BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD

IN CONFIDENCE

Record 1981/40

SUMMARY OF PETROLEUM EXPLORATION

DRILLING, EXMOUTH PLATEAU, TO 31 DECEMBER 1980

by

E. NICHOLAS

CANCELLED

IN CONFIDENCE

Record 1981/40

SUMMARY OF PETROLEUM EXPLORATION

DRILLING, EXMOUTH PLATEAU, TO 31 DECEMBER 1980

by

E. NICHOLAS

CONTENTS

	PAGE
ABSTRACT	i
INTRODUCTION	1
SUMMARY OF GEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS	1
GEOLOGICAL HISTORY	2
STRATIGRAPHY	3
PETROLEUM SOURCE POTENTIAL	7
EXPLORATION PLAYS	8
SUB-UNCONFORMITY PLAY	10
INTRA-TRIASSIC PLAY	14
DELTA CREST PLAY	20
INTRA-DELTA PLAYS	21
FUTURE DROSPECTS	23
REFERENCES	25
APPENDIX 1 RESOURCE ASSESSMENT	29

TABLE 1. Geophysical Surveys, Exmouth Plateau, 19.11.77 to 18.11.80

TABLE 2. Petroleum Exploration wells, Exmouth Plateau, to 31.12.80

TABLE 3. Geochemical and vitrinite reflectance data, Late Triassic to Late Cretaceous section.

TABLE 4. Geochemical and vitrinite reflectance data, Triassic Mungaroo Formation equivalent.

TABLE 5. Geochemical and vitrinite reflectance data, Late Triassic to Late Cretaceous section.

PLATES

1. Exmouth Plateau seismic surveys 1968-1977, and well locations Exmouth Plateau and Barrow and Dampier Sub-basins to 31.12.80
2. Well correlations, Exmouth Plateau to Barrow Sub-basin.

FIGURES

1. Regional setting.
2. Major tectonic elements.

ABSTRACT

The results of petroleum exploration drilling on the Exmouth Plateau in 1979 and 1980 are reviewed. Assessments made in BMR of the hypothetical resources in five of the structures drilled are presented and discussed in the light of the drilling results.

The Exmouth Plateau is located off Australia's northwest continental shelf, and covers an area of about 150 000 km^2, extending from the foot of the upper continental slope in water about 800 m deep to the 2000 m isobath. Up to 10 000 m of Phanerozoic sediments are interpreted to underlie the Exmouth Plateau, of which at least 3000 m were shown by the drilling to constitute a Late Triassic fluviodeltaic sequence, correlated with the Mungaroo Formation on the continental shelf (Rankin Trend). The sediments underlying the plateau, together with those underlying the adjacent shelf in the Barrow and Dampier Sub-basins, were deposited in the northern Carnarvon Basin.

Petroleum exploration on the Exmouth Plateau began on 19 November 1977 when the five exploration permits covering the Plateau were granted to four groups of companies. Following a period of geophysical exploration, drilling began on 5 March 1979 with the spudding in of Zeewulf No. 1 by Esso Australia Ltd in water 1194 m deep using the dynamically positioned drillship, Sedco 472. Esso had completed eight wells by 31 December 1980 and Phillips Australian Oil Company two, in the three permit areas covering the southern half of the plateau. Sandstone reservoirs in the Late Triassic fluvio-deltaic section and/or the Early Cretaceous to Late Jurassic deltaic complex, were the drilling targets. There were two gas discoveries in the Triassic section, in Jupiter No. 1 (Phillips) and Vinck No. 1 (Esso) (gas/condensate), and gas was discovered in the Early Cretaceous deltaic section in Scarborough No. 1. (Esso). In the absence of production technology for natural gas from deepwater areas, these discoveries have no economic significance at the present time.

No significant indications of oil were recorded in the wells. Source-rock studies indicate that oil-prone source rocks occur in the Early Cretaceous and Late Jurassic units, but at the depths intersected the levels of organic maturation are too low for hydrocarbon generation. Source rocks in the Triassic section were predominantly gas-prone, but some were interpreted to have both gas and oil source potential. The Triassic section appears to be mature for hydrocarbon generation at depths below about 3500 m.

INTRODUCTION

The Exmouth Plateau is a marginal plateau located off Australia's northwest continental shelf, covering an area of about 150 000 km^2 extending from the foot of the upper continental slope in water about 800 m deep to the 2000-m isobath. This Record reviews the results of petroleum exploration drilling on the Exmouth Plateau in 1979 and 1980. Assessments made in BMR, of the hypothetical resources in five of the structures drilled, are also reviewed in the light of the drilling results.

SUMMARY OF GEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS

The original interpretation of the geology and structure of the Exmouth Plateau by BMR scientists (Exon & others, 1975; Willcox & Exon, 1976; Exon & Willcox, 1978) was based largely on 12 000 km of gravity, magnetic, and reflection seismic data from the BMR Continental Margin Survey and 6000 km of company data acquired under the terms of the Petroleum (Submerged Lands) Act. Since then an additional 9300 km of seismic data (Plate 1) has been acquired by Geophysical Service International during two Scientific Surveys over the Exmouth Plateau; one in 1976 (No. 10SL), and one in 1977 (No. 11SL), before exploration permits were granted. The 1976 survey was interpreted by Wright & Wheatley (1979) and data from the 1976 and the 1977 surveys were interpreted by Hudbay Oil (Australia) Ltd (Hudbay) (Duke, 1978). The five petroleum exploration permits covering the Exmouth Plateau were granted to four groups of companies on 19 November 1977. Geophysical exploration carried out between then and 18 November 1980, is listed in Table 1.

