PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Northwest Australian Continental Margin [and Discussion]

D. E. Powell, Peter Kent, Kingsley Dunham, G. Karner, M. F. Osmaston and A. S. MacKenzie

Phil. Trans. R. Soc. Lond. A 1982 **305**, 45-62
doi: 10.1098/rsta.1982.0025

Phil. Trans. R. Soc. Lond. A **305**, 45–62 (1982) [45]
Printed in Great Britain

The northwest Australian continental margin

By D. E. Powell
Hudson's Bay Oil and Gas Company Limited, 700 *Second Street, S.W., Calgary, Alberta, Canada T2P 0X5*

The Northwest Shelf of Australia offers a typical example of a 'passive' continental margin. Major intra-cratonic basins of Permian to Middle Jurassic age developed along the present coastline, superimposed to either orthogonally trending Palaeozoic basins or Precambrian basement rocks.

In each of these depocentres distinct lithotectonic units can be recognized that are related to phases of rifting and subsequent continental break-up. The pre-break-up rift valley and intra-cratonic basin stages are represented by a very thick Permian to Middle Jurassic series of mainly fluvio-deltaic sediments but with occasional marine incursions. Break-up took place near the end of the Middle Jurassic and was accompanied by large-scale block faultings with associated uplift and sub-areal erosion. Gradually late Jurassic to early Cretaceous marine sediments transgressed over the eroded surface: within the general transgressive episode, late Callovian, late Oxfordian to Kimmeridgian, late Tithonian to early Cretaceous marine incursions may be singled out. Open marine conditions, related to the breakup of Gondwanaland and opening of the Indian Ocean, became widespread during the Albian in the southern part of the Australian Northwest Shelf and during the Cenomanian in the northern part. The deposition of a thick prograding wedge of mainly carbonate sedimentation since the mid-Eocene resulted in a northwesterly regional tilt of the Shelf.

Hydrocarbon occurrences are related to the tectonic evolution. Early Triassic, early Middle Jurassic, late Oxfordian–Kimmeridgian and early Cretaceous marine incursions are directly related to the deposition of potential source rocks in restricted basins. A regressive phase led to the deposition of Triassic fluviatile sediments with excellent reservoir potential. Break-up tectonism and subsequent marine transgression provided the relevant trapping mechanism and probably the migration paths for the major gas–condensate discoveries of the Rankin Platform. The prolonged high rate of subsidence and accompanying thick sedimentation have ensured that hydrocarbon generation occurred, despite the low geothermal gradient.

Introduction

The Northwest Shelf of Australia is regarded as a good example of a passive 'Atlantic-type' margin that evolved as a result of major rifting on a continental scale, starting in the late Palaeozoic and continuing into the early Cretaceous. These pull-apart movements resulted in the complete disassociation of eastern Gondwanaland with the separation of a western landmass from the Australian Plate.

Geologically the area as a whole comprises a number of Permian and Mesozoic epicontinental basins lying offshore from the Australian craton and developed parallel to the principal rift system. These extend westwards across a series of marginal plateaux to the base of the present continental slope. In the north the margin has been deformed within the Cainozoic orogenic belt of the Indonesian island arc system. The portion of the margin considered in this paper extends over 2000 km north from Northwest Cape towards Darwin and the adjacent portions of the Indonesian Archipelago. Seawards the width of the continental margin varies considerably but averages about 600 km (figure 1).

Geological and geophysical information on this vast area has been obtained from a number of sources. On the inner part of the shelf it has resulted from extensive offshore oil exploration carried out over the past 18 years by several large groups who have acquired over 300000 lines of the seismic data and drilled close to 100 exploratory wells.

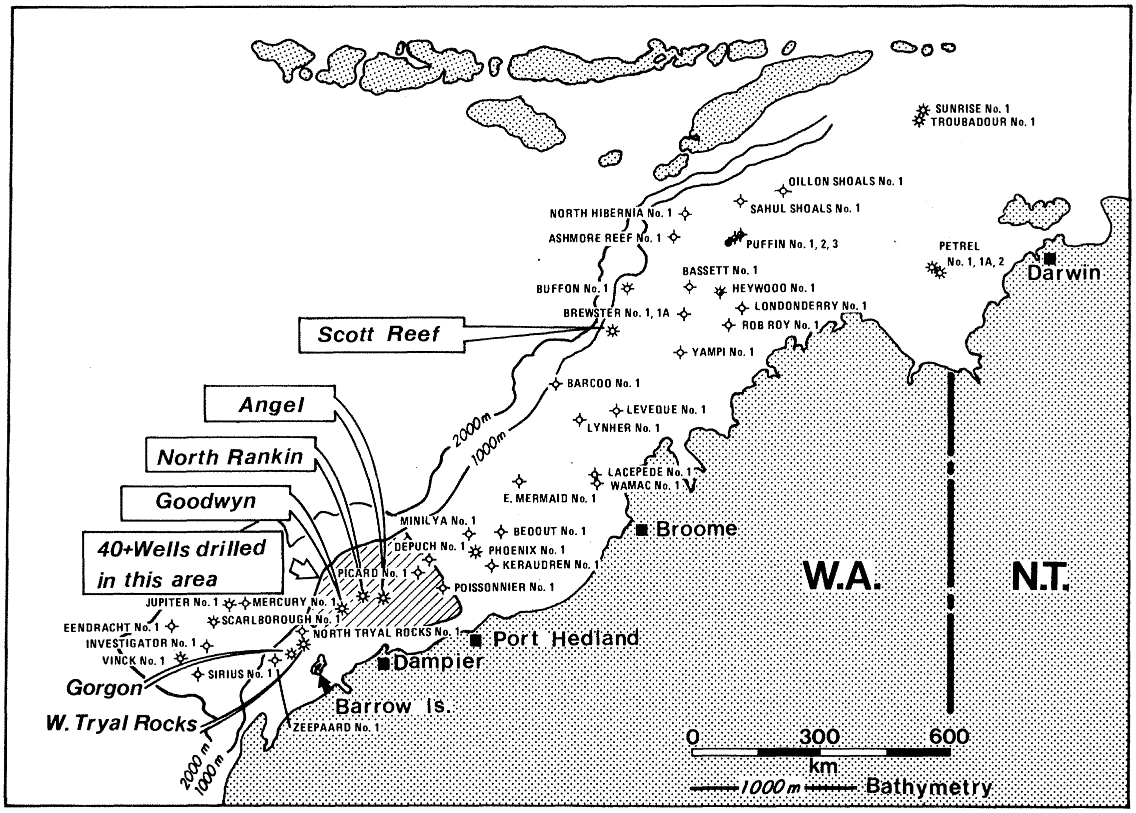

Figure 1. Location map with key exploration wells.

The outer part of the continental margin, extending to water depths of over 4000 m, has been investigated by the Australian Bureau of Mineral Resources who have carried out extensive gravity, magnetic and sparker surveys. In addition, several holes drilled by the *Glomar Challenger* in 1972 as part of the Deep Sea Drilling Project provided valuable information on the age both of the sea floor in the adjacent ocean basins and of the sediments in the Timor Trough. During 1977–9 the B.G.R. of West Germany conducted geoscientific investigations on the outer continental shelf, and recently, oil exploratory drilling has commenced in deep water on the Exmouth Plateau towards the outer continental margin where five wells have now been completed (von Stackelberg *et al.* 1980).

This paper outlines the geological evolution of the continental margin off Northwest Australia from the late Palaeozoic into the Upper Cretaceous and relates this to phases of crustal accretion.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Geological setting

Figure 2 shows the major geological elements, and figures 3 and 4 represent structural cross sections extending across the Browse Basin and Dampier Sub-Basin respectively, and out into the adjacent deep ocean. Gross regional isopachs of the Jurassic, Cretaceous and Tertiary within the main basinal areas are included as figures 5–7.

