicated by palynomorphs.

Depositional environment: The lack of coarse clastics in the thick fossiliferous shale of the Mount Goodwin Formation suggests a distal marine environment such as the outer shelf or slope. However, amongst the fauna in the Port Keats and Petrel 1 area, the presence of conchostracans (which have no other macrofaunal or macrofloral associates where they occur) indicates that at least part of the unit was deposited in freshwater or brackish facies (Tasch and Jones, 1979). Tasch and Jones (1979, p. 28) state that 'the sparsity of biotic associates also implies that the water bodies inhabited by Bonaparte Gulf Basin conchostracans were ephemeral'. The presence of lingulid brachiopods indicates that marine environments interfingered with these marginal-marine sections, or that the conchostracans were transported. The marginal-marine environments were possibly restricted to the edge of the basin while open-marine conditions were

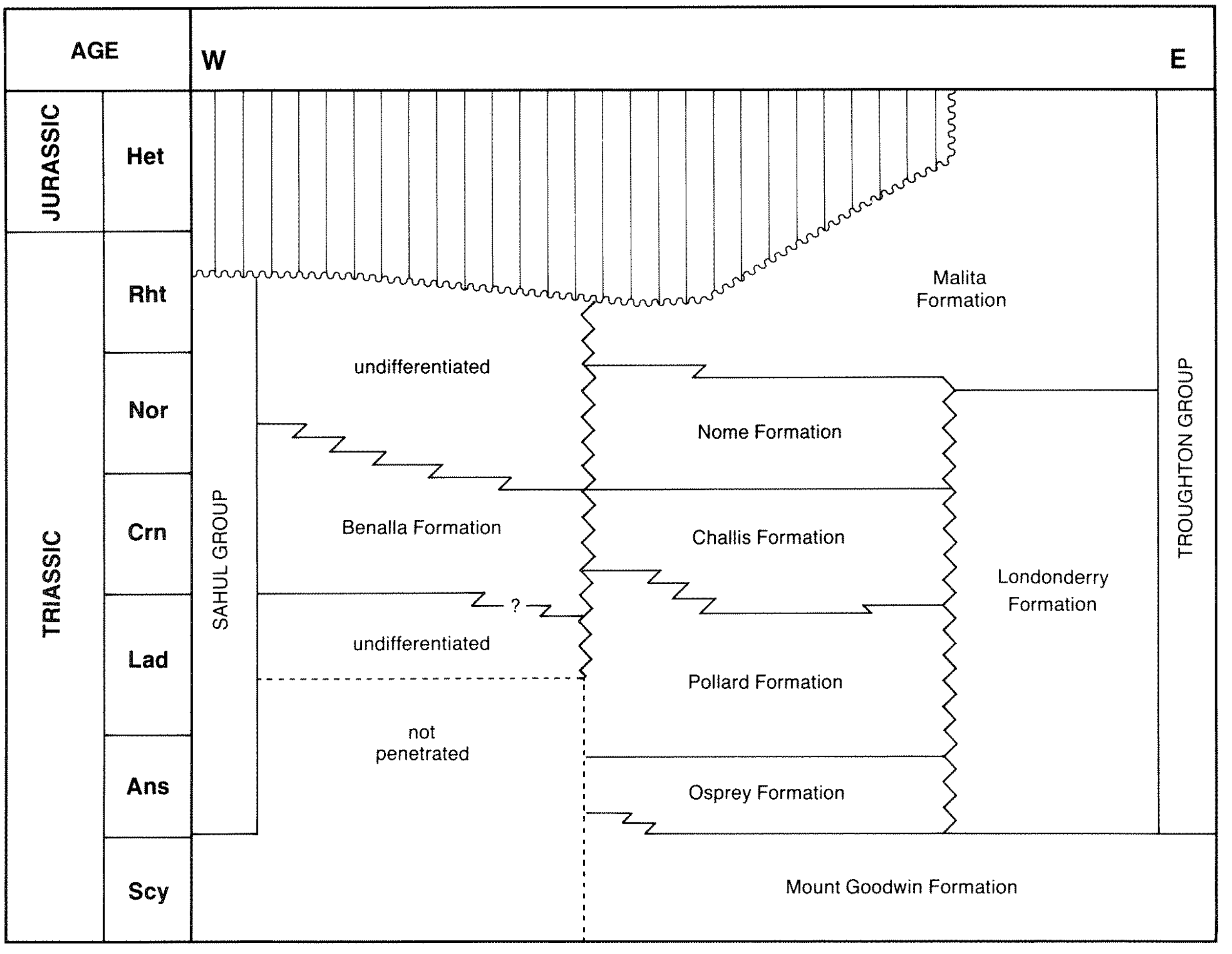


Figure 12. Correlation of units within the Sahul Group.

established to the northwest, similar to the Early Triassic Fitzroy embayment in the Canning Basin (Gorter, 1978).

Sahul Group

The Sahul Group is a lithologically variable clastic - carbonate sequence that lies conformably between the Mount Goodwin and Malita Formations. It also contains reddish brown shale, and minor amounts of coal, evaporite, and volcanic rocks. The Sahul Group is distinguished from enclosing groups by the presence of carbonates. It is similar to the 'Sahul Formation' of Helby (1974b), but the basal shales of that unit are here assigned to the underlying Mount Goodwin Formation.

The group is present across the Londonderry High, Vulcan Sub-basin, and Ashmore Platform. Between the Londonderry High and eastern Ashmore Platform the group is divided into the Osprey, Pollard, Challis, and Nome Formations (in ascending order). The group reaches a maximum thickness of approximately 2200 m in this area. On the western Ashmore Platform, the Benalla Formation lies between two undifferentiated sequences also in the Sahul Group (Fig. 12); carbonates in the Benalla Formation thin to the east and, based largely on log correlations, interfinger with other units in the group. Palynological evidence for such interfingering relationships is sparse, not only because individual zones may be present across two or more formations, but also because older wells were often poorly sampled.

Osprey Formation

Definition: The Osprey Formation is a sequence of interbedded shale and sandstone with thin carbonate beds at its top. The name is from Osprey 1, in which the type section is the interval from 1318 to 1834 m. The formation is differentiated from the underlying Mount Goodwin Formation by the presence of sandstone in the Osprey Formation; the base of the formation is placed at the first appearance of sand (which corresponds to the first significant deflection on the gamma-ray log). A distinctive carbonate at the top of the unit and a lower sand content distinguish the Osprey Formation from the overlying sandy Pollard Formation.

Lithology: The Osprey Formation consists largely of interbedded shale and sandstone. Thin beds of carbonate mark the top of the unit. The carbonate consists of oolitic dolomite or limestone. Most of the few thick sandstones are lenticular, and only the uppermost can be correlated from well to well.

Stratigraphic relationships: The Osprey Formation lies conformably between the Mount Goodwin Formation (below) and the Pollard Formation (above). The Osprey Formation is equivalent to the basal part of the Cape Londonderry Formation to the east. On the Londonderry High the Bathurst Island Group unconformably overlies the formation locally.

Distribution and thickness: The Osprey Formation is known from only six wells: Anderdon 1, Dillon Shoals 1, Crane 1, Osprey 1, Sahul Shoals 1, and Whimbrel 1. these extend from the western side of the Londonderry High across to the northeastern margin of the Ashmore Platform. The unit ranges from 302 to 516 m thick in the wells with uneroded sections.

Fossils and age: The Osprey Formation contains spores and pollen of the *Triplexisporites playfordii* Zone of Helby et al. (1987) which indicate a late Scythinan (Early Triassic) to Anisian (early Middle Triassic) age.

Depositional environment: The presence of marine-shelf carbonates at the top of the Osprey Formation, and marine environments in the conformably underlying Mount Goodwin Formation, suggest that the Osprey Formation was deposited in a similar environment. Part of the unit may also be of marginal-marine origin as it is coeval with the non-marine Cape Londonderry Formation to the east.

Pollard Formation

Definition: The Pollard Formation consists of interbedded sandstone with subordinate shale. It is named after Pollard 1, although the section is incomplete at that well. The type section is from 2417 to 3249 m in Sahul Shoals 1. The relative paucity of carbonate and shale distinguishes it from the overlying Challis Formation. The basal 535 m in Brown Gannet 1 is questionably assigned to the Pollard Formation, based on the similarity of the electric logs to those of the type section.

Lithology: The Pollard Formation is a sand-dominated unit with some shale and rare carbonate. Upward-fining and upward-coarsening cycles are common, especially in the Jabiru and Challis wells where they are up to 100 m thick. These cycles are difficult to correlate which suggests that individual cycles do not have a great lateral extent. In Pollard 1, the Pollard Formation is much more sandy than to the southeast, whereas it is more shaly in Prion 1. To the west, thin carbonate beds are locally common, and their presence suggests that the unit may be equivalent, in part, to the Challis Formation.

Stratigraphic relationships: The Pollard Formation lies conformably between the underlying Osprey Formation and the overlying Challis Formation; the contact with the Challis Formation is diachronous. Log correlations indicate that the top of the Pollard Formation is equivalent to the base of the Benalla Formation; this suggests that the unit may extend into the early Carnian (Late Triassic).

Distribution and thickness: The Pollard Formation has been identified in ten wells on the western half of the Londonderry High and on the eastern half of the Ashmore Platform, and thus has the widest distribution of any formation in the Sahul Group. The unit ranges in thickness from 263 m in Crane 1 to 832 m in Sahul Shoals 1.

Fossils and age: The Pollard Formation contains palynofloras of the *Staurosaccites quadrifidus* and *Samaropollenites speciosus* spore-pollen Zones, and the *Sahulidinium ottii* Zone, of Helby et al. (1987). These zones indicate a latest Anisian to Carnian (Middle to early Late Triassic) age.

Despositional environment: The high proportion of course siliciclastics in upward-coursening and upward-fining cycles of limited lateral extent in the Pollard Formation, and the presence of minor amounts of marine carbonate, suggest a deltaic environment in which several lobes were developed.

Challis Formation

Definition: The Challis Formation consists of interbedded shale, sandstone, and carbonate. In Challis 1, the unit is present over the interval 1387 - 1603 m. However, the type section is in the nearby Jabiru 1A well (2148 - 2707 m), as the section in Challis 1 has been eroded, and does not demonstrate the formation's stratigraphic relationship within the Sahul Group (see Plate 2).

Lithology: The Challis Formation consists of interbedded sandstone, claystone, siltstone, and carbonate. The carbonate is mostly fossiliferous, bioturbated limestone and dolomite, with oolites and oncolites locally abundant.

Stratigraphic relationships: The Challis Formation lies conformably between the underlying Pollard Formation and overlying Nome Formation; the lower contact is diachronous. In Sahul Shoals 1, the unit is overlain by 158 m of interbedded carbonate and siliciclastic strata that have been tentatively assigned to the Benalla Formation. The Challis Formation is equivalent, in part, to the Benalla Formation to the west.

Distribution and thickness: The Challis Formation can be identified from wells in the Jabiru and Challis oilfields, in Crane 1 on the western half of the Londonderry High, and in Sahul Shoals 1 on the northeast of the Ashmore Platform. It ranges in thickness from 286 m in Jabiru 1A to 465 m in Sahul Shoals 1.

Fossils and age: The Challis Formation contains palynomorphs of the *Samaropollenites speciosus* Zone that indicate a Ladinian to Carnian (Middle to Late Triassic) age (Helby et al., 1987). Fossil fragments are present in the carbonates, but have not been identified.

Depositional environment: A shallow, marginal-marine environment is envisaged for most of this formation, based on the common presence of shale, sandstone, and fossiliferous oolitic carbonate. These rock types probably formed in tidally influenced shallow-marine environments that include tidal flats, bays, and channels (Wormald, 1988).

Nome Formation

Definition: The Nome Formation is the uppermost unit of the Sahul Group; it consists of interbedded sandstone, siltstone, and shale, with minor amounts of coal. The unit is named after Nome 1; the type section is in Jabiru 1A (1887 -2148 m), a well that better demonstrates relationships with adjacent formations in the Sahul Group (Plate 2).

Lithology: The Nome Formation is a predominantly siliciclastic unit that consists mainly of interbedded sandstone with grey siltstone and claystone and minor amounts of coal.

Stratigraphic relationships: The Nome Formation lies conformably between the underlying Challis Formation and overlying Malita Formation; the upper contact is probably diachronous. The formation is coeval with the upper part of the Benalla Formation and with an undifferentiated clastic sequence that overlies the Benalla Formation on the Ashmore Platform (Fig. 12).

Depositional environment: The Nome Formation is at present known from Nome 1, Crane 1, and Eider 1 on the Londonderry High, and in the Jabiru oilfield, where it is up to 531 m thick. It is also questionably identified at the base of Prion 1 on the Ashmore Platform.

Fossils and age: The Nome Formation contains palynomorphs of the upper *Samaropollenites speciosus, Minutosaccus crenulatus,* and *Shublikodinium wigginsii* Zones. Although these zones indicate a Ladinian to Norian (Middle to Late Triassic) age (Helby et al., 1987) the unit is probably Carnian to Norian (Late Triassic) in age as the *S. speciosus* Zone is also present in the underlying Challis Formation.

Depositional environment: The stratigraphic position of this largely coarse siliciclastic formation between a marine unit (below) and a non-marine redbed sequence (above), and the presence of minor amounts of coal, suggest either a delta plain to delta front, or a barrier-complex environment.

Benalla Formation

Definition: The Benalla Formation consists of interbedded limestone, sandstone, siltstone, and claystone. The unit is named after Benalla Bank. The type section is in North Hibernia 1 over the interval 2572 to 3631 m. The 'unnamed carbonate beds' and 'lower unnamed clastic beds' in Ashmore Reef 1 (Craig, 1968) are here included in the upper part of the formation (Plate 2).

Lithology: The Benalla Formation is distinguished by the presence of fossiliferous, oolitic, recrystallized, and sandy carbonate. Siliciclastics are interbedded with the carbonates and may be used to define upper and lower carbonate members that have not been named here. Interbedded clastics are commoner on the eastern side of the Ashmore Platform.

Stratigraphic relationships: The type section of the Benalla Formation lies conformably between two undifferentiated, dominantly siliciclastic sequences in the Sahul Group. In Sahul Shoals 1, however, the unit is tentatively identified as overlying the Challis Formation. The limited palynological data available suggests that the Benalla Formation is approximately coeval with the Challis and Nome Formations to the east.

Distribution and thickness: The Benalla Formation is recognized in three wells near the western side of Ashmore Platform: Ashmore Reef 1, Mount Ashmore 1B, and North Hibernia 1. It is also questionably identified to the east in Sahul Shoals 1 and Puffin 1. The only complete section is in North Hibernia 1, where it is 1078 m thick.

Fossils and age: A Carnian - Norian (Late Triassic) age is indicated in most palynological reports in well completion reports. In Puffin 1, by comparison, Helby (*in* ARCO, 1972b) reported the presence of *Samaropollenites speciosus.* This species is indicative of the *Staurosaccites quadrifidus* or *Samaropollenites speciosus* Zones of Helby et al. (1987), and thus suggests a Carnian to Ladinian age. Similarly, spore and pollen assemblages in Mount Ashmore 1B were compared to the *Samaropollenites speciousus* Zone (Wiseman, *in* Woodside, 1981). Unidentified fossils from this unit in Puffin 1 include molluscs, brachiopods, echinoderms, ostracods, algae, and foraminifers (ARCO, 1972b). Jones and Nicoll (1985) recorded the conodont *Epigondolella primitia* from the carbonate unit in Sahul Shoals 1. This species has a range restricted to latest Carnian to earliest Norian and indicates the carbonate is coeval with the Benalla Formation.

Depositional environment: The predominance of fossiliferous and oolitic carbonates indicated a shallow open-marine shelf environment for the Benalla Formation. The coarse clastic component, however, suggest the proximity of deltaic environments.

Troughton Group

The Troughton Group is a Triassic - Jurassic sand-dominated sequence that conformably overlies the Kinmore Group, and has at its top the Callovian 'breakup unconformity'. The group includes, in ascending order, the Cape Londonderry, Malita, and Plover Formations. The name is from Troughton Island, east of Cape Londonderry. The basal formation in the group (Cape Londonderry Formation) is coeval with the Sahul Group to the west; it is distinguished from that group by its lack of carbonates. The Troughton Group represents a regressive - transgressive phase of sedimentation, and, together with the Sahul Group, forms the Triassic - Jurassic pre-rift sequence in the Bonaparte Basin.

Cape Londonderry Formation

Definition: The Cape Londonderry Formation ('Londonderry Formation' of Helby, 1974b) consists of sandstone and lesser amounts of siltstone and shale. The full geographic name should be used for the northwestern Australian unit because the name has been used previously as the 'Londonderry Clay' in New South Wales. The Cape Londonderry Formation is equivalent to the 'Undifferentiated Middle to Upper Triassic' below the 'Upper Triassic redbeds' of ARCO (1971b). The type section is the interval 2471 - 2887 m in Petrel 1 (Helby, 1974b).

Lithology: The Cape Londonderry Formation consists predominantly of quartzitic sandstone with scattered pebbles in the courser grained horizons. Minor siltstone and mudstone interbeds and traces of coal are also present.

Stratigraphic relationships: The Cape Londonderry Formation conformably overlies the Mount Goodwin Formation. The formation is coeval with the Sahul Group in the west of the basin. The transition between the two units occurs over the eastern Londonderry High, approximately along longitude 126° E.

Distribution and thickness: The Cape Londonderry Formation is restricted to the central part of the Petrel Sub-basin north of Penguin 1, and the eastern side of Londonderry High as far west as Peewit 1. It ranges in thickness from 280 to 450 m. North of 12° 30' S, only partial intersections have been made due to the depth of the unit, or to Late Triassic to Early Jurassic erosion.

Fossils and age: Palynological data from the Cape Londonderry Formation are sparse; the unit is interpreted, from its stratigraphic position, to be Smithian to Ladinian (Early to Middle Triassic) in age. This is confirmed by the presence of *Triplexisporites playfordii* Zone in Tern 3 (Helby *in* Chan, 1982b). The identification of *Lunatisporites pellucidus* and *Protohaploxypinus microcorpus* near the base of the unit in Plover 1 (Islam, 1986) indicates a slightly older age (Griesbachian to Smithian) and suggests that the unit may have a diachronous lower contact with the Mount Goodwin Formation.

Depositional environment: The predominance of coarse-grained siliciclastic lithologies throughout the Cape Londonderry Formation indicates a fluvial braided-stream environment. Finer grained rock types and thin coals are probably overbank deposits.

Malita Formation

Definition: The Malita Formation (Helby, 1974b) is equivalent to ARCO's 'Lower Jurassic - Upper Triassic Redbeds'. The unit is presumably named after the Malita Shelf Valley of van Andell and Veevers (1967). The type section is the interval 2229 - 2471 m in Petrel 1 (Helby, 1974b). In the type section, and generally elsewhere, the unit is distinguished from the sand-dominated Cape Londonderry Formation (below) and Plover Formation (above) by the predominance of fine-grained clastics in the redbed sequence. In areas where the contact is gradational, the top of the lowest coal in the Plover Formation.

Lithology: The Malita Formation is characterized by multicoloured siliciclastic rock types (redbeds), especially siltstone and mudstone. Fine- to coarse-grained sandstone is also common throughout the unit, which contains rare occurrences of glauconite and shell fragments.

Stratigraphic relationships: In most of the Petrel Sub-basin the Malita Formation lies conformably between the Cape Londonderry Formation (below) and the Plover Formation (above). In the Tern - Petrel area the Malita Formation is absent, or the lower parts of the unit are missing, presumably due to salt-induced uplift prior to deposition. Onlap of the Malita Formation onto locally emergent areas resulted in non-deposition, or partial deposition, of the unit. West of the Londonderry High the Malita Formation conformably overlies the Sahul Group, or has been removed by Late Jurassic erosion. Limited available palynological data indicate that the upper and lower contacts are probably diachronous.

Distribution and thickness: The Malita Formation is present in the central part of the Petrel Sub-basin, north of 13° 45′ S, and extends west onto the northern part of the Londonderry High and eastern Ashmore Platform. It is also present on the western side of the Ashmore Platform. In the Vulcan Sub-basin and Malita Graben, the Malita Formation has probably been downfaulted to a considerable depth. On the Sahul Platform, western Ashmore Platform, and basin margins, the unit has been removed by erosion. It has a maximum thickness of 392 m in Petrel 3.