Drilling in deep water on the Exmouth Plateau began on 5 March 1979 when Esso Australia Ltd (Esso), using dynamically positioned drill-ships (Sedco 471 and 472), spudded in Zeewulf No. 1 in a water depth of 1194 m. By the end of the year, Esso had completed four wells, and Phillips Australian Oil Company (Phillips), two. Esso drilled a further four wells in 1980, and a well for Phillips was in progress at the end of that year. The wells are listed in Table 2 and locations shown on Plate 1.

Three other wells, Brigadier No. 1, Delambre No. 1, and Gandara No. 1, drilled on the eastern margins of the two northern petroleum exploration permits, WA 90 and 93 P (Plate 1), were located in the outer Dampier Sub-basin and are not included in this Record.

Gas was discovered in Scarborough No. 1 and gas/condensate in Vinck No. 1, both drilled by Esso, and gas was discovered in Jupiter No. 1, drilled by Phillips. Because of the cost and technological difficulty of piping the gas to shore, these discoveries are classed as non-economic, although there is a future possibility of using the gas as a feedstock in floating methanol or gasoline plants or in floating LNG plants. Gas or gas/condensate-shows of varying significance were recorded in the remaining Esso wells, but there were no indications of oil.

GEOLOGICAL HISTORY

The following brief summary is based on Exon & Willcox (1978), Chaney (1978), Esso (1978), and von Stackelberg & others (1980).

The regional setting of the Exmouth Plateau and the major tectonic elements are shown in Figures 1 and 2. The Plateau is bounded to the southeast by the Barrow and Dampier Sub-basins, and to the north, west, and south by the Argo, Gascoyne, and Cuvier Abyssal Plains.

Up to 10 000 m of Phanerozoic sediments are estimated to underlie the Exmouth Plateau, of which up to 5000 m are likely to be Palaeozoic. To date, the oldest sediments drilled are of Late Triassic age.

The sedimentary rocks of the Exmouth Plateau, together with those of the Barrow and Dampier Sub-basins, were deposited in the northern Carnarvon Basin. Sedimentation from at least the Permian onwards, was controll[ed] by a series of diastrophic events during the break up of Gondwanaland and the evolution of Australia's northwestern and western continental margin. Arching of the area in the Late Carboniferous, was followed by rifting in the Permian, Triassic, and Jurassic, and deposition of shallow marine and fluviodeltaic sediments. These sediments were extensively block-faulted during the rifting phase in the Late Triassic-Middle Jurassic (Fitzroy Movement of Gorter & others, 1979); uplift and deep erosion of the block-faulted sequence marking the culmination of the tensional phase.

In the Early Jurassic, the Plateau subsided north of an easterly-trending hinge line, and a northwesterly-thickening wedge of Early Jurassic carbonates overlain by Middle Jurassic coal measures was deposited in the area of the present northern margin (von Stackelberg & others, 1980). In the central and southwestern area of the Plateau sedimentation rates were low during this period, and carbonate sediments were deposited from Late Triassic to Middle Jurassic (Plate 2).