The onshore geology of northwest Australia is dominated by three large Archaean–

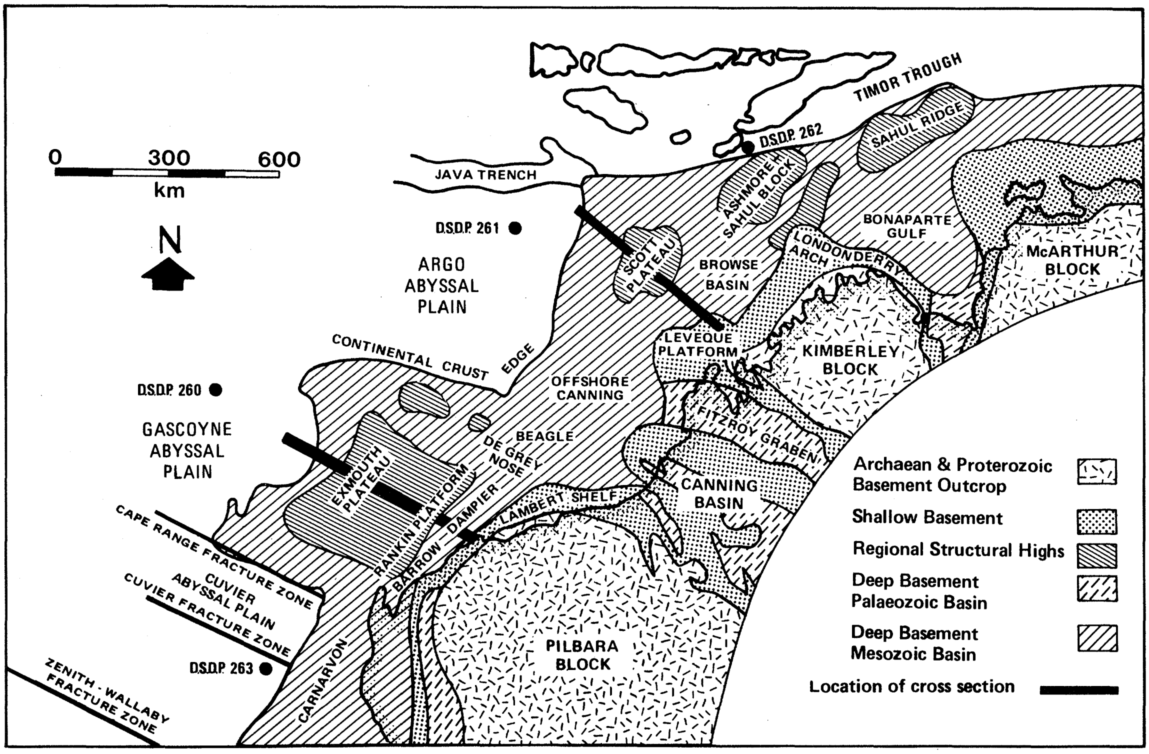

Figure 2. Tectonic elements.

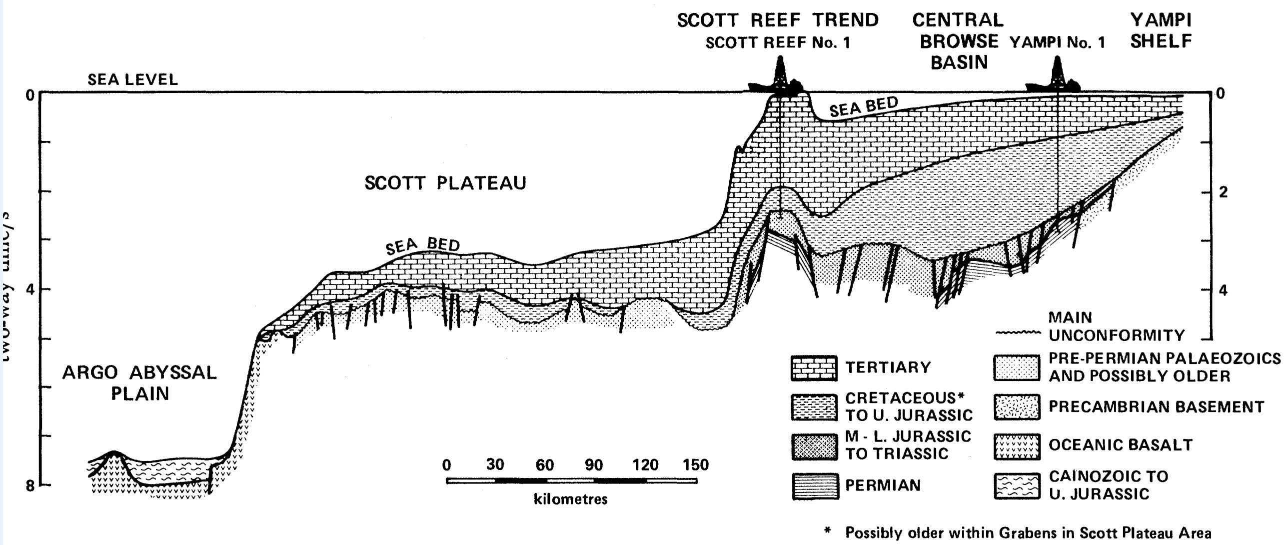

Figure 3. Generalized structural cross section, Yampi Shelf to Argo Abyssal Plain.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Proterozoic shield areas: the Pilbara, Kimberley and McArthur Blocks. These are separated by two northwest-trending intra-cratonic basins of mainly Palaeozoic age, namely the Canning Basin and the Bonaparte Gulf Basin, which are believed to have been initiated in the late Proterozoic as a result of crustal fragmentation.

Offshore a number of northeast-trending Permian to Tertiary epicontinental basins and sub-basins are located on the inner continental margin. The epicontinental basins developed off

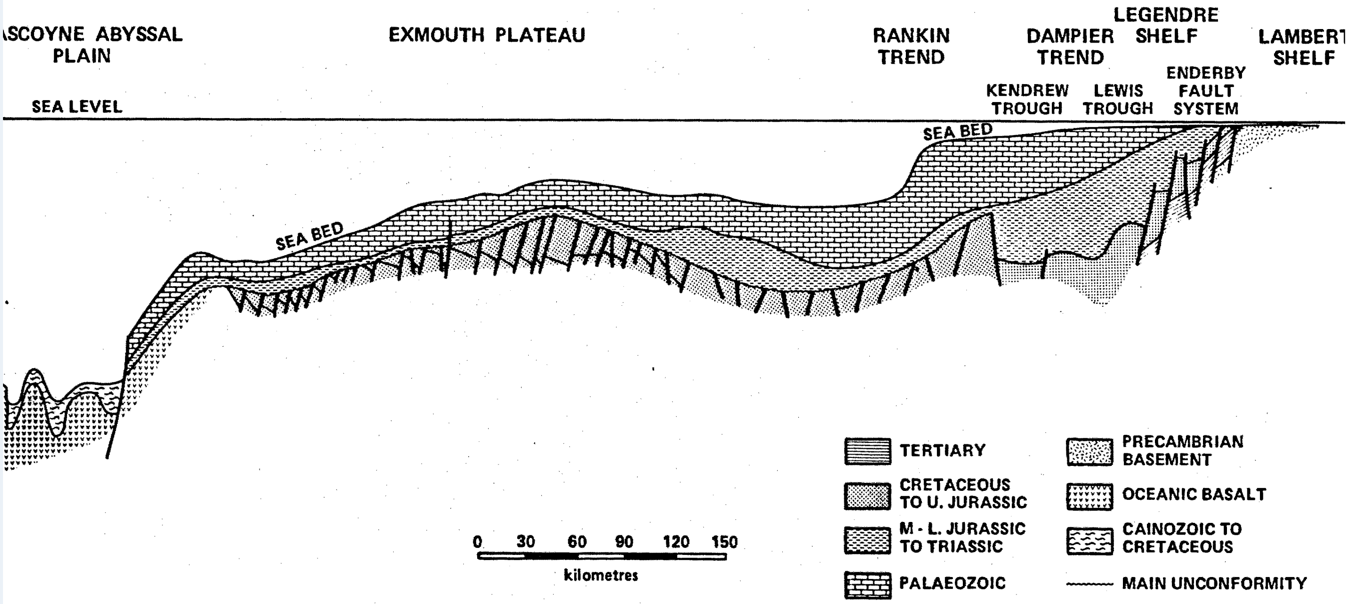

FIGURE 4. Generalized structural cross section, Lambert Shelf to Gascoyne Abyssal Plain.