Fossils and age: Palaeontological evidence for the age of the Malita Formation is sparse. However, spores and pollen of the *Samaropollenites speciosus, Minutosaccus crenulatus* and *Corollina torosa* Zones of Helby et al. (1987) are present in this formation in the west of the basin. These zones indicate a Carnian (Late Triassic) to Pliensbachian (Early Jurassic) age. In the Petrel Sub-basin, the *Corollina torosa* Zone is present high in the sequence, and indicates a time transgressive upper contact. By comparison, Islam (1986) identified Palynological Unit PJ3.1 to PJ3.2 (Price et al., 1985) from this formation in Plover 1, and PJ1 to PJ5 in Tamar 1. These identifications are anomalous, as they suggest a Toarcian to Callovian (Early to Middle Jurassic) age (Price et al., 1985).

Depositional environment: The paucity of marine fossils, and the presence of 'redbeds' throughout the Malita Formation indicate a strongly oxidizing, probably non-marine environment of deposition. Rare shell fragments and glauconite may have been washed in from adjacent open-marine environments.

Plover Formation

Definition: The Plover Formation ('Petrel C' of ARCO, 1971b) consists of sandstone with minor amounts of shale and coal, at the top of the Troughton Group. The type section proposed by Hughes (1978) for 'Member C' (1820 - 2229 m in Petrel 1) is retained for the Plover Formation. The name 'Petrel Formation' is abandoned because that unit incorporates distinct sequences on either side of the Callovian breakup unconformity. The part of the 'Petrel Formation' which lies below the breakup unconformity is placed in the Plover Formation, and the part above the unconformity is placed in the Flamingo Group. The contact between the two units cannot be easily defined in some wells (e.g. Flamingo 1 and Frigate 1) because both are frequently sandy.

Lithology: The Plover Formation consists largely of sandstone, but significant siltstone and claystone interbeds occur throughout the unit. The sandstone is fine to coarse grained and often slightly glauconitic. Siltstone and claystone interbeds are usually carbonaceous, but may be slightly calcareous with rare shell fragments and glauconite. Limestone and coal are minor constituents, but are much more common in this unit than in other formations in the Troughton Group.

Stratigraphic relationships: From the available palynological data, the Plover Formation is here interpreted to conformably, but diachronously, overlie the Malita Formation. MacDaniel (1988), however, considered that this contact was disconformable around the Londonderry High, but conformable elsewhere.

Distribution and thickness: The Plover Formation is largely restricted to the central Petrel Sub-basin north of Penguin 1. It also extends onto the northern and western Londonderry High, across the Vulcan Sub-basin onto the eastern Ashmore Platform, and across the Malita Graben onto the Sahul Platform. It may also be present onshore in the Northern Territory in the 'Petrel Formation' of Hughes (1978). The Plover Formation ranges in thickness from 104 to 672 m. Erosion during the Oxfordian - Kimmeridgian ('breakup unconformity') has removed much of the unit, especially on the central part of the Londonderry High, and the present thickness is probably much less than the original thickness of the unit.

Fossils and age: In the west of the basin the *Corollina torosa, Callialasporites turbatus, Dictyosporites complex,* and *Contignisporites cooksoninae* spore-pollen Zones, and the *Dapcodinium priscum* and *Dissiliodinium caddaense* dinoflagellate Zones, have been identified from the Plover Formation (Helby *in* ARCO, 1975; BHP, 1984a,b,c,d; Holten 1985a, 1986). Helby et al. (1987) assigned a Sinemurian to Callovian (Early to Middle Jurassic) age to these zones. The lower age limit of the Plover Formation may be Pliensbachian, as the Hettangian to Pliensbachian *C. torosa* Zone is also present in the underlying Malita Formation. In the eastern part of the basin, palynological data from the Plover Formation are much sparser, especially in the older wells. Although most of the data suggest a similar age to that from the wells in the western half of the basin, Helby (*in* ARCO, 1978) identified the Tithonian (latest Jurassic) *Dingodinium jurassicum* Zone in this unit in Frigate 1. Similarly, the Callovian (Middle Jurassic) to Kimmeridgian (Late Jurassic) age assigned by Islam (1986) to the Plover Formation in Plover 1 and Tamar 1 is anomalous, as it is younger than other ages determined for the formation.

Depositional environment: The Plover Formation is a predominantly coarse-grained siliciclastic unit that contains minor marine indications and thin coals, indicating deposition under fluvial to coastal conditions. Most of the formation is probably deltaic in origin.

Ungrouped Mesozoic unit

Ashmore Volcanics

Definition: The Ashmore Volcanics ('Ashmore volcanic beds' of Craig, 1968) is a sequence of altered basalt flows and acid volcanics of presumed Late Jurassic age. The type section is the interval 2469 - 2787 m in Ashmore Reef 1. In the adjacent Browse Basin, similar volcanics are mostly Early Triassic in age.

Lithology: The Ashmore Volcanics consist of altered amygdaloidal basalt, olivine basalt flows, tuff, and interbedded claystone.

Stratigraphic relationships: The Ashmore Volcanics overlie undifferentiated Late Triassic Sahul Group, and are overlain in turn by the ?Darwin Formation. The unit may be laterally equivalent to the Late Jurassic sequence of volcanic tuff, sandstone, and shale in Mount Ashmore 1B. If so, a disconformable relationship with the underlying Sahul Group is implied.

Distribution and thickness: The Ashmore Volcanics are known only from Ashmore Reef 1, where they are 317 m thick.

Fossils and age: The Ashmore Volcanics are unfossiliferous. McDougal (*in* Craig, 1968) obtained K - Ar radiometric dates of 137 ± 3 Ma from core 18, and 129 ± 3 Ma from core 19 in this well. He suggested that there has been a greater leakage of radiogenic argon from core 19, as that core lies 169 m below core 18. Consequently, the older age from core 18 is regarded as the minimum age for the unit. Recalculating these dates using Steiger and Jager's (1977) decay constants adds about one million years to each determination, i.e. a minimum age of Middle Neocomian according to the time scale of Harland et al. (1982). The Tithonian age, as the overlying Darwin Formation has been dated Late Jurassic to Early Cretaceous (B.E. Balme *in* Craig, 1968).

The Ashmore Volcanics are probably Early to Middle Jurassic in age, as most volcanic activity in rift sequences occurs before breakup. Alternatively, the unit may be coeval with the Oxfordian to Kimmeridgian (Late Jurassic) volcanic tuffs and sedimentary rocks in Mount Ashmore 1B. This latter correlation is closer to the K - Ar dates from Ashmore Reef 1, and implies that the unit was extruded shortly after breakup.

Depositional environment: The depositional environment of the Ashmore Volcanics is difficult to determine given the lack of information on both the texture and the nature of flow contacts within the unit. The lack of a precise age for the unit also hinders determination of the environmental setting, as either a subaerial or submarine environment is possible, depending on whether a pre-breakup or post-breakup palaeogeographic setting is invoked.

Flamingo Group

The Flamingo Group is a sequence of Late Jurassic to Early Cretaceous sandstone and shale which unconformably to disconformably overlies the Troughton Group. Although the group is widespread, its lateral continuity between sub-basins is difficult to establish with the existing well control. The Flamingo Group includes all of the sedimentary sequence above the Callovian breakup unconformity and below the 'Valanginian unconformity'. Palynological and seismic evidence is often necessary to help distinguish the group, since it may be difficult to differentiate from the underlying unit on lithological evidence alone. On the Londonderry High (e.g. Flamingo 1), and in places in the Petrel Sub-basin (e.g. Frigate 1), the lower contact often consists of a sandstone overlying another sandstone. Previously, the group was included in the 'Petrel Formation' (ARCO, 1971b; Hughes, 1978).

The Flamingo Group includes rock units equivalent to the 'Petrel A and B' of ARCO (1971b), or 'Members A and B' of Hughes (1978). ARCO's informal units have only local lithologic and age significance within the Petrel Sub-basin; the names have been inappropriately applied to wells outside this sub-basin. The 'Petrel A and B' are renamed the Sandpiper Sandstone and Frigate Shale, respectively. A thick Oxfordian to Berriasian shale and basal sandstone unit in the Vulcan Sub-basin is named the Swan Formation. The thin Berriasian to Tithonian sandstone and shale sequence on the Londonderry High (referred to as the 'Flamingo Shale' plus 'Petrel A and B' by Osborne, 1979) comprises an unnamed unit within the Flamingo Group (Fig. 13). Similarly, the thin sandstone and shale sequence of the same age on the western side of the Ashmore Platform is regarded as undifferentiated Flamingo Group. In the Malita Graben, the group is known only in Heron 1, where 800 m of poorly dated shale and limestone underlies the Bathurst Island Group.

Frigate Shale

Definition: The name 'Frigate Shale' replaces the informal 'Member B' or 'Petrel B' of Hughes (1978). This unit is named after Frigate 1 and the type section is the interval 1571 - 1820 m in Petrel 1 (Hughes, 1978).

Lithology: The Frigate Shale consists largely of grey to green-grey shale and siltstone, with thin beds of fine-grained sandstone and sandy limestone. The finer grained sediments are micaceous, slightly glauconitic and pyritic, and locally contain shelly material. In Frigate 1, thick sandstone with minor amounts of shale conformably underlies glauconitic and micaceous shale. This coarse-grained interval is probably a marginal facies of the Frigate Shale.

Stratigraphic relationships: The Frigate Shale disconformably overlies the Plover Formation of the Troughton Group. It is coeval with the Swan Formation in the Vulcan Sub-basin (Fig. 13).

Distribution and thickness: The Frigate Shale is present throughout the Petrel Sub-basin, except south of Penguin 1. The unit has a maximum thickness of 250 m in Petrel 1 and thins towards the Londonderry High and Sahul Platform.

Fossils and age: Helby (1974a) determined an Oxfordian to Tithonian (Late Jurassic) age for the Frigate Shale.

Depositional environment: The presence of shelly material and glauconitic lithologies in this fine-grained unit indicates deposition in a low-energy marine-shelf environment.

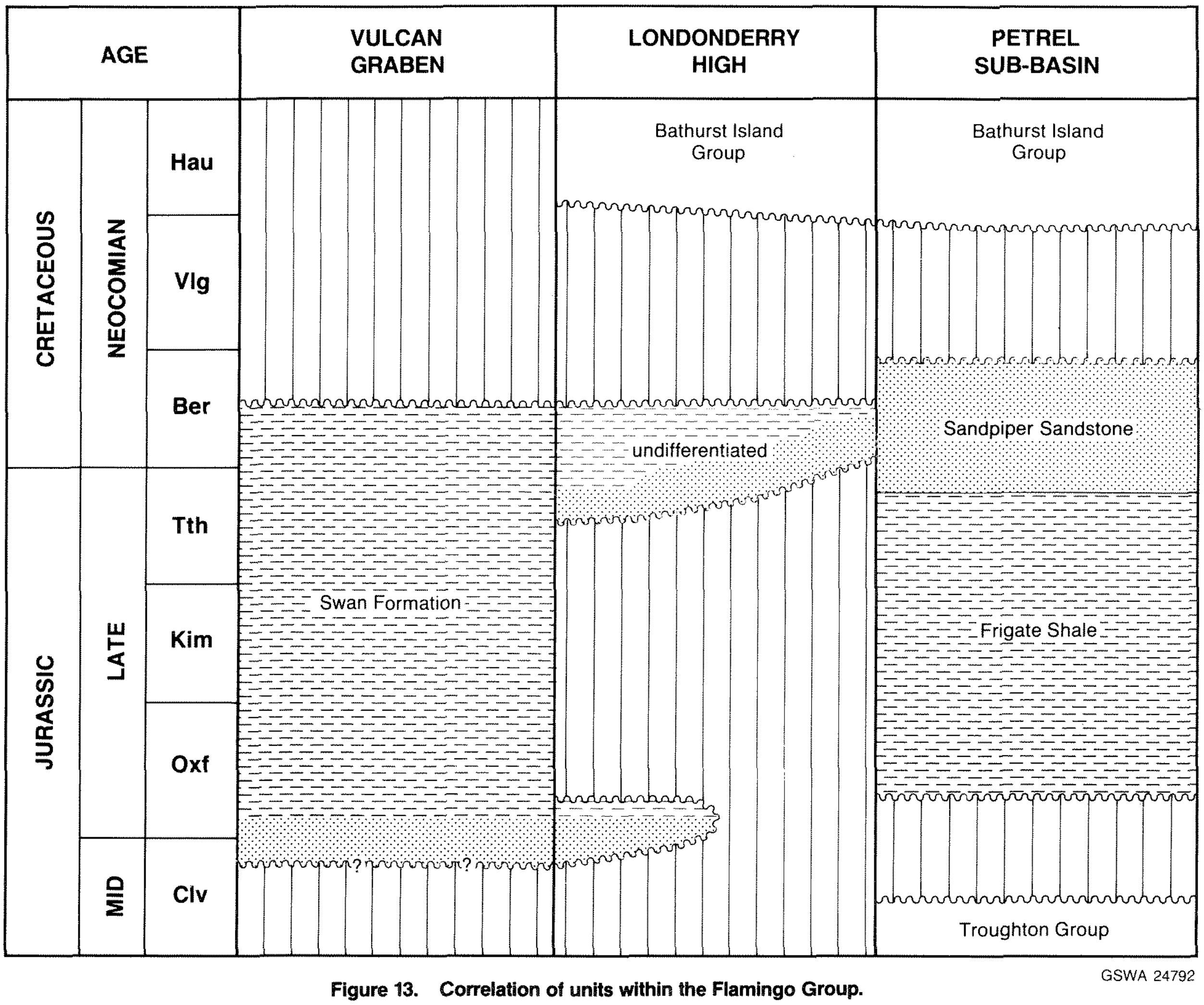


Figure 13. Correlation of units within the Flamingo Group.

Sandpiper Sandstone

Definition: The name 'Sandpiper Sandstone' replaces the informal 'Member C' or 'Petrel C' of Hughes (1978). The unit is named after Sandpiper 1; the type section is the interval 1329 - 1571 m in Petrel 1 (Hughes, 1978).

Lithology: The Sandpiper Sandstone is dominated by slightly glauconitic and pyritic sandstone, and lesser amounts of siltstone and mudstone.

Stratigraphic relationships: The Sandpiper Sandstone conformably overlies the Frigate Shale. The unit is coeval with the upper part of the Swan Formation in the Vulcan Graben, and with undifferentiated Flamingo Group on the Londonderry High.

Distribution and thickness: The Sandpiper Sandstone is present throughout the Petrel Sub-basin, north of 14° S. The maximum thickness is 270 m, in Gull 1, and it thins towards the Londonderry High and Sahul Platform.

Fossils and age: Palynological evidence suggests a Tithonian to Berriasian (latest Jurassic to earliest Cretaceous) age. Shelly material, including the bivalve *Inoceramus,* has been recognized in cuttings from this unit.

Depositional environment: Glauconitic lithologies and the marine microfauna in the Sandpiper Sandstone indicate deposition under marine conditions.

Swan Formation

Definition: The Swan Formation is a thick sequence of fine siliciclastic rocks which contain variable amounts of sandstone. The type section is the interval 2482 - 4064 m in Swan 2, and is the thickest observed section. The interval 2333 - 2721 m in East Swan 1 is selected as a reference section, because the type section does not penetrate the basal sandstone. This basal sandstone is referred to as the '*W. spectabilis* sand' by MacDaniel (1988) in the Jabiru wells.

Lithology: The Swan Formation consists predominantly of shale and siltstone, and variable amounts of sandstone. A distinct basal sandstone is frequently present.

Stratigraphic relationships: The contact between the Swan Formation and the underlying Plover Formation varies from disconformable to unconformable. The overlying Bathurst Island Group is disconformable on the Swan Formation. The Sandpiper Sandstone and Frigate Shale in the Petrel Sub-basin are coeval with the Swan Formation (Fig. 13).

Distribution and thickness: The Swan Formation is restricted to the Vulcan Sub-basin, where it ranges in thickness from 250 to more than 1500 m.

Fossils and age: The basal part of the Swan Formation contains dinoflagellates of the *Rigaudella aemula* and *Wanaea spectabilis* Zones of Helby et al. (1987), which

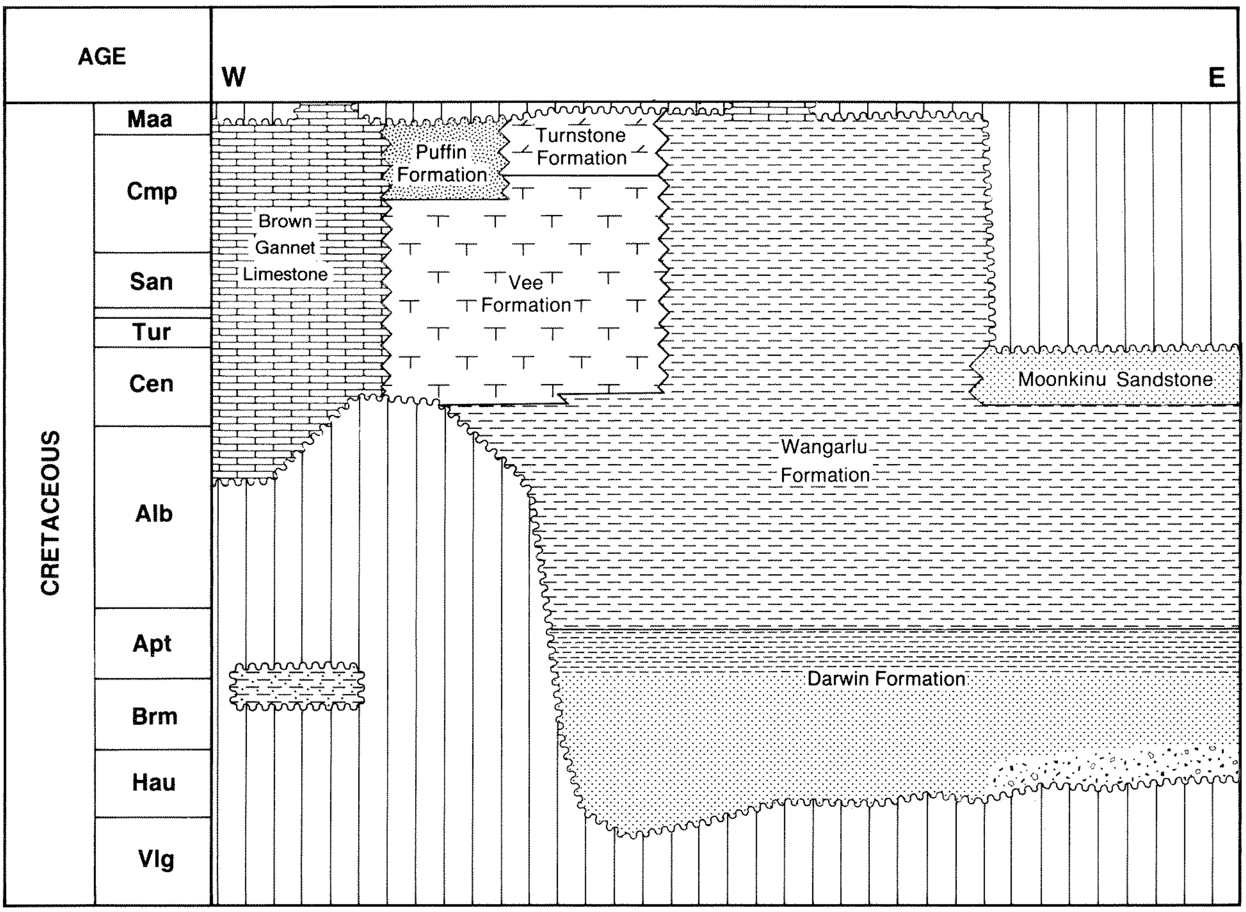


Figure 14. Correlation of units within the Bathurst Island Group.

indicate an Oxfordian to possibly Callovian (Middle to Late Jurassic) age. Helby (1974a) suggested an Oxfordian (Late Jurassic) to Berriasian (Early Cretaceous) age for the Swan Formation in Swan 1.

Depositional environment: The Swan Formation is a marine unit throughout, as it contains a diverse microflora that includes dinoflagellates and acritarchs. It was deposited in a rapidly subsiding trough, with little coarse terrigenous input.

Bathurst Island Group

The Bathurst Island Group (Bathurst Island Formation of Hughes and Senior, 1974; Hughes, 1978) is a lithologically variable group which consists of siltstone, mudstone, marl, limestone, and sandstone. It overlies the 'Valanginian unconformity', and is conformably or disconformably overlain by Cainozoic carbonate and clastic rocks.

Some of the members of the Bathurst Island Formation recognized by Hughes and Senior (1974) and Hughes (1978) in the Money Shoals Basin extend into the Bonaparte Basin and are here given formation status as the Darwin and Wangarlu Formations, and Moonkinu Sandstone (the 'Marligur Member' is not present in the Bonaparte Basin, and is not dealt with here). In the western part of the basin, four formations have been identified in the group: the Vee, Puffin, and Turnstone Formations, and the Brown Gannet Limestone. The first three units are restricted to the Londonderry High, Vulcan Sub-basin, and eastern Ashmore Platform. They are partly equivalent to the fourth unit, the Brown Gannet Limestone, which is present on the Ashmore Platform (Fig. 14).