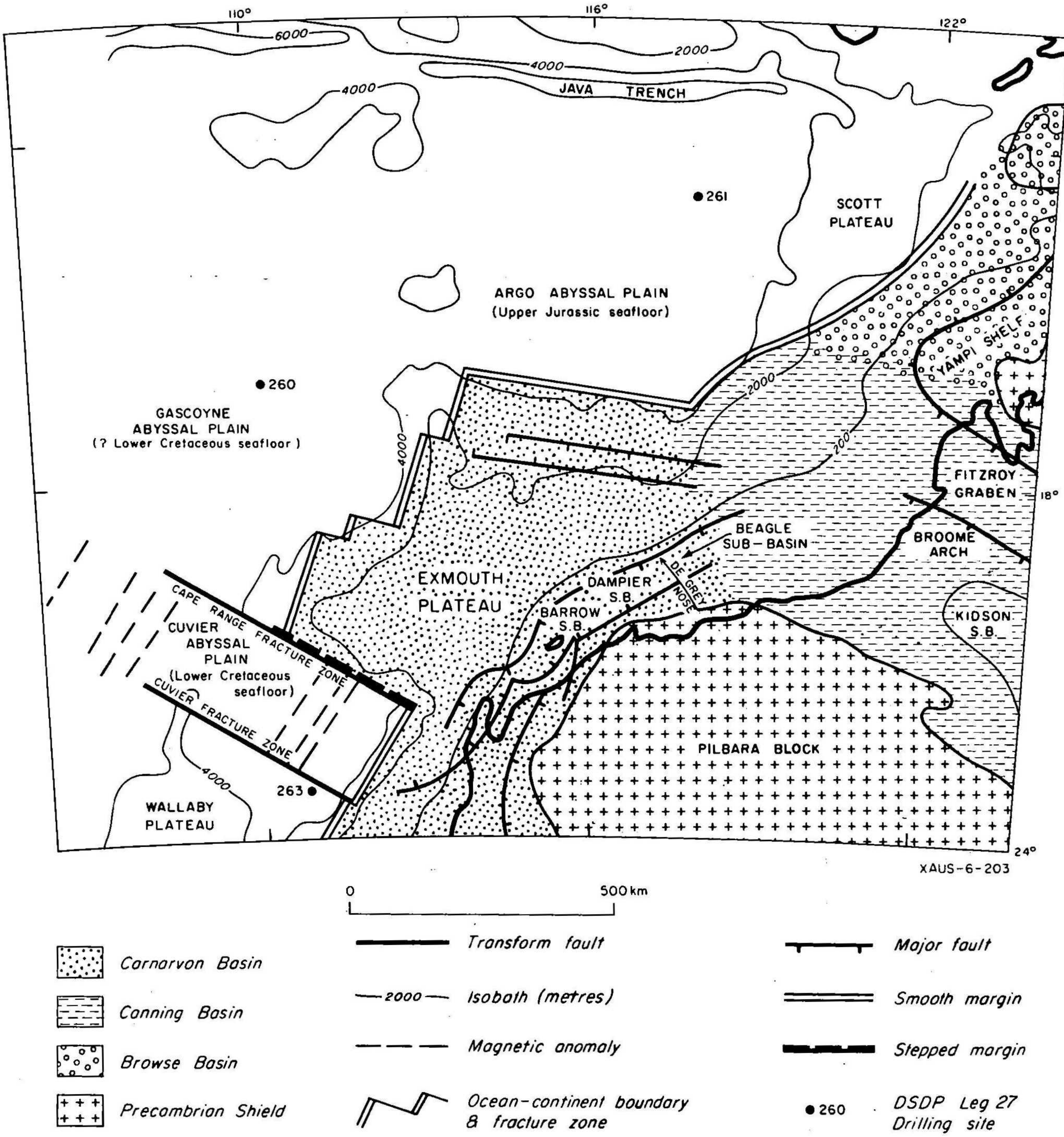


Fig. 1 Regional Setting (after Chaney, 1978)