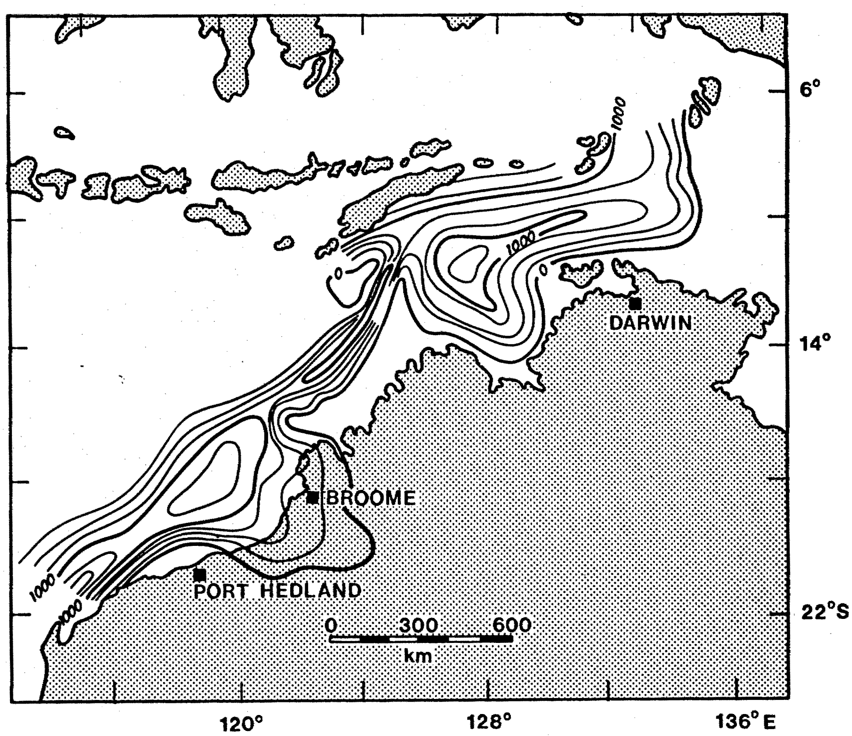

FIGURE 5. Jurassic isopach (metres).

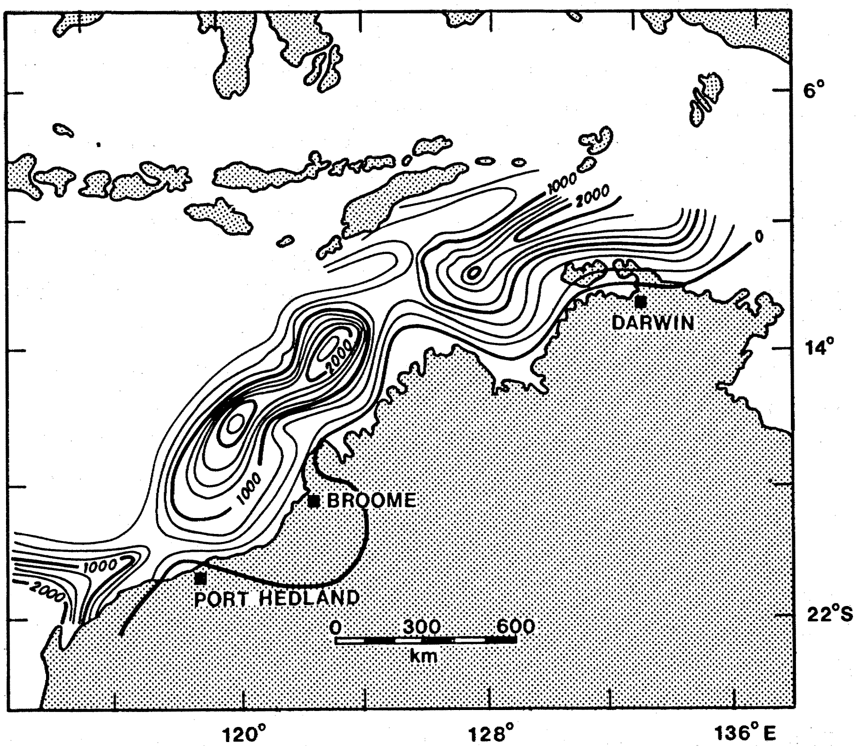

Figure 6. Cretaceous isopach (metres).

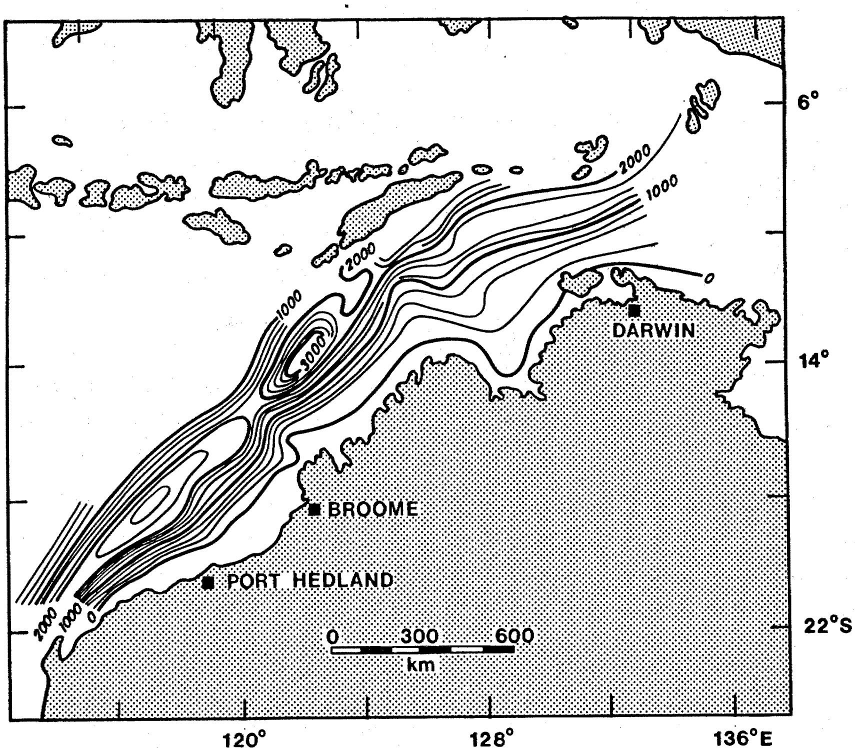

Figure 7. Tertiary isopach (metres).

northwest Australia were formed entirely over continental crust, with basement representing an extension of the onshore shield area. Proterozoic basement rocks have been penetrated by several wells near the inner margins of the northern Carnarvon and Browse Basins, but farther offshore basement lies below current drilling depths.

The three southernmost sub-basins in the area under review, namely the Barrow, Dampier and Beagle sub-basins, form the northern extension of the Carnarvon Basin. They represent major Triassic to Cretaceous downwarps, bounded on the eastern side by complex, essentially down-to-the-basin fault zones. All three exhibit a number of positive trends, paralleling a central basin area. The most pronounced is the Rankin Platform, a fault-controlled regional high feature situated along the outer seaward margin of both the Barrow and Dampier sub-basins, and on which several major hydrocarbon discoveries have been made.

West of the northern Carnarvon Basin a broad structural low separates the Rankin Platform from another regionally high area, lying in water depths of 900–2000 m and known as the Exmouth Plateau. Falvey (1972) considered this to be a marginal plateau of continental crustal material that foundered during the differential vertical movements after continental break-up. Recent work, however, has shown that the plateau was a depositional entity of the Northern Carnarvon Basin for much of the early Mesozoic and owes its present position in deep water to the fact that the Tertiary prograding carbonate wedge has not yet covered it. Seismic correlation into the plateau area from well control on the Rankin Platform suggests that a thick, faulted, Permian to Triassic sequence is overlain by relatively thin Cretaceous to Recent sediments (Branson 1974). The western margin of the plateau is characterized by strong northeast-trending fault blocks downthrowing westwards to the Gascoyne Abyssal Plain. This fault zone represents a rapid thinning of the continental crust down to the 4000 m isobath, located some 600 km offshore, which marks the approximate boundary between continental and oceanic crust.

North of the Carnarvon Basin the Mesozoic offshore Canning Basin is a northeast-trending linear basin containing over 5000 m of sediments. It differs from the Carnarvon Basin in that it generally does not exhibit the intense fault block tectonics that characterize the former feature.

Farther north, the Browse Basin comprises a major northeast-trending late Palaeozoic to Recent sedimentary basin, which lies entirely offshore from the Precambrian Kimberley Block and has an areal extent of about 100000 km^2. Some 10000 m of Mesozoic–Tertiary sediments were laid down in the main depocentre. The seaward limit of substantial Jurassic–Cretaceous sedimentation is represented by another marginal plateau area, termed the Scott Plateau, which lies mainly between the 2000 m and 3000 m isobaths. Magnetic and gravity evidence indicates the presence of shallow basement over the northern part of the Scott Plateau and tentative seismic correlation suggests that in this area early Palaeozoic or older rocks, or both, are overlain by thin uppermost Cretaceous to Recent sediments (figure 3). Elsewhere on the plateau, however, fault-controlled structural lows could contain Triassic and possible Jurassic rocks.