The thickest sections of Bathurst Island Group are located in the Petrel Sub-basin and Malita Graben, where up to 2000 m (mostly Wangarlu Formation) is present. The group thins markedly to the west; on the Ashmore Platform, for example, it is 100 to 300 m thick.

Darwin Formation

Definition: The Darwin Formation ('Port Darwin Beds' of Jensen, 1914) is here named for the distinctive radiolarian shale, fine sandstone, and basal conglomerate which is exposed in the coastal cliffs in and around Darwin (Noakes, 1949). Subsequently, Hughes (1978) proposed the cliffs at Fannie Bay, Darwin, as the type section. Due to its distinctive gamma-ray signature, the unit is easily recognized in the subsurface, even when it is only 5 m thick. Although previously included in the 'Mullamen Group' by Noakes (1949) and 'Mullamen Beds' by Skwarko (1966), Hughes (1978) suggested that this name should be abandoned as it incorporated sediment from both the Darwin and 'Petrel' Formations.

Lithology: In the type section, the Darwin Formation consists of a basal conglomerate overlain by up to 8 m of fine sandstone, which is in turn overlain by up to 11 m of radiolarian shale (Skwarko, 1966). In the subsurface, the Darwin Formation consists of basal glauconitic claystone and greensand, overlain by radiolarian claystone to calcareous sandstone. The glauconite content of the basal sandstone in outcrop is masked by ferruginization. Near Darwin, the basal sandstone of the formation is estimated to contain up to 90% glauconite grains (Pietsch, 1983).

Stratigraphic relationships: In the type area, the Darwin Formation unconformably overlies Proterozoic basement, with an angular relationship. In most of the Bonaparte Basin, the unit lies above the 'Valanginian unconformity', and overlies the Flamingo Group either disconformably or unconformably. However, near the western margin of the basin it unconformably overlies the Sahul Group.

Distribution and thickness: The Darwin Formation is widely distributed across both the Bonaparte and Money Shoals Basins. It is 52 m thick in Flat Top 1 and in a bore near Gunn Point (Pietsch, 1985), but thins to the north and west. In the Bonaparte Basin the unit appears to be missing over much of the Ashmore Platform, but this may be due to thinning to the extent that it can not be detected easily on wireline logs.

Fossils and age: Palynological and foraminiferal assemblages generally indicate a Valanginian to Aptian (Early Cretaceous) age (Helby, 1974a; Burger *in* Hughes, 1978), although the unit occasionally extends into the Albian (Rexilius, 1987, 1988). In the type area, near Darwin, the only fossils present are readiolarians, which were first described by Hinde (1893), and belemnites; neither fossil group is useful for dating. Other invertebrate fossils present in the Darwin Formation include molluscs, brachiopods, echinoids, bryozoans, and corals. Of these, only the molluscs have been described (Skwarko, 1966).

Depositional environment: The fossil content of the Darwin Formation, and its presence on Proterozoic basement at Darwin, suggests a shallow-marine environment. The formation of glauconite requires a slow rate of deposition and some bottom currents (Hocking, Moors, and van de Graaff, 1988). The widespread distribution of the glauconitic, basal part of this unit indicates a period of low terrigenous influx into the marine-shelf environment, and subdued basin topography similar to the conditions Hocking, Voon, and Collins (1988) suggested for the Mardie Greensand in the Carnarvon Basin. Although radiolarites may be deposited in intertidal to abyssal depths (McBride and Folk, 1979), the stratigraphic position of the radiolarian-rich upper part of the unit indicates deposition in shallow waters. This part of the Darwin Formation may be correlated with, and has a similar origin to, the Windalia Radiolarite in the Carnarvon Basin (Hocking, Voon, and Collins, 1988).

Wangarlu Formation

Definition: The Wangarlu Formation ('Wangarlu Mudstone Member' of Hughes and Senior, 1974; Hughes, 1978) consists predominantly of fine-grained siliciclastic rocks and variable amounts of sandstone and carbonate. The type section is in the cliffs on the northwest side of Wangarlu Bay, Cobourg Peninsula (Hughes and Senior, 1974). In this section, only 14 m is exposed (Hughes, 1978). The interval 817 - 2848 m in Jacaranda 1 is selected as a reference section, because only part of the unit is represented in the type section.

Lithology: The dominant lithology of the Wangarlu Formation is micaceous mudstone. Variable amounts of glauconitic siltstone, sandstone, marl and limestone are also present. In outcrop, a marker horizon of carbonate and bioturbated siliciclastic rocks overlies the radiolarian-rich Darwin Formation. This marker, and overlying claystone, was included in the Darwin Formation by Pietsch and Sturt-Smith (1987); lithologically, it is better assigned to the Wangarlu Formation.

Stratigraphic relationships: The Wangarlu Formation conformably overlies the Darwin Formation and is conformably to disconformably overlain by the Hibernia Formation. In the west of the basin, the Wangarlu Formation passes laterally into the Vee and Turnstone Formations. In the Money Shoals Basin, it is conformably overlain by the Moonkinu Sandstone. In the Bonaparte Basin, the Wangarlu Formation is laterally equivalent to the Moonkinu Sandstone (Fig. 14).

Distribution and thickness: The Wangarlu Formation extends from the Money Shoals Basin, across the Bonaparte Basin as far west as the Londonderry High, where it is tentatively identified underlying the Vee Formation (Plate 3). It reaches a maximum thickness of over 2000 m in the Malita Graben. The Wangarlu Formation thins to the west, but part of this thinning is due to a facies change into carbonate rocks of the Vee and Turnstone Formations.

Fossils and age: In the type section of the Wangarlu Formation, only the Cenomanian part of the unit is present. In offshore well sections, however, the unit is Albian to Maastrichtian in age. Late Albian ammonites (Whitehouse, 1928; Henderson, 1990) and a backbone cast of the icthyosaurus *Platypterygius australis* (Mitchie *in* Pietsch and Sturt-Smith, 1987) have been found in the basal horizon of the Wangarlu Formation in the Darwin area.

Depositional environment: The Wangarlu Formation is a marine unit which contains neritic to bathyal, as well as reworked fluvial, microfaunas (Rexilius, 1987, 1988). Much of the shale in the formation is probably prodeltaic in origin, and the transgressive sands in the southwest of the basin may have been deposited in deltaic or shoreface environments.

Moonkinu Sandstone

Definition: The Moonkinu Sandstone ('Moonkinu Member' of Hughes and Senior, 1974; Hughes, 1978) is distinguished from the underlying Wangarlu Formation by the presence of fine sandstone with lesser amounts of siltstone and mudstone. The type section is in the cliffs adjacent to Moonkinu Beach on Bathurst Island (Hughes and Senior, 1974).

Lithology: In outcrop, the Moonkinu Sandstone consists of fine-grained, cross-bedded, grey to yellow sandstone, interbedded with lesser amounts of dark to light grey siltstone and mudstone.

Stratigraphic relationships: In the Money Shoals Basin and the eastern Bonaparte Basin, the Moonkinu Sandstone conformably overlies the Wangarlu Formation. It is coeval with part of the Wangarlu Formation to the west, and may interfinger with it.

Distribution and thickness: The Moonkinu Sandstone appears to be restricted to the part of the Darwin Shelf that lies in the Money Shoals Basin, but it may extend into the Bonaparte Basin. Due to the difficulty of distinguishing the Moonkinu Sandstone from other sands high in the Wangarlu Formation in the Bonaparte Basin, its distribution cannot be easily determined in that basin. The unit is up to 400 m thick in Tinganoo Bay 1 on the east of Melville Island.

Fossils and age: Macrofossils and palynoflora from outcrop and shallow bores indicate a Cenomanian age

(Henderson, in press; Burger *in* Hughes, 1978). By comparison, similar sands at the top of the Wangarlu Formation, west of the Darwin Shelf, range from Coniacian to Maastrichtian in age.

Depositional environment: Hughes (1978) suggested a shallow marine to deltaic environment of deposition for the 'Moonkinu Member'. However, the unit is restricted to Cenomanian siliciclastic rocks on the Darwin Shelf, and the sedimentary structures described by Hughes (1978) from the type section are here considered to indicate a shoreface environment.

Vee Formation

Definition: The Vee Formation is a predominantly carbonate unit and is named after Vee Shoal. The presence of fine-grained sedimentary rocks distinguishes the unit from the Brown Gannet Limestone. The type section is the interval 2254 - 2391 m in Skua 1 (Plate 3).

Lithology: The Vee Formation consists of interbedded marl, calcilutite, calcareous claystone, and limestone.

Stratigraphic relationships: The Vee Formation is conformable on shales of the ?Wangarlu Formation, and grades into the Brown Gannet Limestone to the west. It is coeval with part of the Wangarlu Formation to the east, although interfingering relationships are not known.

Distribution and thickness: The Vee Formation is generally confined to the area between the eastern Ashmore Platform and western Londonderry High, and it is up to 364 m thick. It is also present in Mount Ashmore 1B, south of the Ashmore Platform.

Fossils and age: Foraminiferal assemblages indicate an early Cenomanian to early Campanian (Late Cretaceous) age for the Vee Formation.

Depositional environment: Foraminifers in the Vee Formation indicate an outer neritic to upper bathyal environment (Rexilius, 1987).

Turnstone Formation

Definition: The Turnstone Formation consists largely of calcareous claystone. The type section is in Turnstone 1, between 925 and 1120 m (Plate 3).

Lithology: The Turnstone Formation consists of calcareous claystone with minor amounts of marl and argillaceous limestone.

Stratigraphic relationships: The Turnstone Formation is conformable on the Vee Formation and grades laterally into the Puffin Formation to the southwest. It is coeval with the upper part of the Wangarlu Formation to the east.

Distribution and thickness: The Turnstone Formation is confined to the western Londonderry High, where it reaches a maximum thickness of 198 m in the type section.

Fossils and age: Foraminiferal assemblages from the Turnstone Formation indicate a Campanian to Maastrichtian (Late Cretaceous) age.

Depositional environment: Foraminifers from the Turnstone Formation indicate an outer neritic to upper bathyal environments (Rexilius, 1987).

Puffin Formation

Definition: The Puffin Formation consists of lenticular sandstones interbedded with shale. The type section is in Grebe 1 between 2125 and 2630 m (Plate 3).

Lithology: The Puffin Formation consists of quartz sandstone, which contains traces of pyrite and glauconite, and interbedded mudstone, calcareous mudstone, and siltstone. Log correlations, especially between the Puffin wells, indicate that the sands are lenticular.

Stratigraphic relationships: The Puffin Formation is conformable on, but diachronous with, the Vee Formation; it grades laterally into the Brown Gannet Limestone to the west, and the Turnstone Formation to the northeast.

Distribution and thickness: The Puffin Formation is restricted to the eastern Ashmore Platform and Vulcan Sub-basin, and reaches a maximum thickness of 570 m in the Vulcan Sub-basin.

Fossils and age: Foraminiferal assemblages indicate a Campanian to Maastrichtian (Late Cretaceous) age for the Puffin Formation. Dinoflagellates from the type section include those from the *Samlandia carnarvonensis* to *Tectatodinium rugulatum* Zones, and indicate a late Campanian (Late Cretaceous) to possibly Danian (early Paleocene) age (McMinn, 1985, 1988). Fragments of the bivalve *Inoceramus* have been reported from the type section.

Depositional environment: Sands in the Puffin Formation are interbedded with shales deposited in a moderately deep shelf environment, and probably represent offshore bars or ridges.

Brown Gannet Limestone

Definition: The Brown Gannet Limestone consists of fossiliferous carbonate. The name replaces the informal 'Woodbine Beds' of Craig (1968), as that name has prior use in Victoria. The type section is between 1940 and 2167 m in Brown Gannet 1 (Plate 3).

Lithology: The Brown Gannet Limestone consists of interbedded limestone, marl, and minor amounts of calcareous shale.

Stratigraphic relationships: The Brown Gannet Limestone unconformably overlies the Sahul Group, except in Ashmore Reef 1 where it disconformably overlies the Darwin Formation. It interfingers with the Puffin, Vee, and Turnstone Formations to the east, and is coeval with the Wangarlu Formation.

Distribution and thickness: The Brown Gannet Limestone is present only on the Ashmore Platform; it thickens westwards from 83 m in Pollard 1, to 294 m in North Hibernia 1.

Fossils and age: Foraminiferal assemblages indicate an Albian to Maastrichtian (Early to Late Cretaceous) age for the Brown Gannet Limestone.

Depositional environment: The Brown Gannet Limestone was deposited as a carbonate shoal in the west of the basin; clastic input was minimal.

Ungrouped Cainozoic units

The Cainozoic sequence in the Bonaparte Basin incorporates one, or possibly two, major breaks (Fig. 15). These are an Oligocene disconformity and a possible Late Miocene to Early Pliocene disconformity. The sequence is carbonate dominated; dating relies entirely on foraminifers. Consequently, sections in which foraminifers are scarce are difficult to tie to those where they are abundant; as a rule, such sections are here excluded from formal units, but are mentioned as possible correlatives of such units.

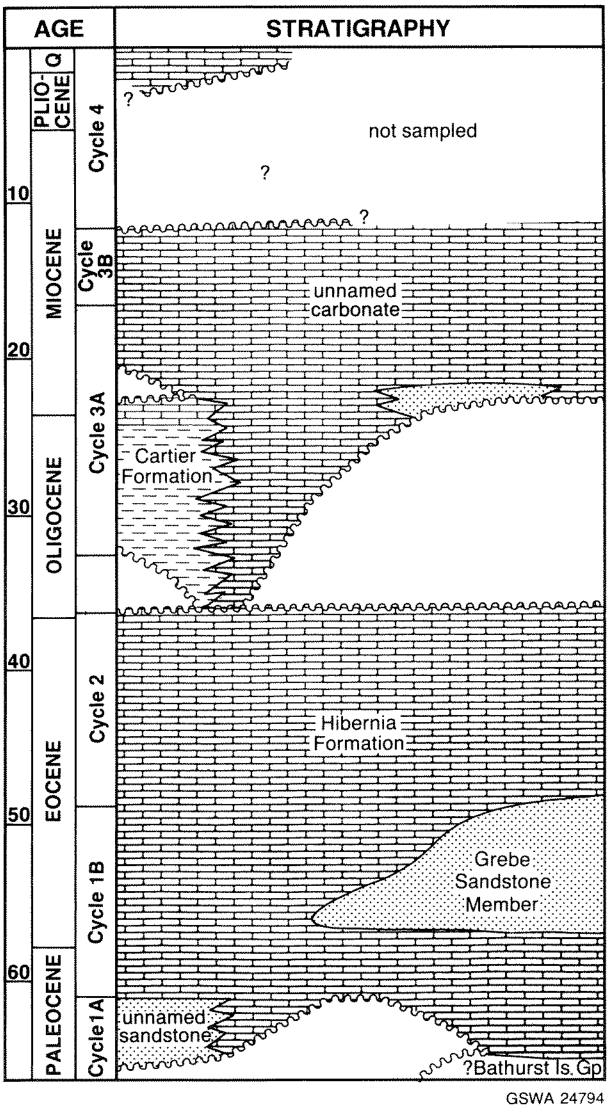


Figure 15. Correlation of Cainozoic units (after Apthorpe, 1988)

Unnamed sandstone

A Lower Paleocene sandstone is present in the west of the basin. It is poorly fossiliferous, and therefore has not been named.

Lithology: This unit consists largely of quartz sandstone with minor interbeds of mudstone.

Stratigraphic relationships: The sandstone sequence conformably to disconformably overlies the Bathurst Island Group in the west of the Bonaparte Basin, and interfingers with the basal part of the Hibernia Formation. The unit is probably equivalent, in part, to a sandstone unit in the Browse Basin of Senonian (Late Cretaceous) to Eocene age (Elliott, 1990).

Distribution and thickness: The sandstone is present in a few wells over the Londonderry High and Vulcan Sub-basin. It ranges in thickness from 20 to 147 m in the Bonaparte Basin, compared with a maximum of 1000 m in Caswell 1 in the Browse Basin

Fossils and age: In the Bonaparte Basin this sandstone unit is poorly fossiliferous, and contains rare foraminifers. The early Paleocene age has been derived largely from the age of the enclosing formations.

Depositional environment: The low numbers of foraminifers, and the interfingering relationship with the Hibernia Formation, indicate a marginal-marine environment. Apthorpe (1988) showed a coastal-complex environment for some of these sands in the Browse Basin.

Hibernia Formation

Definition: The Hibernia Formation ('Hibernia Beds' of Craig, 1968) consists of fossiliferous limestone, and minor amounts of shale, sandstone, and marl. An Eocene sandstone (Grebe Sandstone Member) is present in the middle of the formation and appears to separate two carbonate sequences with different log characteristics. However, the sandstone is absent over much of the Ashmore and Sahul Platforms; in those areas distinction of an upper and lower carbonate unit is not possible. The type section of the formation is the interval 1222 - 1994 m in Ashmore Reef 1.

Lithology: The Hibernia Formation is a predominantly carbonate unit, but in the eastern part of the basin, interbedded coarse-grained siliciclastic horizons are common. Carbonate rock types are mainly calcilutite and calcarenite, often recrystallized, and containing chert nodules in places. Minor amounts of calcareous shale, marl, and dolomite are also present. The siliciclastic horizons consist largely of quartz sandstone interbedded with some greensand and mudstone.

Stratigraphic relationships: The Hibernia Formation conformably to disconformably overlies the Bathurst Island Group. Along the southern margin of the Vulcan Sub-basin, and on the Londonderry High, the unit interfingers with an early Cainozoic unnamed sandstone.

Distribution and thickness: The Hibernia Formation has an extensive distribution in the northwest of the basin, where it passes to the south into the Browse Basin. The formation is commonly 400 to 1300 m thick; the thickest sections are along the Malita Graben and southern Sahul Platform, as well as the Vulcan Sub-basin and eastern Ashmore Platform.

Fossils and age: Foraminifera faunas indicate a Paleocene to Eocene age for the Hibernia Formation. Bivalves and bryozoans have also been recorded from the unit.

Depositional environment: Inner-shelf to slope environments are represented in the Hibernia Formation, and are well illustrated in a series of palaeogeographic maps by Apthorpe (1988).

Grebe Sandstone Member

Definition: The Grebe Sandstone Member is a predominatly arenaceous unit within the Hibernia Formation. The type section is in Grebe 1 over the interval 1541 - 1661 m (Plate 3).

Lithology: The Grebe Sandstone Member consists of quartz sandstone with minor amounts of marl and limestone.

Stratigraphic relationships: The Grebe Sandstone Member is conformable within the Hibernia Formation.

Distribution and thickness: The Grebe Sandstone Member extends from the eastern Ashmore Platform to the centre of the northern Petrel Sub-basin; it is up to 270 m thick.

Fossils and age: Based on the age of the enclosing Hibernia Formation, the Grebe Sandstone Member is late Paleocene to early Eocene in age.

Depositional environment: The Grebe Sandstone Member was probably deposited in a marginal-marine environment, as it is a poorly fossiliferous, and enclosed by marine carbonate. Apthorpe (1988) considered this sandstone to have been deposited in a shallow inner-shelf environment, and coeval sandstone to the southwest in a coastal-plain environment.

Cartier Formation

Definition: The Cartier Formation ('Cartier Beds' of Craig, 1968) consists of shale with minor units of marl and limestone. The type section is the interval 803 - 1222 m in Ashmore Reef 1. Carbonate of Aquitanian (earliest Miocene) age, which Craig (1968) excluded from the Cartier Formation, is here included.

Lithology: In the type section, the Cartier Formation consists of shale, which passes up into marl and calcilutite. A similar section is also present in North Hibernia 1.

Stratigraphic relationships: The Cartier Formation lies disconformably on the Hibernia Formation and is disconformably overlain by unnamed carbonates of Miocene age. It is coeval with unnamed carbonates which conformably overlie the Hibernia Formation in Brown Gannet 1. Other possibly coeval sections in the basin were shown by Apthorpe (1988, fig. 31).

Distribution and thickness: The Cartier Formation is restricted to Ashmore Reef 1 (419 m) and North Hibernia 1 (197 m) on the western part of the Ashmore Platform. Coeval sedimentary rocks are present in the outer part of the basin in Brown Gannet 1, Dillon Shoals 1, Flamingo 1, Sunrise 1, and Troubadour 1 (Apthorpe, 1988, figs 30 - 31).

Fossils and age: The Cartier Formation contains large numbers of Oligocene to Aquitanian (earliest Miocene) foraminifers.

Depositional environment: Apthorpe (1988, fig. 31) indicated that the Cartier Formation was deposited in a continental slope environment.