RESTRICTED

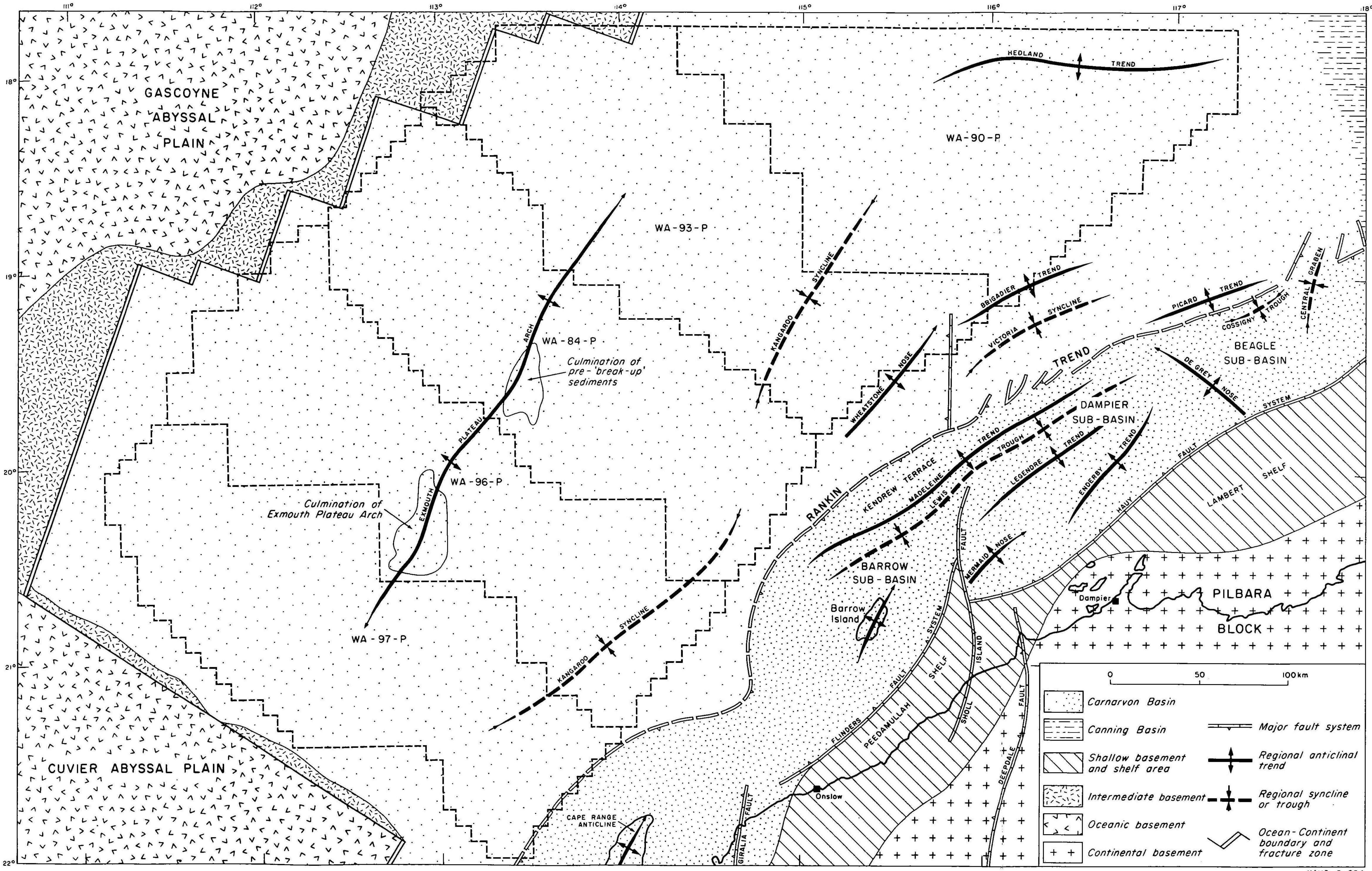


Fig. 2 Major tectonic elements (after Chaney, 1979)

RESTRICTED

The northeastern margin of the Exmouth Plateau formed as a result of seafloor-spreading in the region of the Argo Abyssal Plain, which separated the Plateau from a northern landmass. The onset of seafloor-spreading was late Middle to early Late Jurassic based on magnetic anomalies and data from DSDP Site 261.

During the marine transgression that followed separation from the northern landmass, terrigenous sediments were deposited in restricted marine environments over the highly irregular topographic surface of the block-faulted sequence, and in the southern area a major deltaic complex prograded northwards until sediment supply was cut-off by the development of the southwestern margin; the onset of seafloor-spreading in the region of the Cuvier Abyssal Plain is dated on magnetic anomalies as Early Cretaceous (late Neocomian). Magnetic anomalies in the Gascoyne Abyssal Plain suggest the same age for the development of the northwestern margin (Larson & others, 1979).

Predominantly carbonate sediments have been deposited in open ocean environments since the Late Cretaceous. It has been estimated that the Plateau sank 2000 to 3000 m, mainly in the Late Cretaceous and Early Tertiary, and accumulated an average thickness of 800 m of sediment (von Stackelberg & others, 1980). The sedimentation rate of 800 m per million years is one third that of rates on the adjacent shelf. Gentle warping of the Plateau in the Late Miocene produced the Exmouth Plateau Arch.

STRATIGRAPHY

The stratigraphic correlation of wells for which completion reports are available is shown in Plate 2.

The stratigraphy is described in relation to three time intervals; Triassic to Middle Jurassic; Late Jurassic and Early Cretaceous; and Late Cretaceous to Recent. These intervals represent the rifting, continental break up, and open ocean phases in the geological evolution of the Exmouth Plateau.

Stratigraphic information is from company well completion reports, or other sources as cited.

Middle Triassic to Middle Jurassic

With the exception of Scarborough No. 1, all the wells reached total depth in a fluvio-deltaic Triassic sequence correlated with the Mungaroo Formation in the Barrow and Dampier Sub-basins. The greatest thickness of 3051 m, was penetrated by Jupiter No. 1 which was located on the crest of the Exmouth Plateau Arch at the culmination of the pre-'break-up' block-faulted sequence. Palynological evidence dates the sequence as Late Triassic, with the possibility that in Jupiter No. 1 the lower part may extend into the Middle Triassic (Ladinian), although the spores in the basal 600 m are too poorly preserved for a reliable age determination. The formation comprises an interbedded sequence of sandstone, siltstone, claystone, shale, and minor coal. Beds of sedimentary quartzite are common in the lower part of Jupiter No. 1 and Mercury No. 1.

The Mercury No. 1 completion report (Phillips, 1980b, appendix 6), contains a detailed analysis of the depositional environment of the Late Triassic sequence. This report integrates the information from Jupiter No. 1 and Mercury No. 1 with the results of a study of Late Triassic depositional environments in the Dampier Sub-basin carried out prior to drilling in WA 84-P on the Exmouth Plateau (Vos, 1978). The pre-drill study, showed that the Middle and Late Triassic sediments in the Dampier Sub-basin are characteristically alluvial plain deposits. Fossiliferous and burrowed shales and siltstones containing glauconite, which occur in the upper part of the sequence, are indicative of transgressive marine conditions.

On the Exmouth Plateau, the thick sandstone units in the Late Triassic section in Mercury No. 1 are predominantly distributary fluvial channel sands, and farther west in Jupiter No. 1, distributary-mouth bar, distributary channel, and reworked deltaic sandstone (delta plain deposits), indicating that the Triassic sequence in the central and western part of WA 84-P may contain only thin distributary-mouth bar sandstones, and prodelta deposits. However, there is also the possibility that thick beach barrier sandstone sequences may occur west of the Jupiter location.

Farther south in the Esso permits, the drilling has provided evidence of an increasingly more-marine depositional environment in the Late Triassic towards the southwest, with a lower delta plain environment interpreted in Investigator No. 1 and marginal marine at the Vinck location. In Vinck No. 1 the interpretation is supported by the presence of dinoflagellates and acritarchs together with coal and woody material in the Mungaroo Formation equivalent. The sequence contains deltaic depositional cycles separated by marine claystone units; a claystone unit at the top of the sequence represents a final marine transgression prior to the Late Triassic-Middle Jurassic rifting. At Eendracht No. 1, the most-westerly well drilled on the Plateau, a preliminary report on the Rhaetian-Norian clastic sequence (Esso, 1981a) interprets the top 372 m as marine, and the underlying sequence as marginal marine to non-marine. Facies studies and a preliminary dipmeter analysis indicate that the Norian section is a deltaic sequence prograding from the north.