Gravity, magnetic and seismic evidence all clearly indicate that the continental crust extends westward from the coast across the Scott and Exmouth marginal plateaux. The geophysical data off the western margin of the Australian continent was reviewed by Branson (1974), who calculated, from the Bouguer gravity values, a westward thinning of the crust from a standard 35 km under the continent itself to about 22 km at the outer edge of both the Exmouth and

Scott plateaux. West of the marginal plateaux, geophysical evidence indicates a relatively rapid thinning of continental crust, generally through a block-faulted transitional zone, plunging to the abyssal plains, which are floored by oceanic crust. The outer limit of the continental margin off Western Australia is approximately defined by the 4000 m isobath. Both the Scott and Exmouth plateaux are excellent example of starved passive margins with low sedimentation rates after break-up.

Some 6000 m of Palaeozoic sediments comprising Cambrian–Ordovician clastics, Silurian–Devonian evaporites, Devonian reefal and basinal facies and a Carboniferous–Permian deltaic complex filled the northwest-trending Bonaparte Gulf Basin. The outer portion of the basin, which underlies the Timor Sea, also exhibits the same northeast structural grain and has a substantially similar Mesozoic evolution to that of the other marginal basins.

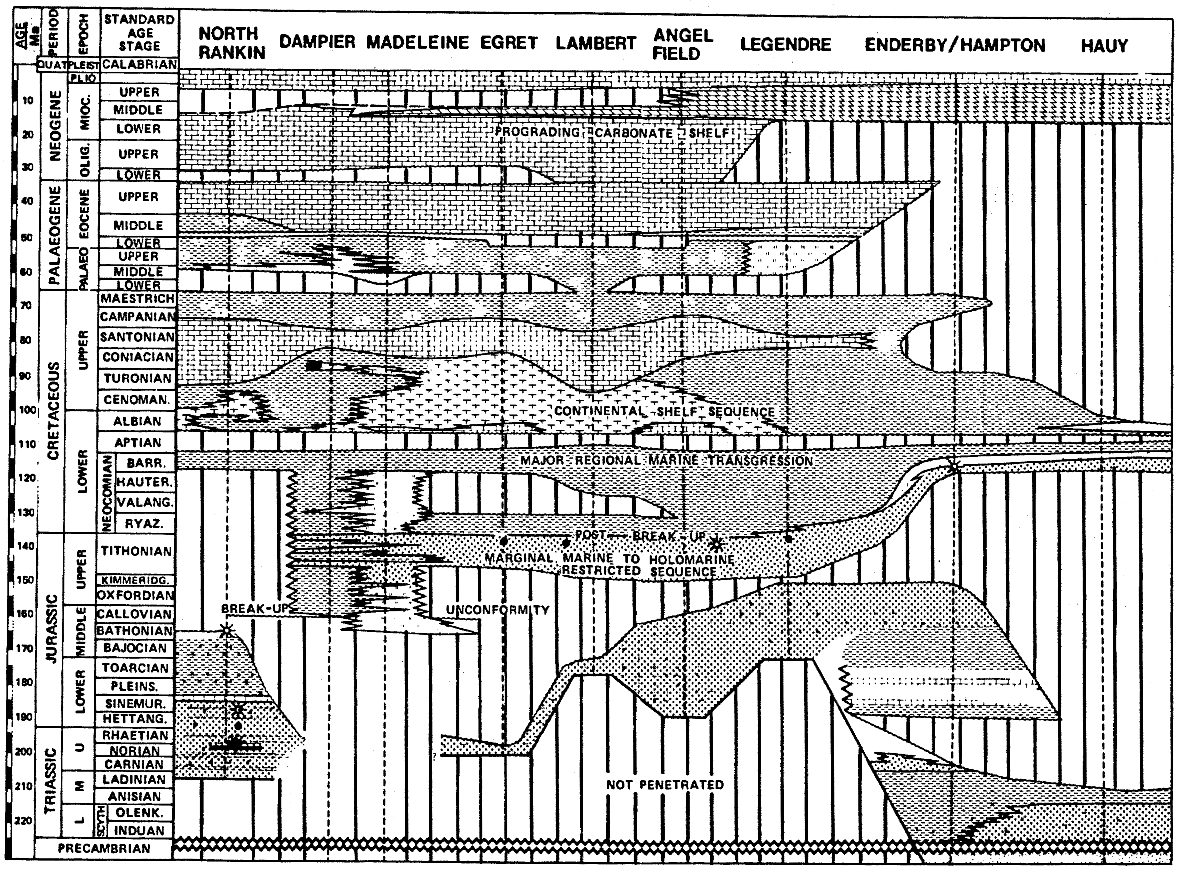

Figure 8. Dampier Sub-Basin lithostratigraphy.

Major tectonic features of the Bonaparte Gulf Basin include an uplifted area of thick Triassic sediments referred to as the Ashmore–Sahul Block and the Sahul Ridge, which is a basement high feature forming the northern limit of the Palaeozoic Bonaparte Gulf Basin.

Stratigraphy

Figures 8, 9 and 10 summarize the lithostratigraphy of the Dampier Sub-Basin, the offshore Canning and the Browse basins. Figure 11 extends westwards from the Dampier Sub-Basin over the Exmouth Plateau. Sedimentation in all cases has been controlled by phases of rifting movements of which the most important occurred at the end of the Permian, during the late Triassic, towards the end of the Middle Jurassic and during the Lower Cretaceous. The repeated tensional stresses were responsible for producing the regional structural trends which exercised a dominant control on subsequent sedimentation. As a result four major lithotectonic units are recognized and can be correlated with sequential stages of the continental rifting process.

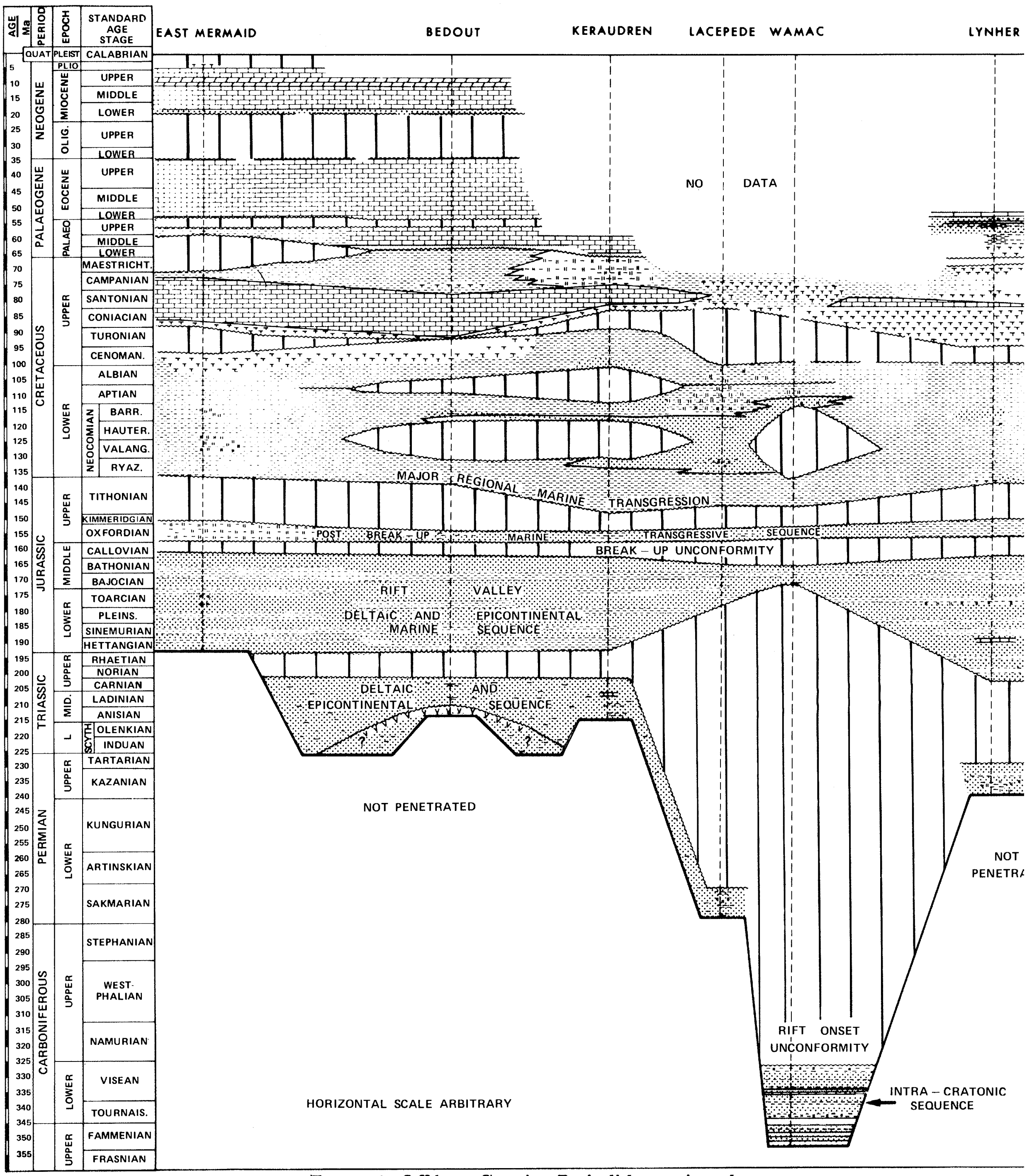

FIGURE 9. Offshore Canning Basin lithostratigraphy.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