Unnamed carbonate

A carbonate-dominated sequence of Miocene age overlies the Hibernia or Cartier Formations. It is not given formal status, because the upper part of the sequence is poorly defined except in Ashmore Reef 1 and Dillon Shoals 1 where a Pliocene - Quaternary carbonate disconformably overlies the Miocene carbonate. The upper 200 to 300 m in most wells is unsampled; consequently, the presence or absence of a Pliocene - Quaternary sequence above the Miocene carbonate cannot be readily demonstrated.

Lithology: The unnamed carbonate unit consists predominantly of bioclastic calcarenite. Minor sandstone and peaty to lignitic organic horizons are also present.

Stratigraphic relationships: The carbonate sequence disconformably overlies the Hibernia or Cartier Formations. In Brown Gannet 1, however, the unit appears to be conformable on the underlying Hibernia Formation, and is, in part, equivalent to the Cartier Formation (Fig. 15).

Distribution and thickness: The unnamed carbonate is present in the north and northwest of the basin. It does not extend south of the Plover wells and Gull 1 in the Petrel Sub-basin. In general, the unit exceeds 400 m in thickness, but thinner intersections are found in the west of the Ashmore Platform and in the Petrel Sub-basin. The thickest intervals are along the western side of the Vulcan Sub-basin and adjoining eastern Ashmore Platform. A maximum thickness of 1024 m was intersected in Grebe 1.

Fossils and age: Foraminifers of Miocene age are present throughout the unnamed corbonate unit. In North Hibernia 1 and Brown Gannet 1, Oligocene faunas are also present. Bryozoans and corals are abundant.

Depositional environment: Lagoonal to inner-shelf environments are represented in the unnamed carbonate unit (Apthorpe, 1988). The distribution of these environments is similar to the present day, although the shelf is now somewhat narrower than it was in the Miocene.

Palaeogeography and basin evolution

Sedimentary rocks present in the offshore Bonaparte Basin probably range in age from Cambrian to Holocene; they can be grouped into ten major depositional sequences, each of which is differentiated by regional breaks in sedimentation and/or a significant change in the style of sedimentation. The ten sequences represent seven phases of basin evolution (Fig. 16):

(a) Cambrian to Ordovician interior sag;
(b) Silurian to Early Devonian ?trough infill;
(c) Late Devonian to Carboniferous northwest-trending
(d) Permo-Carboniferous interior sag;
(e) Latest Permian to Jurassic ?trough infill;
(f) Late Jurassic to earliest Cretaceous northeast-trending rifting, and continental breakup; and
(g) Cretaceous to Cainozoic trailing-edge marginal sag.

The ten major depositional sequences are each discussed below.

Cambrian to Ordovician

A Cambrian succession was identified from seismic data in the southern Petrel Sub-basin by Edgerley and Crist (1974). However, Lee and Gunn (1988) and Gunn (1988a,b) identified the same reflections as the Devonian Cockatoo and Langfield Groups. Confirmation of either interpretation is hindered by the lack of well intersections of the interval in question. While Lee and Gunn (1988) and Gunn (1988a,b) interpreted the overlying evaporitic sequence as part of the 'Lower Milligans Formation', there is no evidence of such evaporites from wells intersecting this or other Carboniferous units. Consequently, a Silurian - Devonian age is favoured for the evaporitic sequence. This suggests a Cambrian, or possibly Proterozoic, age for the underlying section. The difficulty in correlating these moderately strong seismic reflections with those known to represent Proterozoic sedimentary and volcanic rocks below the Plover Shelf (Fig. 5) suggests that a Cambrian age for the sequence below the evaporitic sequence is more likely.

The Cambrian sequence is well exposed onshore, where it consists of two stages of interior sag, both of which were part of a much larger depositional province than the present basin (Mory and Beere, 1988). The initial stage of subaerial volcanism in the Early Cambrian (Antrim Plateau Volcanics) extended across northern Australia and involved an estimated 100 000 km^3 of volcanic rocks. Veevers (1967) suggested that the withdrawal from the mantle of this magma may have initiated the crustal sag which formed the incipient Bonaparte Basin. Alternatively, such volcanism may represent zones of

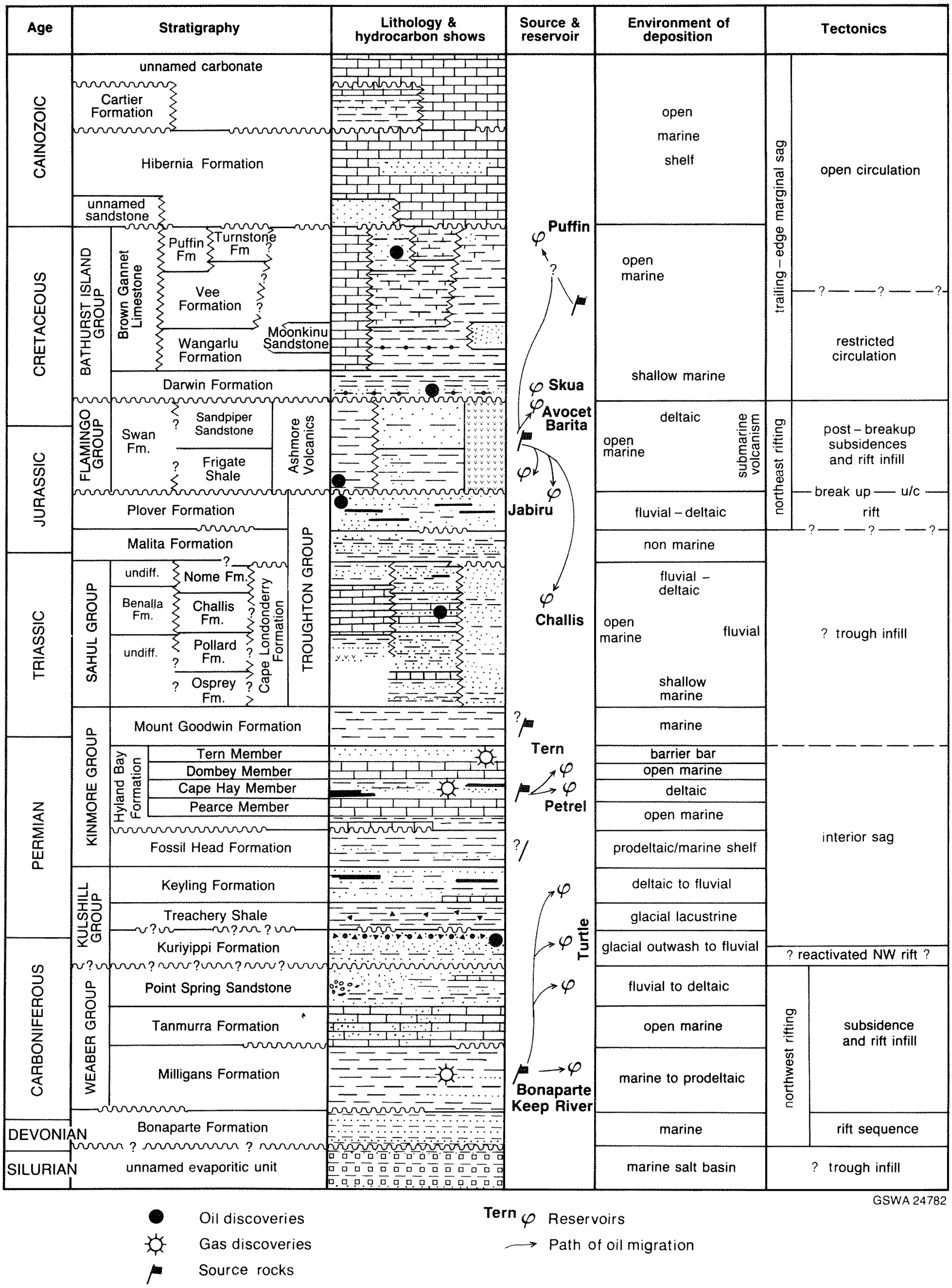


Figure 16. Summary of the Phanerozoic sequence of the offshore Bonaparte Basin.

incipient rifting without later continental separation, i.e. a failed arm (Rampino and Stothers, 1988; Veevers, 1988). This stage was followed by predominantly siliciclastic, shallow to marginal-marine deposition which continued into the Early Ordovician.

Silurian to Early Devonian

Little is known of the Silurian to Early Devonian evaporitic sequence. Its age is deduced from stratigraphic relationships observed largely on seismic data, and by analogy with similar sequences in the Carnarvon and Canning Basins.

The presence of evaporites implies that an incipient Petrel Sub-basin developed in the Silurian following ?Late Ordovician uplift of northwestern Australia. Mory and Dunn (1990) suggested that this period was one of rifting and referred to it as 'protorift' to indicate the speculative nature of the tectonic development of northern Australia at this time. The presence of numerous salt structures indicates that a substantial thickness of evaporites was deposited, and that the Petrel Sub-basin initially developed as a barred hypersaline basin or trough. Based on the distribution of salt structures in the southwest of the Petrel Sub-basin, Edgerley and Crist (1974) proposed that this part of the basin was separated from deeper, open-marine conditions to the north by a tilted fault block or terrace during deposition of the evaporitic sequence. The tilted fault block or terrace presumably formed a sill which trapped dense hypersaline water in the central parts of the Petrel Sub-basin (Figs 17, 18).

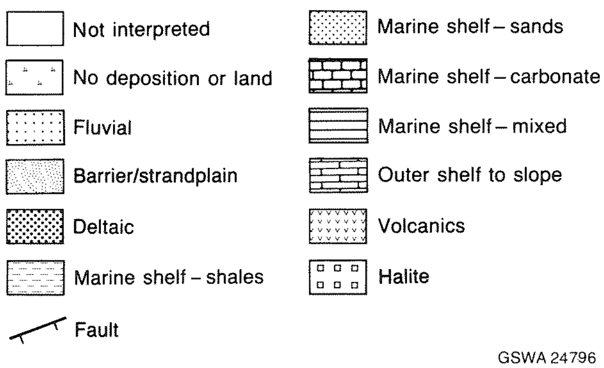


Figure 17. Reference for palaeogeographic maps (Figs 18 - 28).

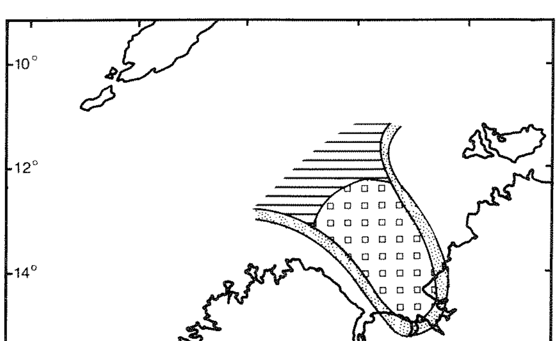


Figure 18. Silurian palaeogeography.

Late Devonian to Carboniferous

In the Late Devonian to Carboniferous, two stages of sedimentation are recognized, both associated with northwest-oriented rifting in the Petrel Sub-basin. In the first stage, Late Devonian to Tournaisian shallow-marine shales and thin sandstones of the Bonaparte Formation approximately equivalent to the 'Lower Milligans Formation' of Lee and Gunn (1988) were deposited. This sequence is up to 3000 m thick, as interpreted from seismic sections, and is equivalent to the continental to shallow-marine deposits in the onshore part of the basin. This onshore sequence was interpreted by Mory and Beere (1988) as a rift sequence in a north-northeast-trending failed arm of a northwest-oriented rift. Lee and Gunn (1988) and Gunn (1988a,b), however, inferred that magnetic mantle material is present in the northwest of the Petrel Sub-basin, and suggested that it was emplaced immediately following deposition of the shallow-marine sequence. Gravity modelling suggests that this material was emplaced in the late Proterozoic or early Phanerozoic (Appendix 2).

In the second stage, up to 3500 m of Visean to Westphalian clastic and some carbonate rocks (Weaber Group) were deposited in marine to fluvial environments as a deltaic basin-fill sequence. This sequence is equivalent to the 'subsidence and rift infill phase' of Brown et al. (1984) in the Canning Basin (Mory and Dunn, 1990).

The Bonaparte Formation consists of a siliciclastic sequence deposited largely by turbidity currents. Although evidence for pre-Famennian rocks is meagre, the unit has been correlated with the Frasnian Cockatoo Group, Famennian Ningbing Group, and Tournaisian Langfield Group in the onshore part of the basin. These three units were deposited in predominantly siliciclastic - continental, carbonate reef complex, and mixed shelf environments respectively.

The Weaber Group overlies the Bonaparte Formation with an angular unconformity on the basin margin, and is apparently conformable in the centre of the Petrel Sub-basin. It consists of a basal shale (Milligans Formation), a middle carbonate unit (Tanmurra Formation) and an upper sandstone and shale sequence (Point Spring Sandstone). The Milligans Formation consists of 200 m to more than 2000 m of offshore-to-basinal shale and minor submarine fan deposits. Rapid thickening of this unit, from the shelves into the Petrel Sub-basin, in the onshore part of the basin indicates an initially high rate of basin subsidence in the Visean. By the time the overlying Tanmurra Formation was deposited, the rate of subsidence and sediment input had declined markedly. Up to 465 m of carbonate were deposited offshore; this interval is coeval with the lower part of the Point Spring Sandstone onshore. Towards the centre of the Petrel Sub-basin a similar facies change from carbonate to siliciclastic lithologies is interpreted from the change in seismic character of the Tanmurra Formation. The Point Spring Sandstone is a deltaic unit that exhibits fluvial, shoreface, distributary-mouth, and crevasse environments in the onshore sections (Mory and Beere, 1988). Offshore, the unit contains thick shales which probably represent prodeltaic to distal distributary deposits.

Lee and Gunn (1988) have interpreted gravity and magnetic data as indicating the presence of normal oceanic basalts in the centre of the Petrel Sub-basin, northwest of the

Petrel structure. They have suggested that these basalts were emplaced at the end of deposition of the Milligans Formation. The presence of such basalts is speculative; gravity modelling indicates that their presence is unlikely (Appendix 2). Confirmation of the presence or absence of these basalts is hindered by the depth to Carboniferous rocks in this area, and the poor quality of regional magnetic data in the basin.

Latest Carboniferous to Permian

Upper Carboniferous to Permian deposits can be divided into a stratigraphically lower, coarse siliciclastic phase, and an upper, mostly fine siliciclastic phase. In the earlier phase (Kulshill Group), the input of coarse-grained siliciclastic sediments was initiated by Late Carboniferous fault movements in the hinterland, and was sustained by Permo-Carboniferous glaciation. The later phase (lower Kinmore Group) reflects generally stable conditions in the hinterland. The two phases of deposition are, for the most part, best known in the southern half of the basin where the palaeoslope was presumably towards the northwest (Figs 19 to 21). The basal non-glacial part of the Kulshill Group is restricted to the northwesterly oriented Petrel Sub-basin, and may have been deposited during a brief reactivation of rifting along that sub-basin. The widespread distribution of the overlying Lower Permian glacial sequence, beyond the central part of the Petrel Sub-basin, suggests that the episode of ?reactivated rifting was followed by simple interior sag.

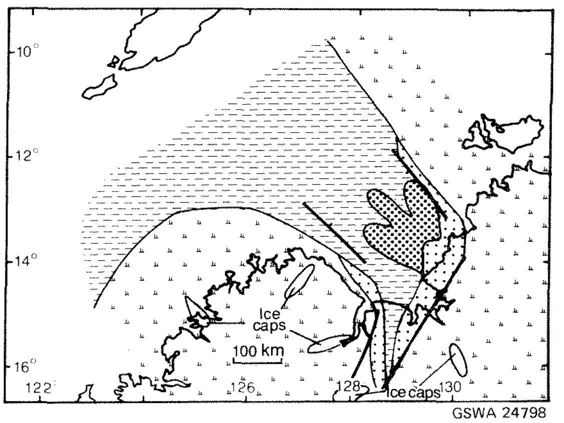


Figure 19. Latest Carboniferous to Early Permian palaeogeography.

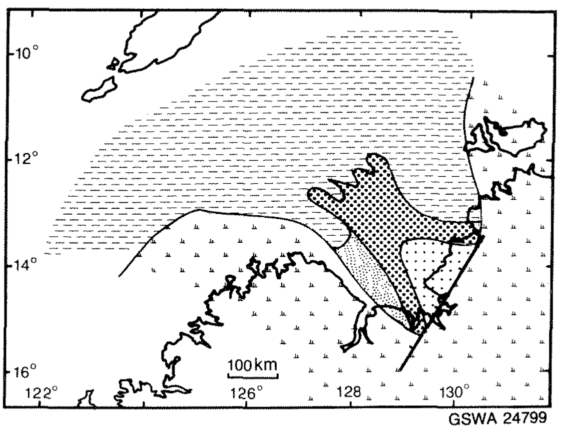


Figure 20. Late Permian (Kungurian to Kazanian) palaeogeography.

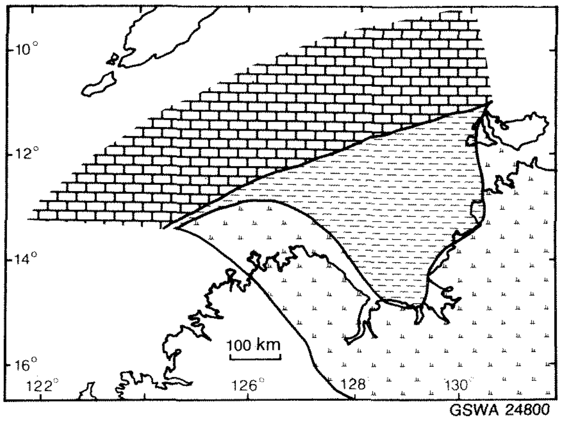


Figure 21. Late Permian (Tatarian) palaeogeography.

Upper Carboniferous to Lower Permian deposition is notable for the large input of fluvio-glacial, coarse siliciclastic sediment (Kulshill Group). After an initial pulse of fluvial, upward-fining cycles, probably as a response to tectonic movements in the hinterland, a glacial sequence was deposited over the Petrel Sub-basin (Kuriyippi Formation). Ice probably covered large parts of the Kimberley and Sturt Blocks. As it retreated, lacustrine or estuarine shale of glacial-outwash origin was deposited with tillite (Treachery Shale). This was followed by the deposition of thin, lenticular carbonates near the base of the overlying Keyling Formation as water temperatures rose and carbonate solubility decreased (Revelle and Fairbridge, 1957). The subsequent thick, fluvio-deltaic, siliciclastic sequence that forms the remainder of the Keyling Formation was deposited as a result of isostatic rebound of the hinterland. The depocentre of this predominantly glacial sequence is near the Petrel Field where a thickness of up to 7000 m is identified on seismic sections (Lee and Gunn, 1988). By comparison, the greatest thickness of the group that can be identified in well sections along the southern margin of the basin is less than 1800 m.

Artinskian to Kazanian sedimentation consisted of a regressive - transgressive cycle: prodeltaic and open-marine shales (Fossil Head Formation) were succeeded by marine and deltaic clastics and some carbonates, and then by a return to marine conditions (Hyland Bay Formation).

Palynological evidence suggests the base of the Fossil Head Formation to be diachronous. It is up to 590 m thick and, in the southern Petrel Sub-basin, its upper part has been eroded. This formation, and the succeeding basal shale and carbonate of the Hyland Bay Formation, were deposited in open-shelf conditions.

The medial deltaic clastic sediments (Cape Hay Member) of the Hyland Bay Formation were deposited in two coarsening-up cycles. They form the reservoir section in the Petrel gasfield (Bhatia et al., 1984; Lee and Gunn, 1988). Up to 30 m of carbonates separate this dominantly sandstone section from an overlying barrier-bar, clastic unit (Tern Member) which is the reservoir unit in the Tern gasfield.

To the northwest, marine shales at the base of the Hyland Bay Formation are coeval with the predominantly coarse siliciclastic sections in the southeast of the basin (Figs 20 and 21). Fossiliferous carbonate and shale dominates the upper part of the Hyland Bay Formation in the northwest of the basin. The carbonate appears to be coeval with similar limestone in Timor (Playford et al., 1975). The broad carbonate platform of Late Permian age along the northern margin of the continental block (MacDaniel, 1988) presumably developed as the supply of coarse siliciclastic sediments declined in the Tatarian (Fig. 21).