A thin Late Triassic (Rhaetian) shallow marine carbonate unit, consisting mainly of marl grading to limestone and siltstone, overlies the Mungaroo Formation equivalent in the central and southwestern area, the contact being conformable at Jupiter No. 1 and Mercury No. 1, and disconformable at Investigator, where the carbonate unit represents a condensed sequence ranging in age from Rhaetian to Late Jurassic. In Mercury No. 1 the age range is Rhaetian to basal Jurassic.

On the northern margin of the Plateau, Late Triassic dredge samples obtained by the RV Sonne included fine-grained carbonaceous micaceous sandstone, siltstone, and shale correlated with the Mungaroo Formation.

In contrast to the thin Early to Middle Jurassic units encountered in the wells in the central and southern areas of the Plateau, von Stackelberg & others (1980) estimate that the northwesterly-prograding wedge of Early Jurassic carbonates and Middle Jurassic coal measures in the northern area is up to 2500 m thick. The carbonates are mainly calcarenites and calcilutites. The calcarenites were deposited in shelf environments ranging from lagoonal to subtidal, bank, and middle-shelf A middle-shelf environment is postulated for the calcilutites. The Middle Jurrassic coal measures are interpreted to contain carbonaceous micaceous claystone grading to siltstone and sandstone, with thin stringers of sub-bituminous coal.

Late Jurassic and Early Cretaceous

Late Jurassic and Early Cretaceous sediments on the Exmouth Plateau were deposited in shallow-marine or deltaic environments during the regional marine transgression that accompanied continental breakup.

In the southwestern area the drilling confirmed the seismic interpretation of a northerly-prograding Late Jurassic-Early Cretaceous delta complex (Main Delta), and of a younger Early Cretaceous delta prograding from the southeast. At Investigator No. 1 on the crest of the Main Delta the sequence was 1728 m thick and four prograding deltaic units were distinguished as follows, in ascending stratigraphic order (Plate 2):

Unit IE - basinal shale facies
Unit ID - turbiditic sandstone facies
Unit IC - prodelta shale/silt facies
Unit IB - delta front sandstone facies

An overlying marine claystone unit (IA) deposited during Valanginian to Hauterivian time, is correlated with sand-prone delta front units of the Upper Delta sequence intersected at Zeewulf No. 1 (ZA and ZB).

Only at Resolution No. 1, on the deepest horst tested, was a significant thickness (797 m) of *Late Jurassic shallow marine sediments intersected. The sequence consists of dark-grey claystone grading to light-grey siltstone in the upper part. The sediments are fossiliferous and, particularly the claystone, rich in carbonaceous material. The sequence is equated with the Dingo Claystone in the Barrow and Dampier Sub-basins. Early Cretaceous shallow-marine sediments overlie the deltaic section in the south and the rifted Triassic-Middle Jurassic section north of the delta fronts. The sequence is equated with the Winning Group, and units correlated with the Muderong Shale, the Windalia Radiolarite, and the Gearle Siltstone are distinguished. At Jupiter No. 1, the Muderong Shale equivalent is 234 m thick and consists predominantly of dark to medium-grey, slightly calcareous claystone. The Windalia Radiolarite consists of 23 m of light-green, silty, calcareous claystone with a high montmorillonite content, and the Gearle Siltstone is a 46-m thick unit of light-brown, silty, calcareous claystone containing abundant birds-eye structure and minor shell fragments. In all the wells, a time break of variable length separates the Winning Group equivalent from the overlying, deeper-water, dominantly carbonate sequence. At Zeewulf No. 1, the hiatus spans the interval from lowermost Albian to uppermost Neocomian and at Investigator No. 1, Scarborough No. 1, and Resolution No. 1, it occurs within the Aptian.

Late Cretaceous to Recent

The Late Cretaceous to Recent sequence on the Exmouth Plateau exhibits the transition from clastic to predominantly carbonate sedimentation, and from shelf to bathyal environments that began in the uppermost Early Cretaceous.

---

* Also intersected in Zeepaard No. 1 on preliminary Company data

During the drilling operations, the youngest samples taken were from the Late Paleocene or Late Cretaceous section, except at Zeewulf where drop cores were taken through the Cainozoic.

At Zeewulf No. 1, a Cainozoic sequence of foraminiferal ooze and foraminiferal calcareous claystone is disconformable on a Late Cretaceous (Maastrichtian) unit of calcareous claystone and marl. The Early Paleocene hiatus is a regional seismic marker attributed to current action during low stands of sea level, probably of global extent (von Stackelberg & others, 1980).

The unit of marl and chalk of early Campanian to late Santonian age encountered on the Plateau, is correlated with a planktonic foraminiferal limestone, the Toolonga Calcilutite which was widely deposited on the adjacent shelf.

The lithological change from predominantly clastic to predominantly carbonate sediments forms a prominent regional seismic marker on the Plateau which has been tied in the wells to near the base of the Toolonga Calcilutite equivalent.