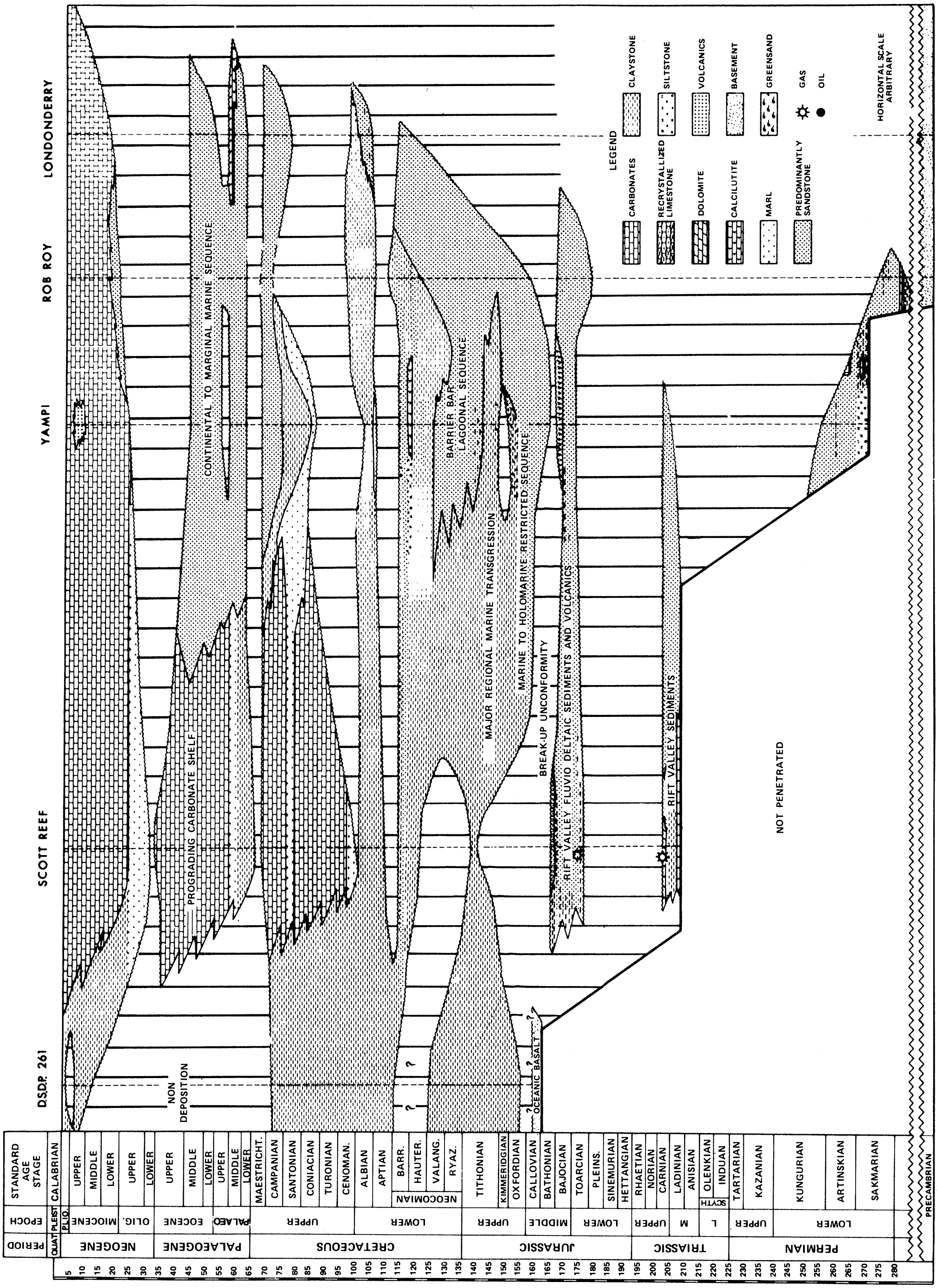

FIGURE 10. Browse Basin lithostratigraphy.

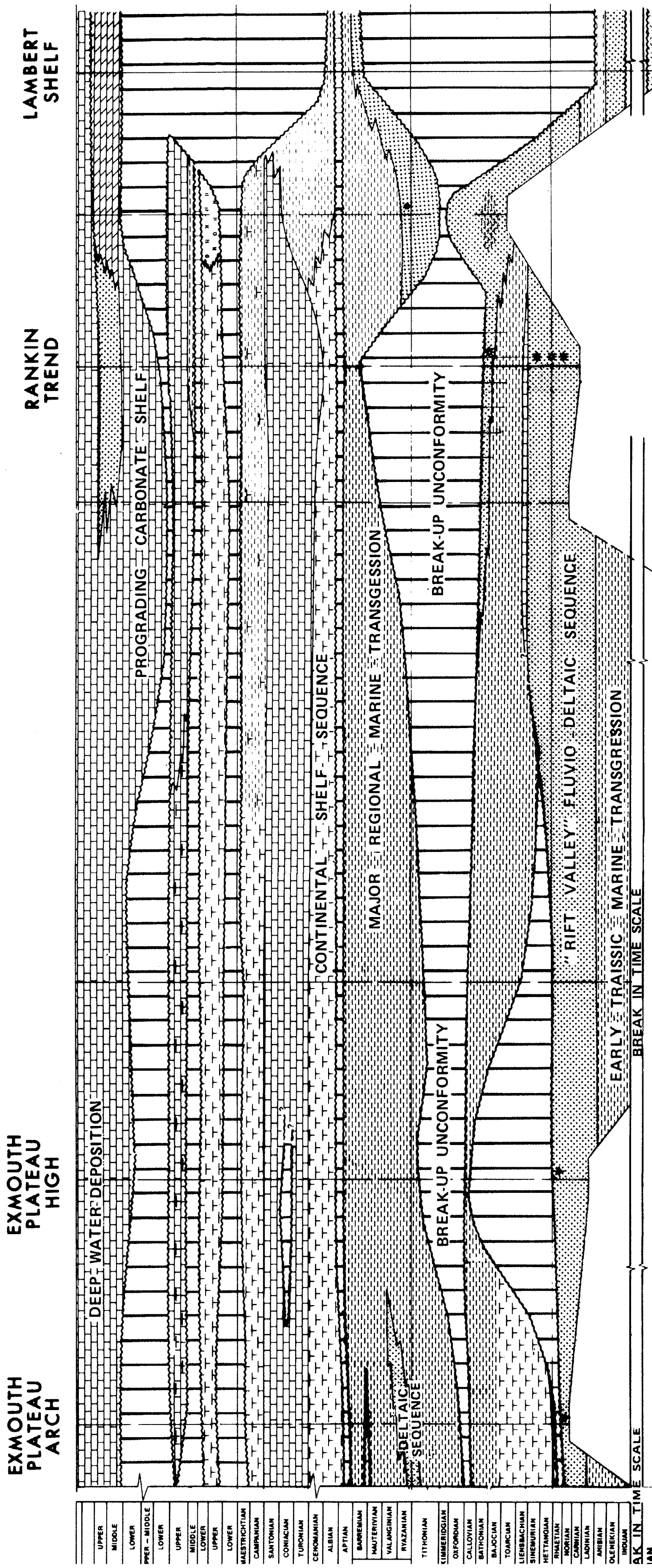

FIGURE 11. Northern Carnarvon Basin lithostratigraphy.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Permo-Carboniferous to Upper Triassic

Regional uplift of the Archaean–Proterozoic shield area accompanied by rifting was responsible for the opening of an elongate trough near the coastline of present-day Western Australia. In the offshore Northern Carnarvon Basin, little is known of this earlier depositional cycle as Permian and older rocks have been penetrated only in a few wells located near the Pilbara Shelf. From the limited subsurface data, together with outcrop evidence to the south, it would appear that the Permian is composed of over 4000 m of marine and marginal marine siltstones, sandstones and shales forming an overall regressive cycle.