Latest Permian to Middle Jurassic

The regressive phase that followed deposition of the Permo-Carboniferous sequence coincides with the end of the phase of Palaeozoic northwest-oriented tectonic activity. Initially, new depocentres were established in the northwest of the basin in the Triassic and, in the Middle Jurassic, northeast-trending structural elements were superimposed on the older northwest-oriented structures. Whereas the coeval sequence in the Carnarvon Basin may be divided into 'pre-rift' and 'rift infill' components, separated by a Pliensbachian (Early Jurassic) 'rift-onset' unconformity (Parry and Smith, 1988), the difficulty of recognizing the Pliensbachian break in the basins to the north, including the Bonaparte Basin, means that these two phases cannot be differentiated easily. Consequently, Mory (1988, 1990) referred to the entire latest Permian to Middle Jurassic succession of the Bonaparte Basin as a 'rift sequence'. By comparison, MacDaniel (1988) recognized a Sinemurian - Pliensbachian (Early Jurassic) break which coincides with flexure along the southern margin of the Vulcan Sub-basin. MacDaniel (1988) also claimed that Lower to Middle Jurassic sediments above this break were deposited in sag basins that largely overlay the major Triassic troughs.

Uppermost Permian to Lower Jurassic deposition commenced with marine siltstones and shales of the Mount Goodwin Formation. This formation has a maximum thickness of 670 m on the Londonderry High, and a comparable thickness (up to 565 m) is present in the central Petrel Sub-basin. The thickness of this formation is unknown to the west of the Londonderry High.

In the southeast of the Petrel Sub-basin, the succeeding siliciclastic Triassic sequence was deposited in a non-marine environment (Troughton Group). Further northwest, a coeval, mixed clastic - carbonate sequence with minor amounts of coal and volcanics (Sahul Group) was deposited in shallow-marine to fluviodeltaic environments (Fig. 22). Although the Sahul Group is over 2000 m thick, the coeval Cape Londonderry Formation (at the base of the Troughton Group) is less than 500 m thick. This thickening suggests that new depocentres formed beyond the Londonderry High during the Triassic (MacDaniel, 1988).

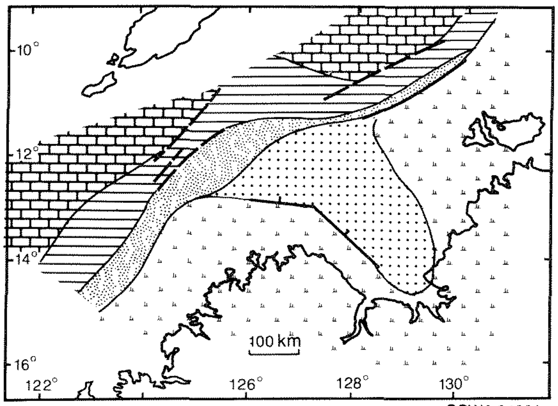


Figure 22. Middle Triassic palaeogeography.

The Sahul Group is present across the Londonderry High to the eastern Ashmore Platform. It is generally a siliciclastic unit with interbedded carbonate, and was deposited in marine-shelf to deltaic environments. Reservoir units in the Challis Field were deposited as estuarine channel sands within the intertidal to marine Challis Formation. On the western Ashmore Platform, thick fossiliferous shelf limestones of the Benalla Formation are partly equivalent to the Challis Formation.

The Late Triassic marine regression culminated with a Carnian to Pliensbachian (Late Triassic to Early Jurassic) redbed sequence (Malita Formation), which is almost 400 m thick in the central Petrel Sub-basin. Redbed deposition extended to at least the western edge of the Londonderry High; this unit has not been identified further west.

In the Early Jurassic, 200 to 672 m of predominantly fluvio-deltaic siliciclastic sediments (Plover Formation) were deposited across the basin (Fig. 23). Callovian to Tithonian (Middle to Late Jurassic) erosion has removed this sequence from most of the central and eastern Londonderry High, and may explain its apparent absence on the Ashmore Platform.

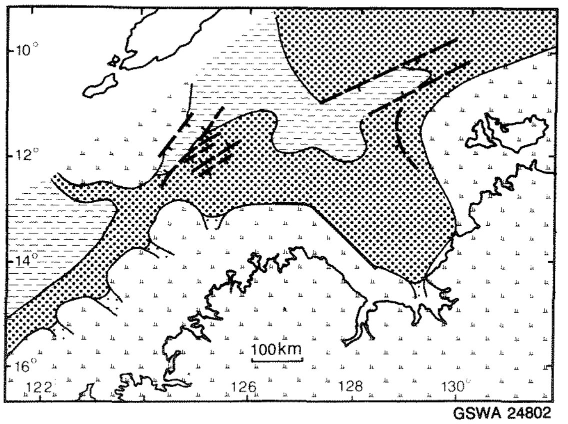


Figure 23. Early to Middle Jurassic palaeogeography.

Pre-Oxfordian (Middle Jurassic) uplift, associated with the North West Shelf 'breakup' is responsible for the major northeast-oriented structural elements in the northwest Bonaparte Basin. Triassic faulting and flexuring along the edge of the Early Triassic depocentre may have been reactivated, masking earlier activity. Erosion associated with this uplift removed at least the top of the Plover Formation and much of the underlying units on the Ashmore and Sahul Platforms and the Londonderry High.

Late Jurassic to earliest Cretaceous

This sequence (Flamingo Group and Ashmore Volcanics) onlaps the breakup unconformity surface; sedimentation recommenced first in the deep parts of the Vulcan Sub-basin. Sea-floor spreading to the west of the Ashmore Platform began in the Callovian (Veevers, 1984); the volcanics in Ashmore Reef 1 and Mount Ashmore 1B probably represent the southeastern limit of related volcanism.

The Flamingo Group is present in the Vulcan and Petrel Sub-basins, the Malita Graben, and on the western Ashmore Platform and Londonderry High. It is undifferentiated over the basement highs, where it shows considerable variation in lithology, and is generally less than 50 m thick. By comparison, at least 1500 m of shale with a thin basal sandstone (Swan

Formation) is present in the Vulcan Sub-basin. About 500 m of sandstone (Sandpiper Sandstone) and shale (Frigate Shale) in the Petrel Sub-basin, and almost 800 m of shale (in Heron 1) in the Malita Graben, was deposited at this time. The Flamingo Group overlies the Plover Formation, and has been dated as early Oxfordian to Berriasian (Late Jurassic to earliest Cretaceous). The Oxfordian age indicates that sedimentation recommenced immediately after breakup.

On the Londonderry High, by comparison, the oldest rocks in the Flamingo Group are Tithonian (latest Jurassic). This suggests that this region was emergent, or an area of non-deposition, for most of the Late Jurassic. Deposition immediately following breakup was confined to the Vulcan and Petrel Sub-basins, and possibly the Malita Graben to the northeast. By the Tithonian and Berriasian, siliciclastic sedimentation extended over most of the basin (Fig. 24).

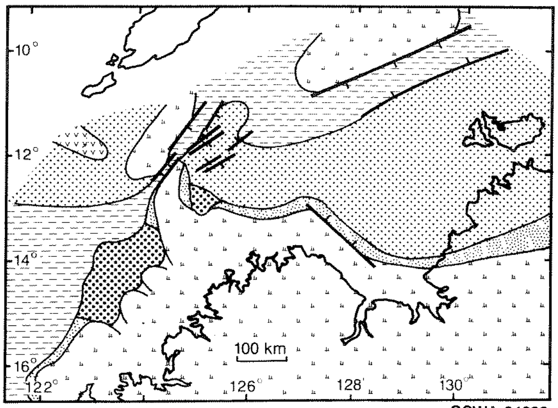


Figure 24. Latest Jurassic to earliest Cretaceous palaeogeography.

The regional Valanginian unconformity within the post-breakup sequence occurs as a small hiatus in the Vulcan Sub-basin. However, considerable erosion took place over elevated areas such as the Londonderry High and Ashmore Platform. This break is probably due to a relative fall in sea-level and has been related to a change in the sea-floor spreading centre (MacDaniel, 1988).

Cretaceous

The Bathurst Island Group makes up the bulk of the post-breakup stage Cretaceous rocks in the Petrel Sub-basin and Malita Graben, and it reaches a thickness of 2000 m. To the west, this sequence thins to less than 500 m.

A condensed Valanginian to earliest Aptian unit of greensand, with glauconitic and radiolarian-bearing claystone (Darwin Formation) was deposited across the basin above the Valanginian unconformity. The formation is up to 52 m thick, and indicates a much reduced sediment supply and subdued basin topography. The western Ashmore Platform was probably emergent, or an area of non-deposition, from this time until the late Albian. In the Carnarvon Basin, greensands (Mardie Greensand and Birdrong Sandstone), coeval with the lower part of the Darwin Formation, were deposited in a marine-shelf setting (Hocking, Voon and Collins, 1988). In the Officer and southern Canning Basins, radiolarite, equivalent to the upper part of the Darwin Formation, was deposited in an epicontinental sea. This unit (Bejah Claystone) was deposited during a period of high sea-level in which little land was available to supply detritus (Jackson and van de Graaff, 1981).

The succeeding micaceous siltstone (Wangarlu Formation) was deposited from the early Albian to the Maastrichtian (latest Cretaceous) in the Petrel Sub-basin. During the Albian, marine siltstones and claystones were deposited on the Sturt Block to the east, and extend across the basin to the western side of the Ashmore Platform. By the end of the Albian, a carbonate marine shelf was established over the western Ashmore Platform. To the east, uplift of the Sturt Block was the most likely cause of the deposition of shoreline sands on the Darwin Shelf. These sands, of probable Cenomanian age, mark the top of the Cretaceous sequence over this sub-basin; mid-Cainozoic erosion has probably removed the remainder of the Cretaceous from the Darwin Shelf.

Over most of the North West Shelf, an abrupt change from siliceous- to calcareous-pelagic deposition occurred during the Santonian. This change to carbonate lithology has been related to increased oceanic circulation, as a wide ocean developed after breakup (Exon and Willcox, 1980). In the Petrel Sub-basin and Malita Graben, however, a large input of fine-grained siliciclastic sediments resulted in clastic sedimentation (Wangarlu Formation) for the remainder of the Cretaceous; over 2000 m of Wangarlu Formation was deposited in the Malita Graben. These sediments were probably derived from an extensive land surface south of the basin (Tennant Creek Surface of Hays, 1967).

Deposition of lenticular sandstone units across the Vulcan Sub-basin and eastern Ashmore Platform (Puffin Formation) occurred in the Campanian and Maastrichtian. These sands appear to have been derived from the eastern margin of the Browse Basin; they were deposited on a moderately deep shelf and may represent subtidal channels. Coeval sands in the eastern Petrel Sub-basin, however, were deposited in shallow water as shoreline deposits (Fig. 25).

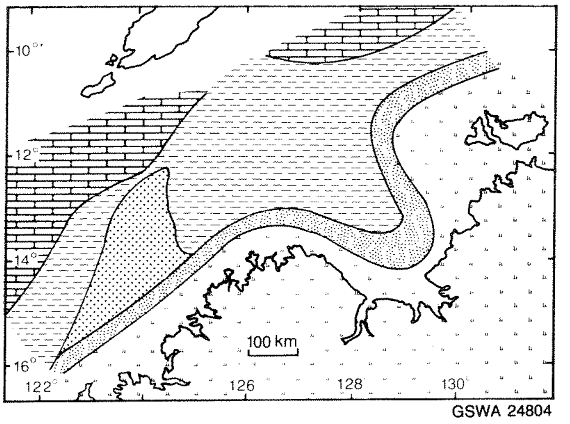


Figure 25. Late Cretaceous palaeogeography.

Paleocene to Eocene

After development of the Tennant Creek Surface (Hays, 1967) south of the Bonaparte Basin, shelf carbonates (Hibernia Formation) prograded across the basin. These carbonates and interbedded sandstones reach a maximum thickness of almost 1300 m in the Vulcan Sub-basin and on the eastern margin of the Ashmore Platform. The sequence thins rapidly to the southeast, to less than 200 m at Osprey 1.

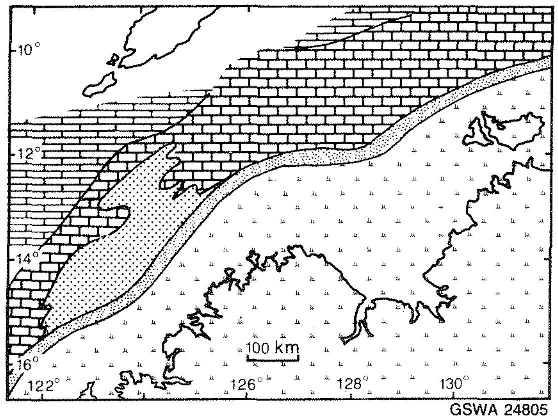


Figure 26. Paleocene to Eocene palaeogeography.

This thinning probably reflects the combined effect of Oligocene erosion, as well as Paleocene to Eocene shelf progradation to the northwest. The northwestern 'Palaeozoic' trend in the Petrel Sub-basin ceased influencing the structural style of the basin during the Paleocene to Eocene (Fig. 26).

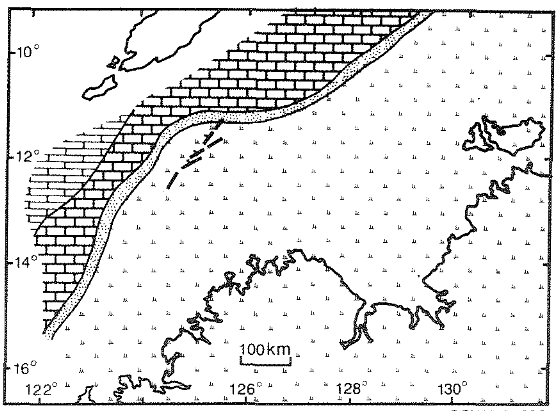


Figure 27. Oligocene palaeogeography.

Oligocene

The Oligocene was a period of marine regression in which sedimentation was restricted to the outer parts of the Ashmore and Sahul Platforms (Cartier Formation — Fig. 27). Exon and Willcox (1980) suggested that the lack of Oligocene rocks over most of the North West Shelf was due to strong circumpolar current activity after the final separation of Australia and Antarctica. This is an unlikely explanation for the Bonaparte Basin, given its distance from the southern margin. The development of the Wave Hill Surface (Hays, 1967) over much of the Sturt Block at this time suggests that the break may have been tectonically controlled, possibly related to rifting north of Timor.

Miocene to Holocene

In the Miocene, shelf carbonates were re-established across the basin. Reefs developed on the outer Ashmore and Sahul Platforms (e.g. Ashmore and Troubadour Reefs) from middle Miocene to Holocene times (Fig. 28). These carbonates are 400 to 1000 m thick on the Ashmore Platform. Thin siliciclastic rocks, which disconformably overlie the Palaeozoic and Mesozoic sequence in the Petrel Sub-basin, probably represent fluvial or shoreline deposition, coeval with the carbonates further offshore.

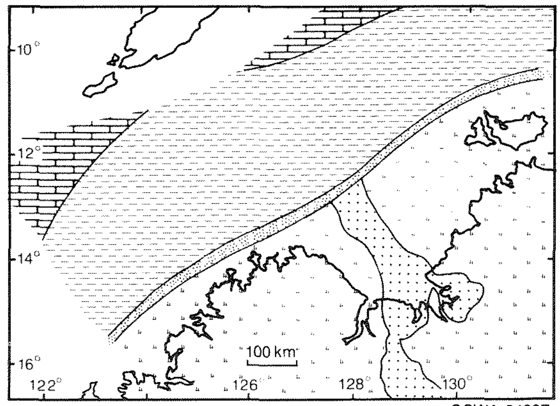


Figure 28. Miocene palaeogeography.

Rapid convergence of Timor and Australia commenced in the Late Miocene to Pliocene, and culminated in continent - arc collision in the Pliocene. This event uplifted the outer part of the Bonaparte Basin, superimposed a set of faults subparallel to the Timor Trough, and reactivated older faults in the northwestern part of the Bonaparte Basin (Veevers, 1984; Woods, 1988).

Petroleum occurrences

The first significant hydrocarbon discovery in the offshore Bonaparte Basin was in 1969 when ARCO's Petrel 1 struck gas and blew out. The largest measured flow from this structure was in Aquitaine's Petrel 3, which flowed at up to 2 043 900 m^3 of gas per day. By comparison, nearby Tern 1 flowed at up to 1 384 300 m^3 of gas per day. The two fields have recoverable reserves of approximately 85 x 10^9 and 15 x 10^9 m^3, respectively. Other gas discoveries in the east of the basin — Troubadour 1 and Sunrise 1, both of which were drilled by BOCAL/Woodside in 1974 - 5 on the Sahul Platform — were smaller. Troubadour 1 flowed 279 000 m^3 of gas and 38.8 kL of condensate per day. Recent gas discoveries are associated with the oil finds in Oliver 1 and Skua 4, both of which were drilled in 1988 by BHP in the west of the basin.

In 1972 ARCO made the first significant oil discovery in the basin. Puffin 2 flowed oil at up to 730 kL per day; but this flow rate was not sustained. All subsequent oil discoveries have been made by BHP in the Territory of Ashmore and Cartier Islands, in the west of the basin. The first was Jabiru 1A (1983), which recorded a maximum unstabilized flow of 1190 kL of oil per day. Production from the field commenced in 1986 at 2100 kL per day from Jabiru 1A, and increased to approximately 4770 kL per day after Jabiru 5A was drilled. To date, seven wells have been drilled in this field. Recoverable reserves are estimated at 7.6 x 10^6 kL. Other BHP discoveries include the Challis field, which has recoverable reserves of oil estimated at 3.5 x 10^6 kL; Skua 3, which flowed at up to 810 kL per day in 1987; and Cassini 1, Oliver 1, Montara 1, and Skua 4 in 1988. These latter four wells have all been suspended. Production from Challis commenced in 1989. Northeastern Challis and Cassini wells have been tied into the Challis field, raising production to 6360 kL per day.

The waters north of 12° S and from 126° E to 129° E have been the subject of a border dispute with Indonesia. In this area the 'Kelp' structure, delineated by Woodside in 1969 - 70, remains undrilled.

Stratigraphic distribution of petroleum

The stratigraphic distribution of petroleum in the Bonaparte Basin provides some insight to the juxtaposition of source and reservoir rocks. However, structural controls have probably been more important in determining the location of the known petroleum fields; this is largely a consequence of exploration having concentrated on structural plays to date.

The distribution of significant source and reservoir rocks is shown in Figure 16, along with the most significant shows in the basin. Units such as the Milligans Formation, known principally from onshore sections, and the Swan Formation contain sandstone reservoirs with petroleum shows sourced from shales within the reservoir unit. However, such a proximity of reservoir and source is uncommon in the basin. Faults such as those along the margin of the Vulcan Sub-basin are important in providing migration paths for hydrocarbons, and juxtaposing source rocks with otherwise isolated reservoirs.

Potential petroleum source rocks are fine-grained siliciclastic rocks that contain organic material. A summary of the distribution of such source rocks for the Permian to Cainozoic sequence of the basin was given by Kraus and Parker (1979). Lavering and Ozimic (1988, 1989) summarized the distribution of petroleum in the basin. All the recent hydrocarbon discoveries in the basin are located in permits in the Territory of Ashmore and Cartier Islands. Although these discoveries are in wells in which the reservoirs range in age from Triassic to Cretaceous, the most likely source for these hydrocarbons is the Late Jurassic Swan Formation (MacDaniel, 1988; Wormald, 1988; Baird and Philip, 1988). In the southeast of the basin, the Petrel and Tern gasfields are probably sourced from shale within the Hyland Bay Formation (Laws and Brown, 1976). Jefferies (1988) suggested that oil shows in Turtle 1 were sourced from either the Milligans Formation, or the Bonaparte Formation; these flank and underlie the Turtle structure.

References

ANFILOFF, V., 1988, Polycyclic rifting an interpretation of gravity and magnetics, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 10 - 12 August 1988, p. 443 - 455.

APTHORPE, M., 1988, Cainozoic depositional history of the North West Shelf, *in* The North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 10 - 12 August 1988, p. 55 - 84.

ARCO, 1969a, Lacrosse No. 1 well completion report: ARCO Ltd (unpublished).

ARCO, 1969b, Petrel No. 1 well completion report: ARCO Ltd (unpublished).

ARCO, 1971a, Petrel No. 1A well completion report: ARCO Ltd (unpublished).

ARCO, 1971b, Petrel No. 2 well completion report: ARCO Ltd (unpublished).

ARCO, 1972a, Osprey No. 1 well completion report: ARCO Ltd (unpublished).

ARCO, 1972b, Puffin No. 1 well completion report: ARCO Ltd (unpublished).

ARCO, 1972c, Pelican Island No. 1 well completion report: ARCO Ltd (unpublished).

ARCO, 1975, Skua 1 well completion report: ARCO Ltd (unpublished).

ARCO, 1978, Frigate No. 1 well completion report: ARCO Ltd (unpublished).

BAIRD, R. A., and PHILIP, R. P., 1988, Hydrocarbon potential of the Upper Jurassic/Lower Cretaceous of the Australian NW Shelf: Journal of Petroleum Geology, v. 11(2), p. 125 - 140.