The maximum thickness of Late Cretaceous to Recent sediments penetrated on the Plateau was approximately 1024 m at Zeewulf No. 1. At Investigator No. 1, on the Exmouth Plateau Arch, seismic data indicates a Cainozoic section of approximately 160 m compared to 600 m at Zeewulf No.1.

PETROLEUM SOURCE POTENTIAL

The petroleum source potential of the sediments underlying the Exmouth Plateau was a major unknown factor in the pre-drill assessment of the area. Predictions were based on analogy with the Barrow and Dampier Sub-basins. Selected data from these basins are shown in Table 3.

In a comprehensive geochemical study of the Northwest Shelf by Robertson Research International Limited (1979), it was concluded that, on the Northwest Shelf generally, the Jurassic sequence had the best source potential, primarily for gas and condensate. Additional gas/condensate source potential was found in Cretaceous shales in the Barrow Sub-basin and the Browse Basin, in fluvio-deltaic Triassic sediments in the Dampier Sub-basin, and Permian shales in the Bonaparte Gulf Basin. In the Barrow and Dampier Sub-basins, oil-prone kerogen occurred in layers and lenses, most commonly in the Upper Jurassic marine shales. Organic maturation gradients based on vitrinite reflectance measurements were found to be relatively low, and present-day temperature gradients are generally below the world-wide average of 3.0°C/100 m, ranging between 2.0°C and 3.8°C/100 m. The organic carbon content of the Jurassic source rocks averaged between one and two percent in the Barrow and Dampier Sub-basins. To explain the observed hydrocarbon accumulations, it was concluded that the large volume of Jurassic source rocks present compensated for their moderate quality. Because the correlative Jurassic sequence on the Exmouth Plateau was predicted to be considerably thinner, and at shallower depth of burial, the report gave a poor rating to the petroleum potential of the area. However, one of the most significant results to emerge from the drilling on the Plateau came from the geochemical evaluation of the Late Triassic Mungaroo Formation equivalent, which in terms of total organic carbon (TOC) content has a higher source potential than was indicated for the Formation in wells on the adjacent shelf. A comparably good potential was also indicated for the Late Jurassic section, intersected only in the eastern parts of the Esso permits.

The geothermal gradients proved to be lower on the Exmouth Plateau than the predicted averages of 3.5°C/100 m (Exon & Willcox, 1978) and 4.0°C/100 m (Chaney, 1978). The following values were estimated:

Investigator No. 1	1.7°C/100 m
Jupiter No. 1	2.86°C/100 m
Mercury No. 1	2.3°C/100 m

The results of source-rock studies carried out on Exmouth Plateau wells are discussed in the following sections in relation to each exploration play.

EXPLORATION PLAYS

Sub-unconformity play

Late Triassic to Early Jurassic sandstone reservoirs below the major unconformity, at or near the top of the block-faulted sequence, constitute one of the major exploration plays on the Exmouth Plateau. Lateral and vertical seal on potential reservoirs within the fault block traps may be provided, either by fine-grained Middle to Late Jurassic sediments present as infill units within the grabens, or by Late Jurassic to Early Cretaceous marine claystone and marl, or in the south by the shale-prone prodelta sequence of the Late Jurassic to Early Cretaceous delta complex. The marine sediments downfaulted against the reservoir sections, and fine-grained intra-Triassic units are possible source rocks.

Intra-Triassic play

An intra-Triassic play is recognised in which deeper Triassic sands are sealed by intra-formational shales. The shales together with the downfaulted marine units, are also potential source rocks.

Delta complex plays

Several plays have been defined involving sandstone reservoirs within the Late Jurassic to Early Cretaceous delta complex (Main Delta), and within a younger, mid-Neocomian delta located in the eastern part of the Esso permits (WA-96-P and WA-97-P).

Delta crest: Closure on the crest of both deltas is provided by depositional dip to the north, and to the south by stratigraphic closure and structural dip resulting from the subsidence associated with the development of the southern margin of the Plateau. Fine-grained sediments within the delta complex (delta front and prodelta units to the north, and coastal and delta plain units to the south) are possible source rocks for the delta crest plays (Esso, 1978).

Intra-delta:(a) Within the Main Delta, transgressive marine shales deposited during several interpreted high stands of sea level were thought to be possible seals for reservoirs in the underlying delta plain sandstones.

(b) Another intra-delta play is based on the interpretation of several submarine fans within the outer (basinward) part of the delta complex, giving rise to the possibility of deep-water turbidite sandstone reservoirs sealed by prodelta shale. Prodelta and transgressive marine shales are possible source rocks.

SUB-UNCONFORMITY PLAY

Tests

Sub-unconformity plays were tested by Zeewulf No. 1, Resolution No. 1, Investigator No. 1, Vinck No. 1, Zeepaard No. 1, and Sirius No. 1 located in WA-96-P and WA-97-P and Jupiter No. 1 and Mercury No. 1 in WA-84-P (Plates 1 & 2).

Zeewulf No. 1 was drilled primarily to test the hydrocarbon potential of interpreted Triassic to Jurassic sediments in a large horst block located in the southeastern part of WA-96-P. As the first well drilled on the Plateau, Zeewulf No. 1 was also a significant stratigraphic investigation; the interpreted mid-Jurassic to Early Cretaceous deltaic sequence being of particular interest because of its importance as a major hydrocarbon play elsewhere on the Plateau.