Farther north, late Carboniferous to Permian rocks rest with angular unconformity on older sediments in both the offshore Canning and Browse Basins. Sparse well control indicates that sedimentation throughout was predominantly clastic in a non-marine fluviatile environment, with occasional marine incursions. The basin configuration is largely unknown, but the rapid thickening away from the basin margins observed on seismic lines is suggestive of deposition in a continually subsiding downwarp. On both well and seismic evidence a maximum of about 4000 m of Upper Carboniferous to Permian sediments appears to be present in this area.

In the Bonaparte Gulf Basin some 4000 m of Upper Carboniferous to Upper Permian fluvio-deltaic sediments are again present. Upper Permian marine shales and biomicrites in Sahul Shoals no. 1 on the Ashmore–Sahul Block reflects an increasing marine influence to the northwest. This, as well as strong faunal affinities, is consistent with the depositional trough's having been in open communication with the Tethyan Sea.

Tensional movements at the end of the Permian are evident in some areas, such as in the inner Browse Basin where they were sufficiently pronounced to cause block faulting. Elsewhere the movements are less evident, and locally in the northern Carnarvon, offshore Canning and Bonaparte Gulf basins the boundary between the Permian and the overlying Triassic seems to be merely disconformable.

The late Permian movements were accompanied by general subsidence, which led to a widespread transgression. Thus early Triassic deposits in the south are composed of marine shales, namely the Locker Shale of the Carnarvon Basin and the Blina Shale of the Canning Basin. Seismic evidence suggests that the Triassic and Permian sequences of the Carnarvon Basin extend westwards without break into the Exmouth Plateau area where a very thick equivalent section is also believed to be present.

Apart from the basal unit, the Triassic sequence is one of gradual regression so that by the late Middle Triassic a fluvio-deltaic environment was established throughout the Northwest Shelf area. In the Northern Carnarvon Basin, the Exmouth Plateau and the Canning Basin, the Middle and Upper Triassic sequence consists of 3000 m of fluvio-deltaic sands and muds. Sedimentation rates were about 50 m/Ma.

Although not encountered by the drill to date, the Lower to early Middle Triassic section in in the Browse Basin is predicted to be similar to that of the Bonaparte Gulf Basin, where Lower and early Middle Triassic marine shales and silts are overlain by a late Middle and early Upper Triassic fluvio-deltaic to shallow marine sequence. More than 2000 m of Upper Triassic marginal marine sediments, together with volcanics and evaporites, accumulated on the Ashmore–Sahul Block.

Lower to Middle Jurassic

A major stage in the fragmentation of the stable crustal unit of Gondwanaland occurred in the late Triassic, when tensional stresses resulted in extensive block faulting. These movements were particularly severe in the northern area (offshore Canning, Browse and Bonaparte Gulf basins), where they were accompanied by widespread erosion, so that subsequent sediments ranging in age from Lower Jurassic to Cretaceous are markedly unconformable on the older sequence. The post-erosion sedimentary cycle commenced in the early Lower Jurassic with red beds, non-marine and deltaic sediments that are widespread in the offshore Canning and Bonaparte Gulf basins. On seismic lines the lowermost beds can be seen to occur within depressions in the irregular palaeotopographic surface, but by the end of the Lower Jurassic most of this palaeotopography had been infilled. The remainder of the Lower to Middle Jurassic sequence in the three northern basins is predominantly non-marine and consists of thick bedded fluvio-deltaic sandstones with interbedded claystones, siltstones and occasional coals. Lower to Middle Jurassic fluvio-deltaic sands belonging to this sequence form the main reservoirs in the Scott Reef Troubadour and Sunrise gas–condensate discoveries.

Late Triassic to early Jurassic movements have also been observed in the Northern Carnarvon Basin, accompanied by uplift along the basin margins and over parts of the Exmouth Plateau. Locally, however, as on parts of the Rankin Platform, fluvio-deltaic sedimentation was continuous from the Triassic through into the Lower to Middle Jurassic. In this area an uninterrupted uppermost Triassic to late Middle Jurassic sequence of some 3000 m in thickness is present, with extensive sandstone development in the Upper Triassic passing upwards into predominantly claystones in the Lower to Middle Jurassic. Seismic and well evidence shows this thick Triassic to Jurassic section extends over the Exmouth Plateau, except for those parts of the Plateau that were uplifted during the Late Triassic movements. Early and Middle Jurassic sedimentation rates were 50–100 m/Ma.

Upper Jurassic to early Cretaceous

Pull-apart movements at the end of the Middle Jurassic initiated the principal period of tectonism affecting the Northern Carnarvon Basin. During this period the major positive trends were enhanced and strong uplift occurred on the Rankin Platform and the Exmouth Plateau. The succeeding marine transgression took place over a highly irregular palaeotopographic surface. Upper Jurassic to Lower Cretaceous marine sedimentation commenced in the deeper parts of the basin and, with continued subsidence, gradually submerged the upstanding scarps of the Rankin Platform, which were all inundated by the Upper Neocomian. Sedimentation rates reached a maximum of 70 m/Ma in the central part of the Barrow and Dampier sub-basins where the sequence is over 5000 m thick, consisting predominantly of claystones. These were deposited in a restricted marine environment, as evidenced by lack of planktonic fauna and the common occurrence of pyrite. In the northeast Dampier Sub-Basin, however, a thick Tithonian sand section was deposited in a nearshore, shallow marine environment. By the late Neocomian, claystone deposition was widespread, and this continued into the Aptian. During the late Jurassic to Neocomian, a delta 2000 m thick built northward onto the Exmouth Plateau and into the Barrow Sub-Basin. In the Canning Basin, Upper Jurassic sediments are generally absent, but a thick Lower Cretaceous claystone sequence of up to 1000 m was laid down on the continental shelf.

Major tensional movements during the Callovian–Oxfordian period are also evident in the Browse and Bonaparte Gulf Basins, being preceded in the former area by outpourings of volcanic basalt. These are recorded from the Scott Reef no. 1, Yampi no. 1, and Lombardina no. 1 wells. In the transgressive series that followed, early paralic sandstone sedimentation was superseded by thick marine claystone deposition, as marine conditions became widespread. A similar depositional environment to that of the Dampier Sub-Basin is generally envisaged for the Upper Jurassic to lowermost Cretaceous sequence of the Browse and Bonaparte Gulf Basins, where thick restricted marine claystones were initially deposited in the troughs, passing laterally into marginal marine to deltaic facies in the more topographically elevated areas.

Late Lower Cretaceous to Tertiary

Throughout the Northwest Shelf a marked change, from a restricted to an open marine facies, is evident during the early Albian. The later Cretaceous consists of deep water marls and calcilutites, passing upwards into a mainly claystone sequence.

An unconformity at base Tertiary level is observed regionally, and is indicative of initial subsidence and general deepening of the depositional environment followed by a gradual regressive cycle. Palaeocene to Lower Eocene sediments are predominantly deep water claystones and calcilutites, but by the Middle Eocene thick calcarenite deposition had been established in an inner-shelf to nearshore environment. Continued regression has resulted in a thick predominantly carbonate wedge prograding over the entire inner shelf. Tertiary sediments at the shelf edge attain a thickness of over 3000 m.

Geological evolution

The geological evolution of the Northwest Shelf can be related closely to a series of continental rifting movements which began in the late Palaeozoic, and which ultimately led to complete break-up of eastern Gondwanaland in Upper Jurassic – Lower Cretaceous times. The lengthy rifting history, associated with the fact that the most intensive tensional phases are not time-equivalent over the entire area, has caused a relatively complex continental margin development, in part characterized by the development of parallel rift valleys that are considered to be aborted rifts. This appears to contrast with the simpler development of the southern Australian rifted margin during the Tertiary (Boeuf & Doust 1975).