BARNES, G., and LEE, R. J., 1984, Skull No. 1 well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

BEERE, G. M., and MORY, A. J., 1986, Revised stratigraphic nomenclature for the onshore Bonaparte and Ord Basins, Western Australia; Western Australian Geological Survey, Record 1986/5.

BHATIA, M. R., THOMAS, M., and BOIRIE, J. M., 1984, Depositional framework and diagenesis of the late Permian gas reservoirs of the Bonaparte Basin: The APEA Journal, v. 24(1), p. 299 -313.

BHP, 1984a, Jabiru 1A well completion report: BHP Petroleum Pty Ltd (unpublished).

BHP, 1984b, Eclipse 1 well completion report: BHP Petroleum Pty Ltd (unpublished).

BHP, 1984c, Jabiru 2 well completion report: BHP Petroleum Pty Ltd unpublished).

BHP, 1984d, Jabiru 3 well completion report: BHP Petroleum Pty Ltd (unpublished).

BHP, 1986, Skua 2 well completion report: BHP Petroleum Pty Ltd (unpublished).

BOUTAKOFF, N., 1963, Geology of the offshore areas of North-Western Australia: APEA Journal, p. 10 - 18.

BRADSHAW, M. T., YEATES, A. N., BEYNON, R. M., BRAKEL, A. T., LANGFORD, P. R., TOTTERDELL, J. M., and YEUNG, M., 1988, Palaeogeographic evolution of the North West Shelf Region, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 10 -12 August 1988, p. 29 - 54.

BRADY, T. J., JAUNCEY, W., and STEIN, C., 1966, The geology of the Bonaparte Gulf Basin: APEA Journal, p. 7 - 11.

BRANSON, J. C., 1978, Evolution of sedimentary basins from Mesozoic times in Australia's continental slope and shelf: Tectonophysics, v. 48, p. 389 - 412.

BROWN, C. M., 1980, Bonaparte Gulf Basin, *in* ESCAP atlas of stratigraphy II, Stratigraphic correlation between sedimentary basins of the ESCAP region, v. 7(5): United Nations, New York, p. 42-51. *Also in* Australia BMR Geology and Geophysics, Record 1979/52 (unpublished).

BROWN, H. Y. L., 1895, Government geologists report on explorations in the Northern Territory: South Australian Parliamentary Paper (Adelaide) 82.

BROWN, S. A., BOSERIO, I. M., JACKSON, K. S., and SPENCE, K. W., 1984, The geological evolution of the Canning Basin implications for petroleum exploration, *in* The Canning Basin, W.A. *edited by* P. G. PURCELL: Geological Society of Australia and Petroleum exploration Society of Australia, Canning Basin Symposium, Perth, W.A., 1984, p. 85 -96.

CAYE, J. P., 1968, The Timor Sea Sahul Shelf area: Australian Petroleum Exploration Association, Journal, v. 8(2), p. 35 - 41.

CAYE, J. P., 1969, Keep River No. 1 well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

CHAN, P. N. K., 1982a, Tern No. 2 well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

CHAN, P. N. K., 1982b, Tern No. 3 well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

COCKBAIN, A. E., 1985, Carboniferous of Western Australia a review: Geological Survey of Western Australia, Report 14, Professional Papers for 1983, p. 14 - 35.

CRAIG, R. W., 1968, Geology *in* Ashmore Reef No. 1 well completion report: B.O.C. of Australia Ltd., Petroleum Search Subsidy Acts Report (unpublished).

CRIST, R. P., and HOBDAY, M., 1973, Diapiric features of the offshore Bonaparte Gulf Basin, northwest Australian shelf: Australian Society Exploration Geophysics, Bulletin 4(1), p. 43 - 66.

DICKINS, J. M., 1963, Permian pelecypods and gastropods from Western Australia: Australia BMR, Bulletin 63.

DICKINS, J. M., ROBERTS, J., and VEEVERS, J. J., 1972, Permian and Mesozoic geology of the northeastern part of the Bonaparte Gulf Basin: Australia BMR, Bulletin 125, p. 75 - 102.

DRUMMOND, J. M., 1963, Compilation and review of the geology of Bonaparte Gulf Basin, 1962: Australia BMR, Record 1963/133 (unpublished).

DUCHEMIN, A. E., and CREEVEY, K., 1966, Aquitaine Kulshill No. 1 well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

EDGERLEY, D. W., and CRIST, R. P., 1974, Salt and diapiric anomalies in the southeast Bonaparte Gulf Basin: Petroleum Exploration Association of Australia, Journal, v. 14, p. 85 - 94.

ELLIOTT, R. M. L., 1990, Browse Basin, *in* The geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 535 - 547.

ETHERIDGE, R., Jr., 1897, The Permo-Carboniferous fossils of Treachery Bay, Victoria River, South Australia: South Australian parliamentary Paper 127 (1896), p. 14 - 16.

ETHERIDGE, R., Jr., 1907, Official contributions to the palaeontology of South Australia: South Australian parliamentary Paper 55 (1906), Supplement, p. 1 - 21.

EXON, N. F., and WILLCOX, J. B., 1980, The Exmouth Plateau: stratigraphy, structure, and petroleum potential: Australia BMR, Bulletin 199.

FAHEY, J. E., and EDGOOSE, C. J., 1986, Anson 4971 1:100 000 geological series, Explanatory notes: Australia, Northern Territory Geological Survey.

FAIRBRIDGE, R. W., 1953, The Sahul Shelf, northern Australia: its structure and geological relationships: Journal and Proceedings of the Royal Society of Western Australia, v. 37, p. 1 - 33.

FORMAN, D. J., KURYLOWICZ, L. E., MAYNEE, S. J., PAINE,A. G. L., PASSMORE, V. L., ROBERTSON, C. S., and WYNBORN, L., 1974, Summary of Phanerozoic sedimentary basins of Australia and adjacent regions: Australia BMR, Record 1974/178.

FOSTER, C. B., 1984, Palynological report, WMC Turtle No. 1, WA 128P, Bonaparte Basin, *in* Western Mining Corporation Limited, Turtle No. 1 well completion report (unpublished).

FOSTER, C. B., 1985, Palynological report, WMC Cambridge No. 1, WA 128P, Bonaparte Basin, *in* Western Mining Corporation Limited, Cambridge No. 1 well completion report (unpublished).

FOSTER, C. B., 1986, Palynological report, *in* Western Mining Corporation Limited, WA 128P Year 1 data review (unpublished).

FOSTER, C. B., and WATERHOUSE, J. B., 1988, The Granulatisporites confluens Oppel-Zone and Early Permian marine faunas from the Grant Formation on the Barbwire Terrace, Canning Basin, Western Australia: Australian Journal of Earth Sciences, v. 35, p. 135 - 157.

GLOVER, J. J., RICHARDSON, L. A., and McGILVRAY, E., 1955, Geological and geophysical report on the Keep River area, Bonaparte Gulf Basin: Associated Australian Oilfields, Minad report (unpublished).

GORTER, J. D., 1978, Triassic environments *in* the Canning Basin, Western Australia: Australia BMR, Journal of Australian Geology and Geophysics 3(1), p. 25 - 33.

GRENFELL, H. R., 1985, A palaeoenvironmental analysis of the Permo-Triassic of the Bonaparte Basin, northwest Australia, based on palynomorphs, *in* Extended Abstracts, Hornibrook Symposium, Christchurch, *edited by* R. COOPER: New Zealand Geological Survey, Department of Scientific and Industrial Research, Record 9, p. 59 - 61.

GREY, K., 1983, Palynology of Devonian/Carboniferous samples from the Hargreaves Member, Cockatoo Sandstone and Milligans Formation, Ningbing area, Bonaparte Basin, Western Australia: Geological Survey of Western Australia Palaeontology Report 21/1983 (unpublished).

GUILLAUME, R. E. F., 1966, Petroleum geology *in* the Bonaparte Gulf Basin, N.T.: Commonwealth Mining and Metallurgy Congress, 8th, Proceedings, v. 5, p. 183 - 196.

GUNN, P. J., 1988a, Bonaparte Rift Basin: effects of axial doming and crustal spreading: Australian Society of Exploration Geophysics, Journal, v. 19, p. 83 - 87.

GUNN, P. J., 1988b, Bonaparte Basin: evolution and structural framework, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 275 - 285.

HARE, R., and THOMAS, G. A., 1961, Spirit Hill No. 1 well completion report: Oil Development NL (unpublished).

HARLAND, W. B., COX, A. V., LLEWELLYN, P. G., SMITH,A. G., and WALTERS, R., 1982, A geologic time scale: Cambridge University Press, 131p.

HAYS, J., 1967. Surfaces and laterites *in* the Northern Territory, *in* Landform studies from Australia and New Guinea, *edited by* J. N. JENNINGS and J. A. MABBUTT: Australia National University Press, Canberra, p. 182 - 210.

HELBY, R. J., 1969, The Carboniferous-Permian boundary in eastern Australia: an interpretation on the basis of palynological information: Geological Society of Australia, Special Publication 2, p. 69 - 72.

HELBY, R. J., 1974a, A palynological study of the Petrel Formation: Report to ARCO Australia Ltd. (unpublished). *Also in* Studies in Australian Mesozoic Palynology, *edited by* P. A. JELL: Association of Australasian Palaeontologists Memoir 4 (1987), fiche 1: 1 - 47, fiche 2: figs 1 - 5, fiche 3: figs 6 - 12.

HELBY, R. J., 1974b, A palynological study of the Cambridge Gulf Group (Triassic - Early Jurassic): Report to ARCO Australia Ltd. (unpublished). Also *in* Studies in Australian Mesozoic Palynology, edited by P. A. JELL: Association of Australasian Palaeontologists Memoir 4 (1987), fiche 1: 49 - 83, fiche 4: figs 2 - 11, fiche 5: figs 12 -15.

HELBY, R. J., MORGAN, R., and PARTRIDGE, A. D., 1987, A palynological zonation of the Australian Mesozoic, *in* Studies in Australian Mesozoic Palynology *edited by* P. A. JELL: Association of Australasian Palaeontologists, Memoir 4, p. 1 - 94

HENDERSON, R. A., 1990, Late Albian ammonites from the Northern Territory, Australia: Alcheringa, v. 14, p. 109 - 148.

HINDE, C. J., 1893, Note on a radiolarian rock from Fanny Bay, Port Darwin, Australia: Quarterly journal of the Geological Society of London, v. 49, p. 221 - 226.

HOCKING, R. M., MOORS, H. T., and van de GRAAFF, W. J. E., 1988, Geology of the Carnarvon Basin: Geological Survey of Western Australia, Bulletin 133.

HOCKING, R. M., VOON, J. W. K., and COLLINS, L. B., 1988, Stratigraphy and sedimentology of the basal Winning Group, northern Carnarvon Basin, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 203 - 224.

HOLTEN, G., 1985a, Swift 1 well completion report: BHP Petroleum (unpublished).

HOLTEN, G., 1985b, Anderdon 1 well completion report: BHP Petroleum (unpublished).

HOLTEN, G., 1986, Eclipse 2 well completion report: BHP Petroleum (unpublished).

HUGHES, R. J., 1978, The geology and mineral occurrences of Bathurst Island, and Cobourg Peninsula, Northern Territory: Australia BMR, Bulletin 177.

HUGHES, R. J., and SENIOR, B. R.,1974, New stratigraphic names for Cretaceous and Cainozoic units of Bathurst and Melville Islands and Cobourg Peninsula, Northern Territory: Australian Oil and Gas Review, v. 20(2), p. 10 - 17.

ISLAM, M. A., 1986, Palynostratigraphic review of five Timor Sea wells: Australasian Palynostratigraphic Services non-exclusive report (unpublished).

JACKSON, M. J., and van de GRAAFF, W. J. E., 1981, Geology of the Officer Basin, Western Australia: Australia BMR, Bulletin 206.

JEFFERIES, P. J., 1988, Geochemistry of the Turtle oil accumulation, offshore southern Bonaparte Basin, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 563 - 569.

JENSEN, H. I., 1914, Geological report on the Darwin mining district; McArthur River district; and the Barkley Tableland: Bulletin of the Northern Territory Department of External Affairs, Melbourne, No.10.

JONES, P. J., and NICOLL, R. S., 1985, Late Triassic conodonts from Sahul Shoals 1, Ashmore Block, northwestern Australia: Australia BMR, Journal of Australian Geology and Geophysics, v. 9, p. 361 -364.

JUTEAU, T., EISSEN, J-P., MONIN, A. S., ZONENSHAIN, L. P., SOROKHTIN, O. C., MATVEENKOV, V. V., and ALMUKHAMEDOV, A. I., 1983, Structure et pĕtrology du rift axial de la Mer Rouge vers 18 Nord. Rĕsultats de la campagne soviĕtique de plongĕes avec submersible (1980): Bulletin des Centres de Recherches, Exploration-Production, Elf-Aquitaine, v. 7(1), p. 217 - 229.

KRAUS, G. P., and PARKER, K. A., 1979, Geochemical evaluation of petroleum source rock *in* Bonaparte Gulf-Timor Sea region, northwestern Australia: American Association of Petroleum Geologists, Bulletin 63(11), p. 2021 - 2041.

KEMP, E. M., BALME, B. E., HELBY, R. J., KYLE, R. A., PLAYFORD, G., and PRICE, P. L., 1977, Carboniferous and Permian palynostratigraphy in Australia and Antartica: a review: BMR Journal of Australian Geology and Geophysics, v. 2, p. 177 - 208.

LANE, C., 1981, Lesueur No. 1 (LSR 1) WA-18-P Australia, Well completion report: Australian Aquitaine Petroleum Pty Ltd (unpublished).

LAVERING, I. H., and OZIMIC, S., 1988, Bonaparte Basin petroleum accumulations, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 331 - 337.

LAVERING, I. H., and OZIMIC, S., 1989, Bonaparte Basin, Western Australia and Northern Territory: Australia BMR, Australian Petroleum Accumulations Report 5.

LAWS, R. A., and BROWN, R. S., 1976, Petroleum geology of the southeastern Bonaparte Gulf Basin: *in* Economic geology of Australia and Papua New Guinea, 3 - Petroleum, *edited by* R.B. LESLIE, H.J. EVANS and C.L. KNIGHT: Australian Institute of Mining and Metallurgy, Monograph Series No. 3, p. 200 - 208.

LAWS, R. A., and KRAUS, G. P., 1974, The regional geology of the Bonaparte Gulf Timor Sea area: APEA Journal, p. 77 - 84.

Le BLANC, M. C., 1964, Bonaparte No. 1 well completion report: Alliance Oil Development Australia N.L. (unpublished). (A summary of this report appeared in Bureau of Mineral Resources, Petroleum Search Subsidy Acts Publication 75, 1966)

Le BLANC, M. C., 1965, Bonaparte No. 2 well completion report: Alliance Oil Development Australia N.L. (unpublished). (A summary of this report appeared in Bureau of Mineral Resources, Petroleum Search Subsidy Acts Publication 75, 1966)

LEE, R. J., and GUNN, P. J., 1988, The Bonaparte Basin, *in* Petroleum in Australia: The First Century: Australian Petroleum Exploration Association/ Macarthur Press, p. 252 - 269.

LOWELL, J. D., 1985. Structural styles in petroleum exploration: Tulsa, Oil and Gas Consultants International, 447p.

MacDANIEL, R. P., 1988, The geological evolution and hydrocarbon potential of the western Timor Sea region, *in* Petroleum *in* Australia: The First Century: APEA/ Macarthur Press, Parramatta, p. 270 - 284.

McBRIDE, E. F., and FOLK, R. L., 1979, Features and origin of Italian Jurassic radiolarites deposited on a continental crust: Journal of Sedimentary Petrology, v. 49(3), P. 837 - 868.

McMINN, A., 1985, Late Cretaceous dinoflagellate palynostratigraphy of northwestern Australia: PhD thesis, Macquarie University, (unpublished).

McMINN, A., 1988, Outline of a Late Cretaceous dinoflagellate zonation of northwestern Australia: Alcheringa, v. 12, p. 137 - 156.

MAMET, B. L., and BELFORD, D. J., 1968, Carboniferous foraminifera, Bonaparte Gulf Basin, northwestern Australia: Micropaleontology, v. 14(3), p. 339 - 347.

MATHESON, R. S., and TEICHERT, C., 1948, Geological reconnaissance of the eastern portion of the Kimberley District, Western Australia: Western Australia Geological Survey, Annual Report for 1945, p. 73 - 87.

MOLLAN, R. W., CRAIG, R. W., and LOFTING, M. J. W., 1969, Geological framework of the continental shelf off northwest Australia: Australian Petroleum Exploration Association, Journal, v. 9, p. 49 - 59.

MOLLAN, R. W., CRAIG, R. W., and LOFTING, M. J. W., 1970, Geological framework of the continental shelf off northwest Australia: American Association of Petroleum Geologists, Bulletin 54, p. 583 - 600.

MORY, A. J., 1988, Regional geology of the offshore Bonaparte Basin, *in* The North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 287 - 310.

MORY, A. J., 1990, Bonaparte Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 380 - 415.

MORY, A. J., and BEERE, G. M., 1988, Geology of the onshore Bonaparte and Ord Basins: Geological Survey of Western Australia, Bulletin 134.

MORY, A. J., and DUNN, P. R., 1990, The geological evolution and mineral potential of the Bonaparte, Canning, Ord and Officer Basins, *in* Geology of mineral deposits of Australia and Papua New Guinea *edited by* F.E. HUGHES: Australian Institute of Mining and Metallurgy Monograph 14.

NOAKES, L. C., 1949, A geological reconnaissance of the Katherine -Darwin region: Australia BMR, Bulletin 16.

OSBORNE, D. G., 1979, Tamar 1 well completion report: Getty Oil Development Co. Ltd (unpublished).

PARRY, J. C., and SMITH, D. N., 1988, The Barrow and Exmouth Sub-basins, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 129 - 145.

PIETSCH, B. A., 1983, Darwin 5073 1:100 000 geological series, Explanatory notes: Australia, Northern Territory Geological Survey.

PIETSCH, B. A., 1985, Koolpinyah 5173 1:100 000 geological series, Explanatory notes: Australia, Northern Territory Geological Survey.

PIETSCH, B. A., and STURT-SMITH, P. G., 1987, Darwin SD 52-4 1:250 000 geological series, Explanatory notes: Australia, Northern Territory Geological Survey.

PLAYFORD, P. E., COPE, R. N., COCKBAIN, A. E., LOW, G. H., and LOWRY, D. C., 1975, Phanerozoic, *in* Geology of Western Australia: Western Australia Geological Survey, Memoir 2, p. 223 -433.

PRICE, P. L., 1983, A Permian palynostratigraphy for Queensland, in Permian Geology of Queensland: Geological Society of Australia, Queensland Division, July, 1982, Brisbane, Proceedings, p. 155 - 211.

PRICE, P. L., FILATOFF, J., WILLIAMS, A. J., PICKERING, S. A., and WOOD, G. R.,1985, Late Palaeozoic and Mesozoic palynostratigraphic units: CSR Oil and Gas Division Report 274/25 (unpublished).

RAMPINO, M. R., and STOTHERS, R. B., 1988, Flood basalt volcanism during the past 250 million years: Science, v. 241, p. 663 -668.

REEVES, F., 1951, Australian oil possibilities: American Association of Petroleum Geologists, Bulletin 35, p. 2479 - 2525.

REVELLE, R., and FAIRBRIDGE, R., 1957, Carbonates and carbon dioxide, *in* Treatise on marine ecology and paleoecology, v. 1, Ecology *edited by* J. W. HEDPETH: Geological Society of America, Memoir 67.

REXILIUS, J. P., 1987, Micropalaeontological analysis, Bathurst Island Formation, Bonaparte Gulf Basin (Eider 1, Flamingo 1, Osprey 1, Tamar 1 and Whimbrel 1): ECL Australia non- exclusive report (unpublished).

REXILIUS, J. P., 1988, Micropalaeontological analysis, Bathurst Island Formation (Flat Top 1, Gull 1, Heron 1, Lynedoch 1, Petrel 1, Plover 3, Shearwater 1 and Troubador 1): International Stratigraphic Consultants non-exclusive report (unpublished).

ROBERTS, J., 1971, Devonian and Carboniferous brachiopods from the Bonaparte Gulf Basin, Northwestern Australia: Australia BMR, Bulletin 122.

ROBERTS, J, and VEEVERS, J. J., 1973, Summary of BMR studies of the onshore Bonaparte Gulf Basin 1963-71: Australia BMR, Bulletin 139, p. 29 - 58.

SHARMA, P. V., 1976, Geophysical methods in geology: Methods in Geochemistry and Geophysics Series, 12: Amsterdam, Elsevier Scientific Publishing Company.