Investigator No. 1 was the first well to be drilled in the central area of the Exmouth Plateau, and the second in WA-96-P. It was located on a large closure mapped at the front of the Main Delta; the sub-unconformity play in a small horst block closure being a tertiary objective.

Resolution No. 1 was located in the eastern part of WA-96-P, the first well to be drilled in the permit. The well was drilled to test predicted Late Triassic sediments in a horst block similar to the Zeewulf structure, but in which a thick graben-infill unit of Jurassic shale-prone sediments was interpreted to overlie the main unconformity, which was estimated to be some 600 m deeper than at Zeewulf No. 1.

Jupiter No. 1 was the first well to be drilled in WA-84-P. It was located on the crest of the Exmouth Plateau Arch, to test a large horst at the culmination of the pre-'break-up' block-faulted sequence (Fig. 2).

The principal drilling targets were predicted Late Jurassic and Late Triassic sandstones. Early Cretaceous fine-grained marine sediments draping the fault block were expected to provide both lateral and vertical seal.

Mercury No. 1 was located in WA-84-P on the eastern flank of the Exmouth Plateau Arch. It was drilled on a structure similar to the one tested by Jupiter No. 1, 36.4 km to the west. The Mercury structure is a northerly-trending fault block, tilted 4 or 5 degrees to the east, and bounded on the west by a major listric fault with a downthrow of 900 m. The well location is slightly to the east of the crest of the structure, to avoid intersection with several minor faults. The drilling target was the Late Triassic clastic section. Reservoir sands were predicted to be better developed at the Mercury location because of closer proximity to the provenance. Early Cretaceous marine sediments draping the fault block were expected to seal the reservoir sequence. The Mercury structure is the closest major closure to the western margin of the Kangaroo Syncline. It was therefore thought to be optimally situated to trap any hydrocarbons generated in the syncline, where it was hoped that the depth of burial had been sufficient for organic maturation of potential source rocks in the Early Cretaceous section.

Vinck No. 1 was drilled in the southwestern part of WA-97-P, approximately 85 km west-southwest of Investigator No. 1. The primary target was the pre-Rhaetian clastic sequence in a large faulted anticline mapped on the Late Triassic (Rhaetian) unconformity. The well was an interesting test of Esso's concept of the thermal history and pre-Rhaetian palaeoenvironments in the southwestern part of the Exmouth Plateau. The well was located to test a culmination on the major anticlinal axis in the southern part of the structure. The location is on the southern, downthrown side of a northeast-trending fault which, on a pre-drill interpretation, was thought to have possibly formed a barrier to hydrocarbons migrating from the southeast. Northwest-trending faults in the southern part of the structure were taken as evidence that the Vinck area was affected by a postulated 'heating event' associated with the development of the southwestern margin of the Plateau, which may have raised the maturation level of the Late Triassic, and perhaps also of the Late Jurassic to mid-Neocomian deltaic sediments. In Investigator No. 1, mature source rocks were intersected 450 - 500 m above the Late Triassic unconformity. The deltaic sequence was predicted to thin from 1728 m in Investigator No. 1 to about 730 m in Vinck No. 1, which could be expected to significantly depress the depth to the mature source rock zone, unless the concept of a Neocomian 'heating event' was valid.

Esso postulated a stronger marine influence in the depositional environment of the pre-Rhaetian sequence at the Vinck No. 1 location, and consequently a greater possibility that the well would encounter oil-prone source rocks, than was the case at Zeewulf No. 1 or Investigator No. 1. The progressive increase in total organic carbon in Late Triassic shales observed from nearshore wells to Investigator No. 1 (West Tryal Rocks No. 1, average 0.6 percent; Zeewulf No. 1, 2.49 percent; Investigator No. 1, 3.12 percent), was an indication of good source potential for the pre-Rhaetian sequence at Vinck No. 1.

Zeepaard No. 1 was located in the northeastern part of WA-96-P, on a high relief horst block, as a test of interpreted Late Triassic clastic sediments beneath the Rhaetian unconformity. The well location is on the northern margin of the deep trough that overlaps and trends parallel to the eastern borders of WA-96-P and WA-97-P. The trough, referred to as the 'Exmouth Sub-basin' by Esso, was the subject of a regional study in 1980 (Esso, 1981a).

Sirius No. 1 was located in the central part of WA-97-P on a structural closure mapped on the top of the Main Delta. As at Investigator No. 1, the sub-unconformity play was a tertiary objective.

Hydrocarbons

The only significant accumulation of hydrocarbons in the sub-unconformity play occured at Jupiter No. 1 where log interpretation indicates a 22.5-m gas-bearing interval at the top of the Mungaroo Formation equivalent with a net pay of 11.7 m. Formation Interval Tests (F.I.T.) at 1918.5 and 1923 m recovered gas. Formation water with minor gas was recovered at 1932.5 m, and formation water at 1979.5 m. Gas analyses are given below:

	% volume	% volume
Methane	96.512	96.595
Ethane	0.0339	0.308
Propane	0.011	0.013
I-Butane	0.009	0.000
N-Butane	0.009	0.000
N-Pentane	0.000	0.001
Hexane	0.025	0.007
Heptane	0.001	0.000
Carbon dioxide	0.022	0.039

	% volume	% volume
Nitrogen	3.066	3.035
Helium	0.000	0.002
	(F.I.T. 4, 1923 m)	(F.I.T. 2, 1923 m)

In Zeewulf No. 1, log interpretation indicated that the interval 3091-3112.5 m, at the top of the Mungaroo Formation euqivalent, had moderate to low gas saturations, and gas and condensate were recovered from two Repeat Formation Tests (R.F.T.) at 3094.5 m.