In the late Palaeozoic an elongate trough was initiated near to and paralleling the edge of the present-day Western Australian landmass. The presence of such a trough was first recognized by Teichert (1939). Its extent and orientation suggests that its inception was caused by major tensional movements normal to the approximate northwest trend of the onshore Palaeozoic intra-cratonic basins. The rift thus formed probably constituted a structurally simple trough extending westwards to at least the limit of the present continental crust, and northwards along the length of the Australian coast. It appears to have been in open communication with the Tethyan Sea, the post-Sakmarian deposits of Western Australia having close faunal similarities with Timor and the Salt Range of northern India (Dickins 1963).

It is considered that many of the major structural trends, which continued to be active throughout the Mesozoic, were initiated during a block faulting phase at the end of the Permian which caused fragmentation of the original trough. It is possible that uplift of the northwestern edge of the Scott Plateau occurred at this time. This is in contrast to the Ashmore–

Sahul Block and Scott Reef areas where a thick Permo-Triassic section, accompanied locally by volcanism, suggests graben fill. It is significant that volcanics are found only in the area that lay closest to the location of the evolving rift axis. Data from wells located east and northeast of the Scott Plateau indicate a west to northwest sediment source during the Triassic. It is considered that an uplifted area adjacent to the rift axis on the western edge of the Scott Plateau could have provided this source.

At the end of the Triassic a further major phase of the rifting process occurred, and was responsible for the main period of structural activity in the northern basins. Uplifted areas at the outer edge of the present-day margins may have included the Ashmore–Sahul Block and parts of the Exmouth Plateau. Erosion of high areas and the deposition of red beds followed by a thick non-marine sequence marks the continuation of a widespread typical rift valley stage.

The effects of the late Triassic movements were less pronounced in the Northern Carnarvon Basin, where they were probably restricted to epeirogenic movements along previously established major northeast trends accompanied by uplift along the basin margins. The observed southward migration of tectonism with time is also observed in the timing of actual break-up of the western margin of the Australian continent, which again began earliest in the northern areas (indicated by results of D.S.D.P. drillholes 261, 260 and 259). Contrary to earlier interpretation, evidence from drilling to date currently suggests that the entire Triassic sequence in the southern basins, which is largely of a fluvio-deltaic nature, was derived from the ancestral Pilbara Block to the south and east. The thick Triassic section present in the Exmouth Plateau area, however, may well have been derived in part from an unidentified landmass that lay farther to the west.

The major period of tectonism in the Northern Carnarvon Basin resulted from the rifting phase that took place at the end of the Middle Jurassic, and which represented the onset of complete continental break-up. Northeast-trending large-scale block faulting established a complex horst and graben infrastructure. General subsidence followed the tensional movements, although the positive areas such as the Rankin Platform remained topographically high. The ensuing Upper Jurassic transgression consequently took place over a palaeotopographic surface of varied relief, with sedimentation that was both local in distribution and environmentally restricted. Upper Jurassic faunas and floras still, however, have a Tethyan aspect. As subsequent rupture of the continental margin took place later and farther out to sea, the Northern Carnarvon Basin can be regarded as an aborted rift that in itself never evolved beyond this stage.

Creation of new oceanic crust occurred to the northwest of the Exmouth Plateau and to the west of the Browse Basin during the late Middle to early Upper Jurassic. Magnetic lineations on the Argo Abyssal Plain, which trend almost east–west north of the Exmouth Plateau (Heirtzler *et al.* 1978) range in age from 148 to 153 Ma, and suggest that that margin formed by a combination of rifting and transform faulting in the Callovian. This dating is also supported by the existence of Oxfordian sediments immediately above oceanic basement at D.S.D.P. Site 261 (Veevers *et al.* 1974). The Middle Jurassic basaltic lavas recorded from several wells in the Browse Basin also probably correlate with this initial formation of new oceanic crust.

Sea floor spreading began later in the southern area. Magnetic anomalies in the Cuvier and Gascoyne abyssal plains range in age from 108 to 123 Ma and suggest that the southwestern and northwestern margins of the Exmouth Plateau formed at the same time in the late Neocomian, i.e. 120–125 Ma. This is confirmed by D.S.D.P. Site 263. The southwestern margin formed as a transform fault (Cape Range Fracture Zone), whereas the northwestern margin is a rifted margin. The separation of Greater India from these two margins drastically reduced the clastic supply to the plateau, and thereafter deltaic sedimentation ceased and subsidence rates exceeded sedimentation. A period of strong north–south orientated faulting is recorded in the late Upper Jurassic or early Cretaceous of the Dampier Sub-Basin (Powell 1973), and is probably also related to this late spreading phase. Regional subsidence followed by a rapid transgression in the Lower Cretaceous marks the dispersal phase of eastern Gondwanaland.

A post-dispersal mature ocean stage, characterised by the establishment of a free circulating system, evolved in the late Lower Cretaceous. The Lower Cretaceous generally exhibits a transitional sequence from a marginal marine-deltaic environment with a virtual absence of Foraminifera to that of an open shelf facies with a diverse planktonic–benthonic assemblage. The change to an unrestricted marine environment ranges from Cenomanian in the Browse Basin to Middle Albian in the Dampier and Beagle sub-basins.

By Upper Cretaceous time an open marine environment was widespread over the entire area and, with minor variations, has persisted to the present day. Continued subsidence of the continental shelf has occurred from the late Cretaceous. A prograding carbonate wedge 3000 m thick has been deposited over the entire inner shelf area since mid-Eocene, as a result of which the shelf now has a general northwesterly regional tilt. This prograding stage is of course characteristic of a fully evolved 'Atlantic-type' margin. By contrast, during the late Cretaceous and Cainozoic the Exmouth Plateau sank 2000–3000 m, and sedimentation did not keep pace; the amount of sediment laid down averages 800 m, representing a sedimentation rate of less than 10 m/Ma.

Hydrocarbon occurrences

All of the prerequisites for major hydrocarbon accumulations can be recognized within the various development stages of the northwest Australian continental margin. The pre-break-up rift valley stage is characterized by rapid deposition of thick, mostly fluvio-deltaic clastics constituting excellent potential reservoirs. The tectonic phase accompanying rifting produced a block faulted substructure over which the initial post-break-up transgression occurred. The resulting fine-grained clastic sequence is an excellent hydrocarbon source rock and in addition is draped over the upstanding horsts to complete the trapping mechanism. Finally, the thick prograding sedimentary wedge deposited during the mature ocean stage depressed the older sediments to levels at which thermal generation of hydrocarbons could take place.

The validity of this model for the mechanism of hydrocarbon generation and entrapment is reflected in the overall results so far obtained from exploration drilling along the continental margin. To the south, in the Barrow Sub-Basin, the Barrow Island Field is a major oil producer with the main production being obtained from Cretaceous sands contained within the post-break-up sequence.

The greatest concentration of discoveries occurs in the adjoining Dampier Sub-Basin, where some large gas–condensate fields and also several smaller accumulations of both oil and gas–condensate have been found to date. These are shown in figure 12, and the stratigraphic positions of some of the hydrocarbon reservoirs are indicated in figure 8. In three of the main fields (North Rankin, Goodwyn and West Tryal Rocks) the reservoir is represented by thick fluvio-deltaic Upper Triassic to Lower Jurassic sands contained within a tilted horst block trap and sealed unconformably by Lower Cretaceous claystones. North Rankin is the largest discovery with estimated recoverable reserves of about 230 km^3 gas together with condensate in the ratio of 0.16 $m^3/10^3\,m^3$ gas. The sandstones have excellent reservoir characteristics with porosities averaging over 20% and generally very high permeabilities.

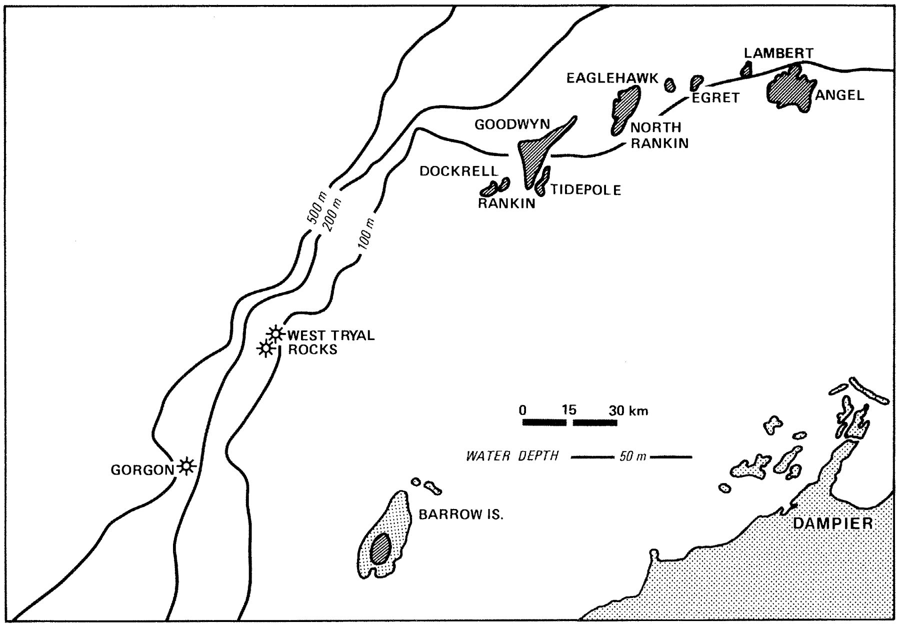

FIGURE 12. Dampier and Barrow sub-basins discoveries.