SKWARKO, S. K., 1966, Cretaceous stratigraphy and palaeontology of the Northern Territory: Australia BMR, Bulletin 73.

SKWARKO, S.K. in press, Correlations and age of the Western Australian Permian strata, *in* Palaeontology of the Permian of Western Australia *edited by* S.K. SKWARKO: Geological Survey of Western Australia, Bulletin 136.

SKWARKO, S. K. in press, Correlations and age of the Western Australian Australia and New Guinea: Australia BMR, Bulletin 150, p. 111 -128.

STEIGER, R. H., and JAGER, E., 1977, Subcommission on geochemistry: Convention on the use of decay constants in geo- and cosmochronology: Earth planetary Science letters, 36, p. 359 - 362.

TASCH, P., and JONES, P. J., 1979, Lower Triassic Conchostraca from the Bonaparte Gulf Basin, northwestern Australia (with a note on Cyzicus (Euestheria) minuta(?) from the Carnarvon Basin, *in* Carboniferous, Permian, and Triassic Conchostracans of Australia three new studies: Australia BMR, Bulletin 185, p. 23 - 30.

THOMAS, G. A., 1957, Oldhaminid brachiopods from the Permian of Northern Australia: Journal of the palaeontological Society of India, D. M. Wadia Jubilee, v. 2, p. 174 - 182.

THOMAS, G. A., 1962, The Carboniferous stratigraphy of the Bonaparte Gulf Basin: Compte Rendu du Quatrième Congres pour l'advancement des ētudes de stratigraphie et de geologie du Carbonifère, Heerlen. 1958. Tome III, 1962, p. 727 - 732.

TRAVES, D. M., 1949, Preliminary report on survey of Ord-Victoria Region, Northern Australian Regional Survey: Australia BMR, Record, 1949/22 (unpublished).

TRAVES, D. M., 1955, The geology of the Ord-Victoria region, Northern Territory: Australia BMR, Bulletin 97.

TRUSHEIM, F., 1960, Mechanism of salt migration *in* northern Germany: American Association of Petroleum Geologists, Bulletin 44(9), p. 1519 -1540.

UTTING, E. P., 1958, Progress geological report, Permit No. 3, Bonaparte Gulf Basin (1957): Westralian Oil Ltd (unpublished).

Van ANDELL, T. H. and VEEVERS, J. J., 1967, Morphology and sediments of the Timor Sea: Australia BMR, Bulletin 83.

VEEVERS, J. J., 1967, The Phanerozoic geological history of northwest Australia: Journal of the Geological Society of Australia, v. 14(2), p. 253 -271.

VEEVERS, J. J. (editor), 1984, Phanerozoic earth history of Australia: Oxford, Clarendon Press, 418p.

VEEVERS, J. J., 1988, Morphotectonics of Australia's northwestern margin - a review, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 19 - 27.

VEEVERS, J. J., and ROBERTS, J., 1968, Upper Palaeozoic rocks, Bonaparte Gulf Basin of Northwestern Australia: Australia BMR, Bulletin 97.

WARRIS, B. J. 1973, Plate tectonics and the evolution of the Timor Sea, northwest Australia: Australian Petroleum Exploration Association, Journal, v. 13, p. 13 - 18.

WILLIAMS, L. W., FOREMAN, D. J., and HAWKINS, P. J., 1973, Sedimentary basins of the Sahul Shelf: Oil and Gas, v. 19(13), p. 15 - 21.

WHITEHOUSE, F. W., 1928, The correlation of the marine Cretaceous deposits of Australia: Australian Association for the Advancement of Science, Report 18, p. 275 - 280.

WOODS, E. P., 1988, Extensional structures on the Jabiru Terrace, Vulcan Sub-basin, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 311 - 330.

WOODSIDE, 1981, Mount Ashmore No. 1B well completion report: Woodside Offshore Petroleum Pty Ltd (unpublished).

WORMALD, G. B., 1988, The geology of the Challis Oilfield - Timor Sea, Australia, *in* the North West Shelf, Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Symposium, Perth, 1988, p. 425 - 437.

Appendix 1

Gazetteer

Wells used in this study and localities mentioned in text

	Latitude (S) °	′	″	Longitude (E) °	′	″
Anson Bay	13	20		130	05	
Anderdon	12	38	47	124	47	48
Ashmore Reef	12	15		123	05	
Ashmore Reef 1	12	10	43	123	05	10
Avocet 1A	11	22	23	125	45	18
Barita 1	11	26	36	125	43	42
Barnett 1	14	31	50	129	03	39
Bathurst Island	11	30		130	17	
Benalla Bank	12	05		125	49	
Berkley 1	14	00	17	127	49	52
Bonaparte 1	15	01	00	128	44	40
Bonaparte 2	15	05	07	128	43	16
Bougainville 1	13	46	24	129	02	31
Brown Gannet 1	12	06	29	123	51	22
Cambridge 1	14	17	28	128	25	57
Cambridge Gulf	15			128		
Cape Dombey	13	54		129	43	
Cape Hay	14	03		129	28	
Cape Londonderry	13	45		126	09	
Cassini 1	12	08	47	124	58	05
Challis 1	12	07	26	125	00	16
Cliff Head	13	23		130	12	
Cliff Head 1 (coal bore)	14	04		129	32	
Cobourg Peninsula	11	22		132	18	
to	11	16		131	54	
Crane 1	12	07	33	125	37	42
Curlew 1	11	46	14	128	15	50
Cygnet 1	11	53	46	125	56	21
Darwin	12	27		130	50	
Darwinia 1A	11	26	32	127	56	06
Dillon Shoals 1	11	14	21	125	26	49
Drake 1	11	17	06	125	50	08
East Swan 1	12	18	00	124	34	56
Eclipse 1	12	16	17	124	37	08
Eclipse 2	12	14	18	124	38	37
Eider 1	11	23	21	125	44	47
Fannie Bay	12	26		130	49	
Flamingo 1	11	01	34	126	28	55
Flat Top 1	12	22	35	129	15	55
Flinders Shoal	9	40		129	40	
Fossil Head	14	33		129	02	
Frigate 1	13	10	48	127	55	25
Grebe 1	12	27	04	124	14	58
Gull 1	11	56	29	127	54	37
Gunn Point	12	11		131	00	
Heron 1	10	26	27	128	57	05
Hyland Bay	13	59		129	42	
Ibis 1	12	03	43	125	20	47
Jabiru 1A	11	56	01	125	00	15
Jabiru 2	11	56	06	124	59	20
Jabiru 3	11	55	32	125	00	32
Jabiru 4	11	55	18	125	01	12
Jacaranda 1	11	28	15	128	09	50
Joseph Bonaparte Gulf	14			129		
Keep River	15	41		129	02	
Keep River 1	15	10	05	129	05	22
Keyling Inlet	14	49		129	41	
Kinmore 1	14	02	01	129	15	44
Kinmore Point	14	03		129	32	
Kulshill 1	14	21	47	129	32	33
Kulshill 2	14	24	18	129	32	40
Kununurra	15	47		128	44	
Kuriyippi Hills	14	25		129	40	
Lacrosse 1	14	17	51	128	34	58
Lesueur 1	13	57	09	128	07	33
Londonderry Rise	12	15		124	15	
to	12	45		125	45	
Malita Shelf Valley	9	35		128	31	
to	11			128		
Matilda 1	14	27	18	128	45	07
Melville Island	11	40		131		
Milligans No.1 Bore	15	39		129	00	
Montara 1	12	41	22	124	31	54
Moonkinu Beach	11	50		130	28	
Mount Ashmore 1B	12	33	36	123	12	22
Mount Goodwin	14	15		129	34	
Moyle 1	14	19	10	129	46	31
Newby 1	11	50	02	129	06	04
Ningbing 1	15	10	54	128	40	52
Nome 1	11	39	18	125	19	18
North Hibernia 1	11	40	19	123	19	29
Oliver 1	11	38	41	125	00	32
Osprey 1	12	13	09	125	13	15
Pearce Point	14	26		129	21	
Peewit 1	12	39	22	126	01	15
Pelican Island 1	14	46	19	128	46	27
Pelican Islet	14	46	128	47		
Penguin 1	13	36	28	128	28	06
Petrel 1	12	49	35	128	28	27
Petrel 1A	12	49	52	128	28	20
Petrel 2	12	51	14	128	30	50
Petrel 3	12	56	07	128	34	10
Plover 1	12	42	45	126	22	07
Plover 2	12	57	29	126	10	28
Plover 3	12	49	05	126	06	57
Point Spring	15	24		128	53	
Pollard 1	11	39	53	124	34	08
Port Keats	14	09		129	33	
Prion 1	12	24	16	124	09	07
Puffin 1	12	18	30	124	20	01
Puffin 2	12	18	39	124	20	01
Puffin 3	12	17	20	124	21	30
Rainbow 1	11	56	17	124	19	55
Sahul Shoals 1	11	25	36	124	32	50
Sandpiper 1	13	18	53	127	58	35
Shearwater 1	10	30	49	128	18	37
Skua 1	12	30	19	124	25	58
Skua 2	12	30	34	124	24	16
Skua 3	12	30	22	124	24	53
Skua 4	12	25	33	124	25	33
Skull 1	15	17	07	128	57	17
Spirit Hill 1	15	30	20	129	14	18
Sunrise 1	9	35	24	128	09	14
Swan 1	12	11	17	124	30	34
Swan 2	12	11	41	124	29	45
Swift 1	12	32	14	124	27	05
Tamar 1	11	52	15	126	12	40
Tern 1	13	13	15	128	03	53
Tern 2	13	16	44	128	07	58
Tern 3	13	20	10	128	06	16
Tinganoo Bay	11	23		131	28	
Treachery Bay	14	26		129	23	
Troubadour 1	9	44	04	128	07	26
Troughton Island	13	45		126	09	
Turnstone 1	11	44	13	125	17	45
Turtle 1	14	28	36	128	56	42
Utting Gap	14	28		128	36	
Vee Shoal	11	48		123	50	
Vulcan 1B	12	15	33	124	33	01
Wangarlu Bay	11	12		132	20	
Weaber 1	15	21	10	129	07	49
Weaber Range	15	20		128	50	
Whimbrel 1	12	28	58	125	22	40
Woodbine 1	12	38	43	124	08	50

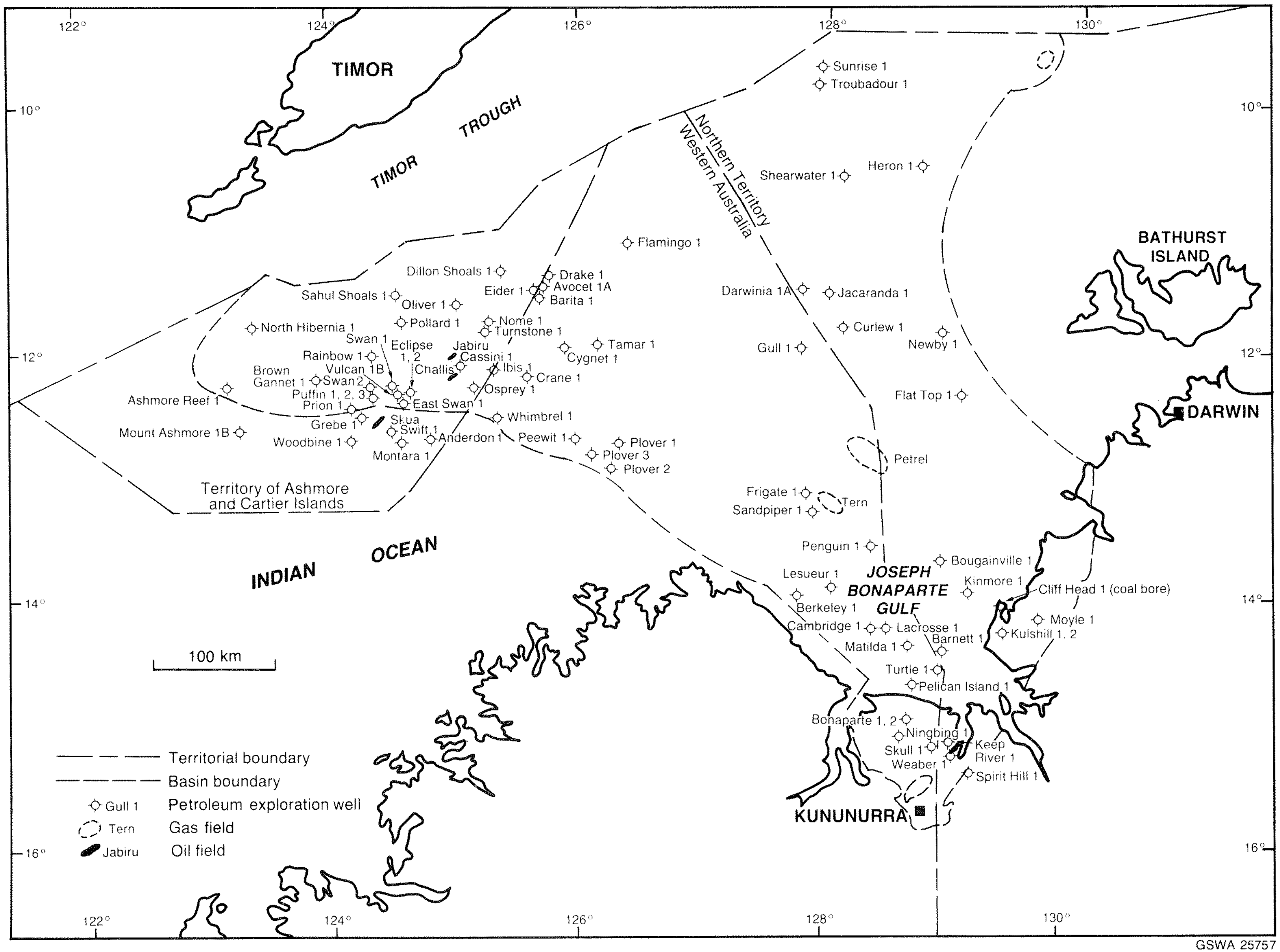


Figure 29. Location map showing wells referred to in this report.

Gravity modelling

Veevers (1984, 1988) interpreted the Bonaparte Basin as a failed arm throughout the Palaeozoic, but did not invoke the presence of oceanic crust in the Petrel Sub-basin. By comparison, Lee and Gunn (1988) and Gunn (1988a,b) suggested that breakup occurred in the Early Carboniferous. Central to their interpretation (based on gravity and magnetic data), is the presence of dense magnetic mantle material and oceanic basalt in the centre of the Petrel Sub-basin. In order to evaluate whether the basin was a failed arm or an active spreading centre, at least in the Carboniferous, it is necessary to demonstrate the presence of oceanic crust in the centre of the Petrel Sub-basin. Since Lee and Gunn did not use gravity modelling to test their ideas, a cross section of the basin through Tern 1 and Petrel 2 (Fig. 30 coinciding with section A - B of Lee and Gunn, 1988, fig. 4) was selected with the aim of resolving whether or not oceanic crust is present in the centre of the Petrel Sub-basin.

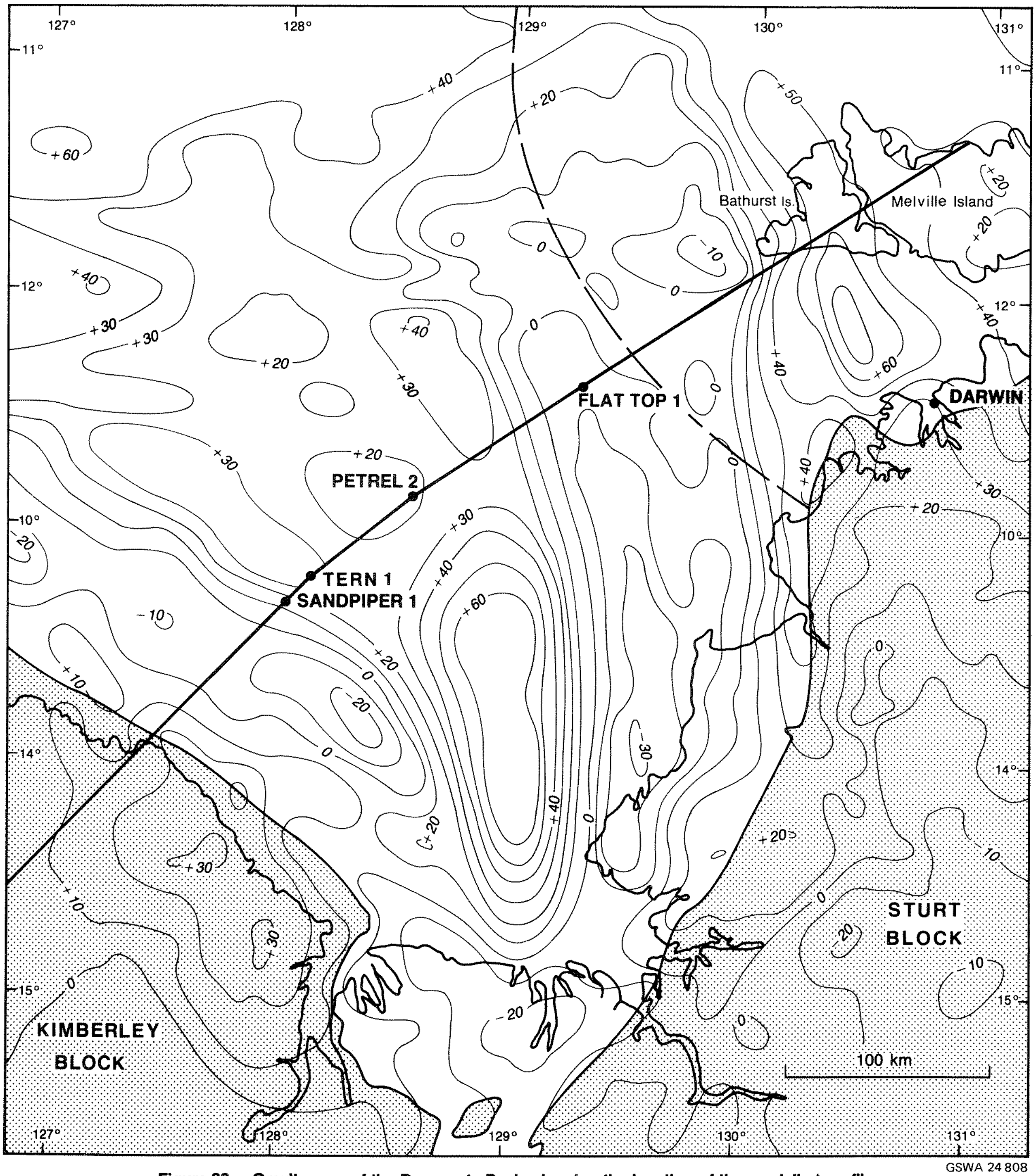


Figure 30. Gravity map of the Bonaparte Basin showing the location of the modelled profile.

The large gravity anomaly in the south of the Petrel Sub-basin has been commented upon by a number of authors. The feature was named the Keep River High by Caye (1968) and the Wickham Gravity High by Crist and Hobday (1973). The latter authors considered that the gravity-high and its associated gravity-lows were the result of salt migration from the centre of the basin towards the basin margins. Brown (1980) suggested that the gravity-high was the result of crustal thinning. Lee and Gunn (1988) and Gunn (1988a,b) expanded upon this interpretation by explaining the symmetric, Y-shaped gravity-high as a scissor-like widening of the 'Bonaparte Rift' about a pole at the southern end of the basin. The northern increase in intensity of the large positive anomaly was interpreted as the result of dykes of mantle material reaching progressively higher levels as rift widening progressed. At the northern end of the gravity anomaly, at the point where it separates into two distinct halves, crustal splitting and the emplacement of oceanic crust was proposed by these workers. By comparison, Anfiloff (1988) suggested that the gravity-high may represent volcanics in the basement. Anfiloff (1988) also considered that the gravity-low to the north represents sedimentary rocks in an old rift system rather than oceanic crust.

Models used

All models were initially based on section A - B of Lee and Gunn (1988, fig. 4) which was extended onto the Kimberley Block and across the Darwin Shelf (Fig. 30). Densities chosen for the bodies in the model are from Sharma (1976): 2.6 g/cm³ for the Palaeozoic sandstone and shale sequence; 2.4 g/cm³ for the unnamed evaporitic sequence; 2.2 g/cm³ for salt; 2.65 g/cm³ for the Proterozoic sequence (predominantly undeformed sedimentary rock); 2.85 g/cm³ for crystalline basement (granite, diorite, and gabbro); 3.0 g/cm³ for basalt; and 3.3 g/cm³ for the upper mantle (ultramafic). The model also includes up to 200 m of water across Joseph Bonaparte Gulf (1.0 g/cm³) which cannot be resolved at the scale used in Figure 31.