Fluvio-deltaic sands of the Upper Triassic 'rift valley stage' also constitute the main reservoirs for the gas–condensate and oil flows from the Rankin, Dockrell and Eaglehawk structures. In the Angel field, the gas–condensate accumulation is contained in sandstone reservoirs within the Upper Jurassic transgressive sequence. Beach, offshore bar and paralic sand facies within this stratigraphic interval also provide the reservoir for the small oil accumulations at Egret and Lambert while in the Legendre area, southeast of Angel, a small oil pool is present in Lower Cretaceous sands.

Despite the variations in reservoir age, the oils and condensates of many of the various Dampier Sub-Basin discoveries show a remarkable similarity in composition and a common source has been invoked for these (Powell & McKirdy 1973). The most likely sources are marine claystones deposited during the Upper Jurassic transgression, which followed the late Middle Jurassic tectonic phase. These claystones, which are rich in both cuticle and sapropel, were deposited in a restricted environment, conducive to organic preservation, and constitute excellent potential source rocks. The transgressive series filled the palaeotopographical lows so that the hydrocarbons generated later were able to migrate into structurally higher traps, such as the Triassic horsts on the Rankin Platform. The Upper Cretaceous marine claystones, which finally inundated the upstanding horsts, have provided a reservoir seal on a regional scale.

The Browse and Bonaparte Gulf basins have been less extensively explored than the Dampier Sub-Basin due mainly to excessive water depths. However, the Scott Reef no. 1 well drilled near the Browse Basin outer margin was another gas–condensate discovery and in the Bonaparte Gulf Basin two gas–condensate discovery wells, Troubadour no. 1 and Sunrise no. 1, were drilled on the Sahul Ridge.

Bibliography (Powell)

Beck, R. H. & Lehner, P. 1974 *Bull. Am. Ass. Petrol. Geol.* **58**, 376–395.
Boeuf, M. G. & Doust, H. 1975 *APEA Jl* **15**, 33–43.
Branson, J. C. 1974 Structures of the Western Margin of the Australian Continent. Bur. Miner. Resour. Aust. Rec. 1974/64. (Unpublished.)
Dickins, J. M. 1963 *Bur. Miner. Resour. Aust. Bull.* no. 63.
Falvey, D. A. 1972 Ph.D. thesis, University of New South Wales.
Falvey, D A 1974 *APEA Jl* **14**, 96–106.
Heirtzler, J. R., Cameron, P. J., Cook, P. J., Powell, T., Roeser, H. A., Sukardi, S. & Veevers, J. J. 1978 *Earth planet. Sci. Lett.* **41**, 21–31.
Laws, R. A. & Kraus, G. P. 1974 *APEA Jl* **14**, 77–84.
Lofting, M. J. W., Crostella, A. & Halse, J. W. 1975 In *Proc. 9th World Petrol. Congr., Tokyo*, 1975.
Powell, D. E. 1973 Paper presented at Australasian Inst. Min. Metallurgy, Western Australia Conference, 1973, pp. 193–204.
Powell, T. G. & McKirdy, D. M. 1973 *APEA Jl* **13**, 81–85.
Schneider, E. D. 1972 *Mem. geol. Soc. Am.* **132**, 109–118.
Teichert, C. 1939 *Aust. J. Sci.* **2**, 84–86.
Veevers, J. J. & Heirtzler, J. R. 1974 *Woods Hole Oceanographic Contribution* no. 3217.
Veevers, J. J., Heirtzler, J. R. *et al.* 1974 *Init. Rep. Deep Sea Drilling Project* **27**, Washington, D.C.: U.S. Government Printing Office.
von Stackelberg, U., Exon, N. F., von Rad, U., Quilty, P., Shafik, S., Beiersdorf, H., Seibertz, E. & Veevers, J. J. 1980 *B.M.R. Jl Aust. Geol. Geophys.* **5**, 113–140.

Discussion

Sir Peter Kent, F.R.S. Though there appears to be a general similarity between the style of faulting off the Australian margin and in the North Sea, the dip of the faults shown on Australian profiles appears to be greater than those in the North Sea. Is this a consequence of the vertical exaggeration in the sections or is there a real difference between the two regions?

D. E. Powell. The steep dips on the profiles are largely a result of the vertical exaggeration. The dips of the faults in the inner part of the basin are probably between 50° and 60°. However, the larger faults on the southwestern side of the Exmouth Plateau have dips as great as 70°, where the margin probably had a large transform component.

Sir Kingsley Dunham, F.R.S. The profiles that Mr Powell showed seem to differ from those on the northern margin of the Bay of Biscay in showing considerably less crustal attenuation. Is this difference supported by more detailed studies?

D. E. Powell. In the Exmouth plateau area in the south, the thick middle to lower Jurassic and also the thick Triassic beds continue westwards, probably as a continuation of the North Carnarvon basin. Further north in the Scott Plateau area the situation is different. The Browse and Bonaparte Gulf basins appear to be limited by an uplifted region of Proterozoic rocks on which no Mesozoic sediments were deposited. The thickness of the continental crust obtained from gravity and magnetic surveys in this area varies from about 30 km near the present Australian coast line to about 22 km beneath the Exmouth Plateau, and 17 km beneath the Scott Plateau. Since this thinning takes place over 600 km the geometry is very different from the Biscay margin.

G. Karner. The rifting style around the Australian margin is characterized by the creation of offshore plateaux, for example the Exmouth and Scott Plateau, by movement on widely separated normal faults. Realizing that the data presented do not directly address this problem, could Mr Powell please comment on this peculiar rifting style perhaps in light of the previous Bay of Biscay papers, where the faults are more closely spaced?

Secondly, I noticed in Mr Powell's cross sections across the Exmouth and Scott Plateaux that the ocean–continent boundary was on the plateau proper. The oldest oceanic crust is therefore elevated at a height of 1–1.5 km relative to the younger oceanic crust. What is the character of the ocean continent boundary? i.e., what is the basalt geochemistry, are they stratified, what was the depositional environment, etc.?

D. E. Powell. There is an abrupt change from oceanic to continental crust. The strata overlying the continental crust can be followed out almost to the continental edge, both by using the drill sections and seismic reflexion, and the D.S.D.P. holes are close to the boundary on the ocean side. The southern and southwestern margins of the Exmouth Plateau must have been produced by transform faulting. The northern margin was probably produced by a combination of rifting and transform faulting. The two boundaries were also produced at different times; that in the north was formed during the Callovian whereas the southern boundary did not form until the early Cretaceous. I do not understand why the lithosphere should deform in different ways around the North Atlantic and off Northwestern Australia.

M. F. Osmaston. What are the ages and character of the oldest drill-sampled rocks on the various offshore structural highs mentioned, notably the Exmouth and Scott Plateau? From reflexion seismic data at these sampled sites how much sedimentary section, if any, lies beyond the depth reached by drilling and can any marked unconformities be discerned therein?

D. E. Powell. The only areas where pre-Permian rocks have been reached by drilling are on the inner parts of the continental margin. On the Sahul ridge the Troubador well reached a granite which produced a pre-Permian date. On the Exmouth plateau I doubt if any of the wells have reached Permian rocks, but I have not seen all the available information. (Dr Murphy of Esso agreed with Mr Powell.)

A. S. MacKenzie. Have the proposed Jurassic origin of the oils and gases, and the Tertiary timing of oil and gas generation, been tested by some organic geochemical or isotopic measurements?

D. E. Powell. There is extensive geochemical evidence for a Jurassic origin of the oils. I originally believed that the Upper Jurassic claystones, laid down during a transgression when the circulation was restricted, formed the principal source rocks in the area. However, it has now been demonstrated that a number of other Lower Jurassic marine incursions also produced deposits that have acted as source rocks. It is more difficult to determine where the gas originates.