Two other changes were made to simplify the modelling. Lee and Gunn's (1988) interpretation of the age of the tilted fault blocks on the edge of the Petrel Sub-basin as Devonian, rather than Cambrian - Proterozoic as shown in Figure 5, cannot be verified by gravity modelling because the difference in density between the two sequences is small. Consequently, the contact between the Phanerozoic and Proterozoic sequences has been smoothed (Fig. 31A - D).

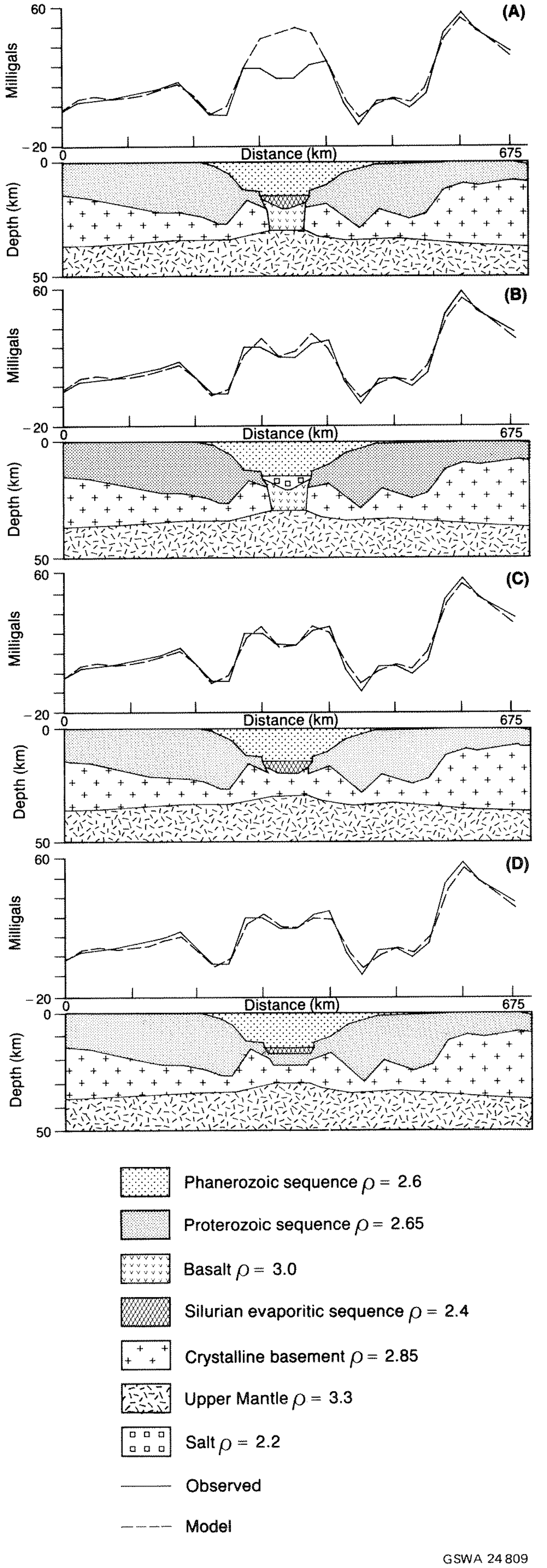


Figure 31. Observed and model gravity profiles and model geometry.
(A) Model based on Lee and Gunn's (1988) section A-B in which oceanic crust is present in the centre of the Petrel Sub-basin. Approximately 5 km of evaporitic sequence (ρ 2.4) is shown overlying oceanic crust (ρ 3.0).
(B) Model in which salt (ρ 2.4) replaces the evaporitic sequence above the oceanic crust in order to suppress the model gravity high shown in (a)
(C) Model in which the oceanic crust in (a) and (b) has been replaced with crystalline basement (ρ 2.85)
(D) Model based on (C) in which Proterozoic sequence (ρ 2.65) extends under the centre of the Petrel Sub-basin.

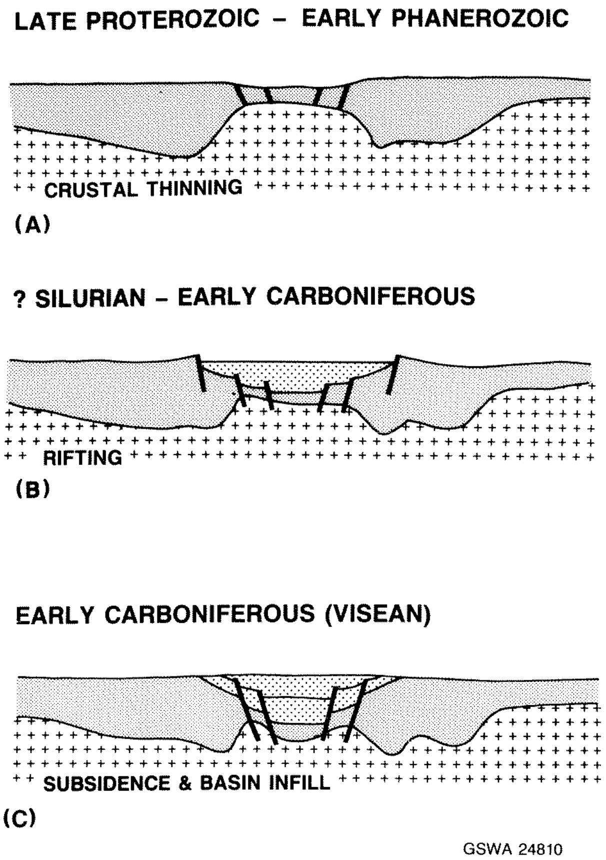


Figure 32. Model for the evolution of the Bonaparte Basin.
(A) late Proterozoic to early Phanerozoic.
(B) ?Silurian to Early Carboniferous (Tournaisian).
(C) late Early Carboniferous (Visean).

Furthermore, models with upper mantle material at high levels in the Petrel Sub-basin resulted in model gravity profiles of considerably greater magnitude than the observed profiles. In order to suppress the model gravity profile, this material was given a sialic rather than mafic density.

Figure 31A is based on section A - B of Lee and Gunn (1988, fig. 4) with the addition of 5 km of evaporitic sequence (2.4 g/cm³) in order to suppress the model gravity in the centre of the Petrel Sub-basin . In Figure 31B the evaporitic sequence has been changed to salt (2.2 g/cm³) in order to further suppress the model gravity above the basalt to match the observed profile. Juteau et al. (1983) demonstrated the presence of salt, presumably sourced from breached fragments of continental crust directly overlying oceanic crust in the Red Sea. While Lee and Gunn (1988) suggested that similar salt movements may have occurred in the Bonaparte Basin, the thickness of salt indicated by the gravity model (Fig. 31B) is unlikely to remain stable, as flowage can be initiated in a 300 m thick salt horizon by as little as 1000 m of overburden (Trusheim, 1960). Consequently, this gravity model indicates that the presence of oceanic crust in the centre of the Petrel Sub-basin is unlikely, and supports Anfiloff's (1988) statement that the magnitude of the gravity-low in the centre of the Petrel Sub-basin is not compatible with a large plug of oceanic crust.

In Figure 31C the basalt was replaced by crystalline basement (2.85 g/cm³). However, this model is geologically implausible as the evaporitic sequence directly overlies crystalline basement. In Figure 31D, a continuous, thin Proterozoic sequence is depicted below the Petrel Sub-basin. This model implies crustal thinning in the late Proterozoic or early Phanerozoic, and allows for a much thinner evaporitic sequence; approximately 2000 m is shown, comparable to the thickness along the edge of the Petrel Sub-basin (Figs 4 and 5). Further modification is possible to completely eliminate the evaporitic sequence from the gravity model. This indicates that the evaporitic sequence in the Bonaparte Basin is too thin to be easily discriminated from other rocks using gravity modelling.

Conclusions

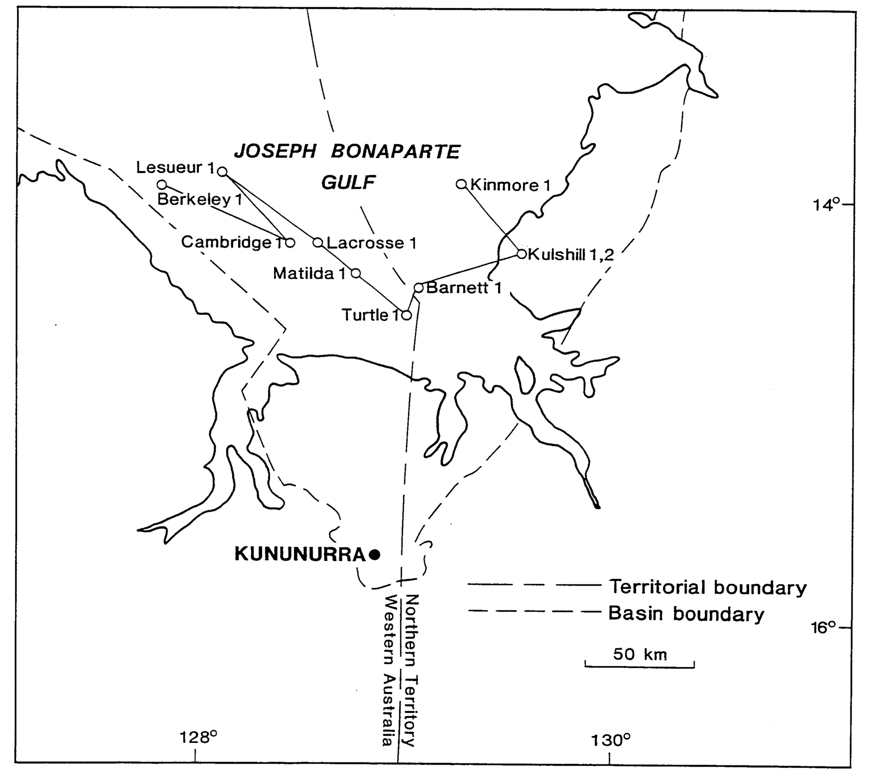
Models in which oceanic basalt is present in the centre of the Petrel Sub-basin require a significant thickness of low density material (e.g. salt). Such material would be unstable, and for this reason oceanic crust is unlikely to be present in the centre of the Petrel Sub-basin. However, the gravity modelling confirms the presence of deep intrusions in the Petrel Sub-basin. These were probably emplaced during a period of crustal thinning in the late Proterozoic or early Phanerozoic, and are responsible for the gravity-high in the south of the Petrel Sub-basin. A model for the evolution of the northern part of the Petrel Sub-basin, based on the final gravity model (Fig. 31 D), is shown in Figure 32. In this area, crustal thinning in the late Proterozoic or early Phanerozoic (Fig. 32A) was modified by middle Phanerozoic rifting (Fig. 32B) and subsidence (Fig. 32C). As a result, two basement highs, which correspond to the northern part of the Y-shaped gravity-high in the Petrel Sub-basin, were produced.

P.E. PLAYFORD
DIRECTOR, GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA

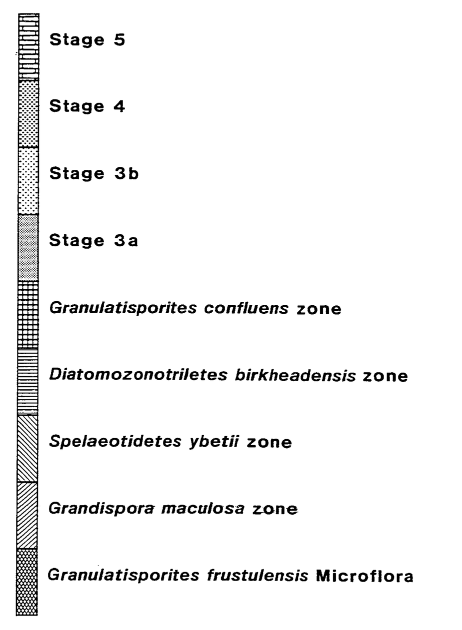
HON. GORDON HILL, M.L.A.
MINISTER FOR MINES
D.R. KELLY DIRECTOR GENERAL OF MINES

CORRELATION OF THE UPPER WEABER GROUP AND KULSHILL GROUP BASED ON GAMMA-RAY AND SONIC LOGS

Datum: base of Treachery Shale
Compiled by A.J.Mory



Key to palynological zones
(see Figures 8 & 10 for ages)

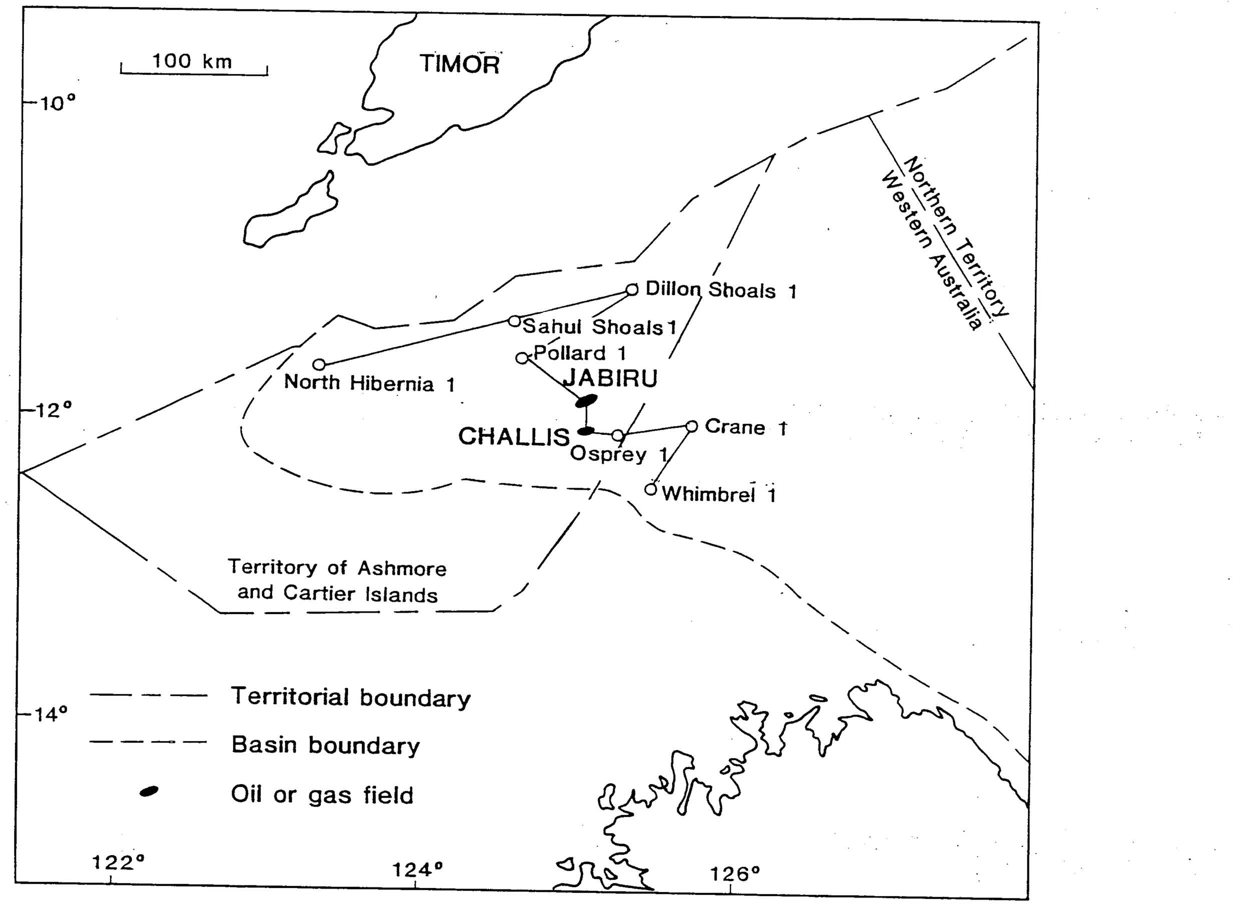


P.E. PLAYFORD
DIRECTOR, GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA

HON. GORDON HILL, M.L.A.
MINISTER FOR MINES
D.R. KELLY DIRECTOR GENERAL OF MINES

CORRELATION OF UNITS WITHIN THE SAHUL AND TROUGHTON GROUPS BASED ON GAMMA-RAY AND SONIC LOGS

Datum: top of Osprey Formation
Compiled by A.J.Mory

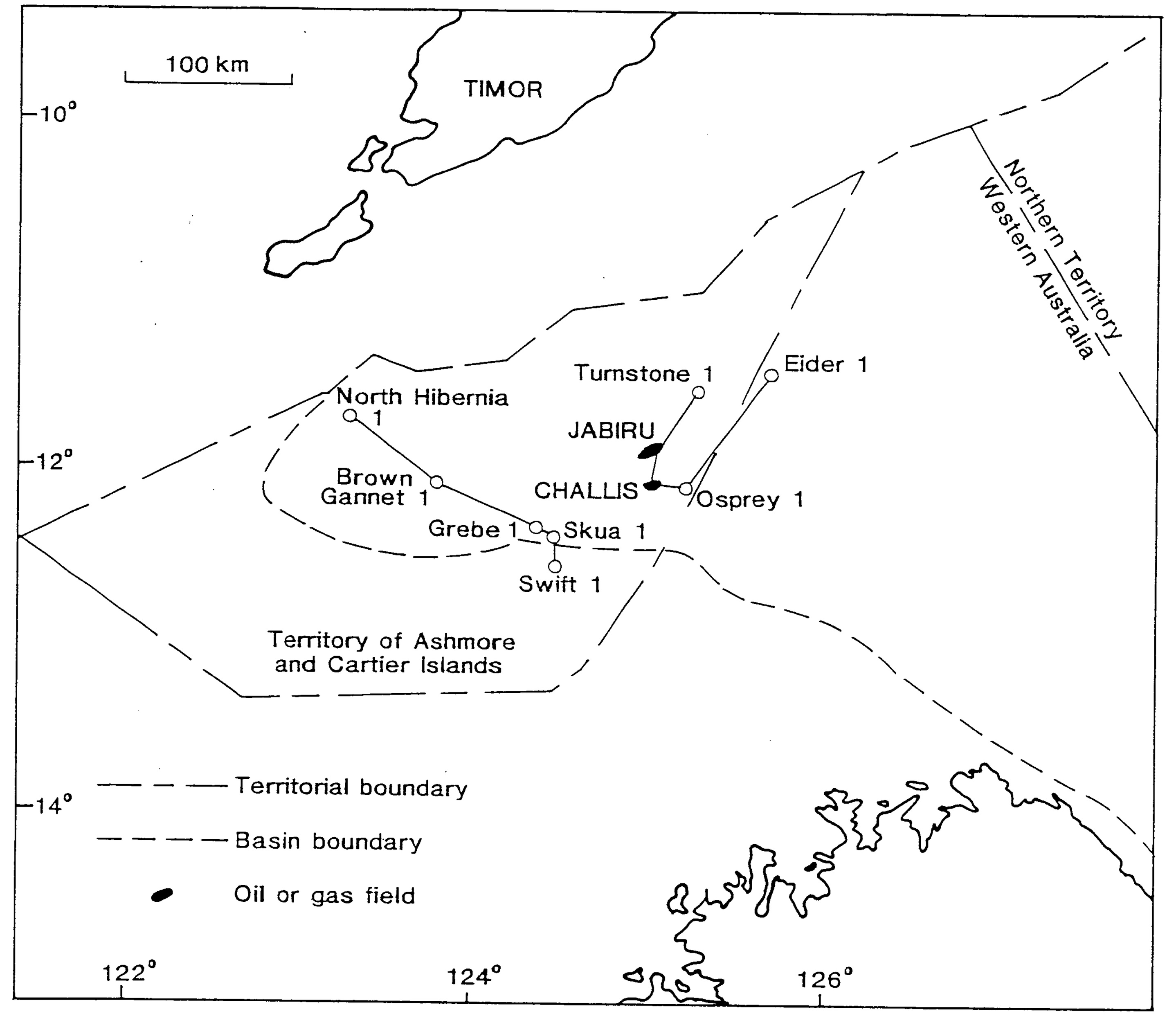


P.E. PLAYFORD
DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

HON. GORDON HILL, M.L.A.
MINISTER FOR MINES
D.R. KELLY DIRECTOR GENERAL OF MINES

CORRELATION OF THE BATHURST ISLAND GROUP BASED ON GAMMA-RAY AND SONIC LOGS

Datum: top of Bathurst Island Group
Compiled by A.J.Mory



Key to ages

	Age unknown	Tur	Turonian
Maa	Maastrichtian	Cen	Cenomanian
Cmp	Campanian	Alb	Albian
San	Santonian	Apt	Aptian
Con	Coniacian	Neo	Neocomian