In the Mungaroo Formation equivalent in Investigator No. 1, gas readings of up to 120 units were recorded in low permeability sandstones from the top of the formation (3364 m) to total depth (3745.6 m). Log analysis of the sands indicates water saturations from 48 to 86 percent, and R.F.T.s produced small amounts of wet gas, filtrate, and questionable oil films. The gas analysis is compared below with analyses of gas produced from a wireline test in Zeewulf No. 1, and a drill-stem test (D.S.T.) in North Rankin No. 1; the most notable feature is the higher carbon dioxide content in the gas from Investigator No. 1

	Investigator No. 1 (% volume)	Zeewulf No. 1 (% volume)	North Rankin No. 1 (% volume)
Methane	86.60	85.45	88.70
Ethane	3.67	5.45	5.60
Propane	1.15	2.26	1.80
Butane	0.43	0.89	0.56
Pentane	0.15	0.25	0.16
Hexane plus	0.19	0.15	0.13
Carbon dioxide	4.39	0.23	2.30
Nitrogen	3.42	5.32	0.72
Hydrogen sulphide	0.00	0.00	ND
	(R.F.T. 5, 3407 m)	(R.F.T. 3, 3094.5 m)	(D.S.T.10, 3206.3-3209.4 m)

Although the data are inconclusive, pressure measurements can be interpreted to indicate either the presence of a series of large gas columns in discrete reservoirs, or the onset of an abnormal pressure regime. Comparison with the gas analyses from Jupiter No. 1 shows the gas from Zeewulf No. 1 and Investigator No. 1 to have a significantly lower methane and higher carbon dioxide content.

The only indications of hydrocarbons in Resolution No. 1 were very weak gas shows in a 2-m thick sandstone unit below the unconformity at the top of the Triassic section. Overpressuring occurred in the overlying Late Jurassic shale (Dingo Claystone equivalent).

Preliminary company evaluations are available for Zeepaard No. 1 and Sirius No. 1 (Esso, 1981a). At Zeepaard No. 1, as at Resolution No. 1 at the southern end of the 'Exmouth Sub-basin' trough, the Late Jurassic section was overpressured. Dry gas was recovered from an F.I.T. at 4011 to 4016.5 m in the Mungaroo Formation equivalent, and preliminary wireline-log analysis indicates that the formation also contains a thin (2.5 m) gas-bearing sand at 4161 m. At Sirius No. 1, gas and condensate was recovered from F.I.T.'s in four, relatively thin, reservoir sands between 3115 and 3240 m at the top of the Mungaroo Formation equivalent.

INTRA-TRIASSIC PLAY

Tests

The Triassic section was penetrated to varying depths by all the wells except Scarborough No. 1 which was terminated in the Main Delta.

Eendracht No. 1, located on a horst block in the northwestern part of WA-96-P, was the only well drilled specifically to test the intra-Triassic play; no reservoir sands were predicted at the top of the Late Triassic clastic section at Eendracht. The northwestern area contains numerous, mainly easterly-tilted fault blocks. Movement, controlled by major north-south trending faults, occurred mainly in the Jurassic and Early Cretaceous. The target at Eendracht No. 1 was the pre-Rhaetian Late Triassic section, and the well was regarded as a critical test of the stratigraphy, reservoir characteristics, and source rock potential of the area, where it was predicted that the pre-Rhaetian Triassic section would contain good quality beach and near-shore reservoir sands overlain by a pre-Rhaetian marine shale. At Eendracht No. 1, the Triassic section was significantly shallower than in the wells drilled to the south and east and, consequently, could be expected to be immature for hydrocarbon generation. It was hoped that Eendracht No. 1 and the other prospects in the northwestern part of the permit would be optimally located to have trapped hydrocarbons migrating either vertically, or from the south and southeast. High-amplitude seismic anomalies within the pre-Rhaetian section at Eendracht No. 1 were interpreted as possible gas accumulations.

Hydrocarbons

On a preliminary company evaluation (Esso, 1981a), Eendracht No. 1 encountered five gas-bearing sandstone reservoirs within the Mungaroo Formation equivalent between 2467 and 2652 m. A total net gas-bearing section of 25.5 m is interpreted from wireline logs and F.I.T. results. An F.I.T from 2535.5 m recovered 1.6 cubic metres (56.6 cubic feet) of gas, and an F.I.T. from 2651 m recovered 3.6 cubic metres (126 cubic feet) of gas and 60 millilitres of condensate.

Vinck No. 1 encountered a number of gas and gas/condensate zones within the Mungaroo Formation from 2797 m to total depth. Samples were recovered from wireline tests at 3205.5, 3606, and 3798.5 m. No recovery was possible from tight sands below 3800 m.

Reservoirs - sub-unconformity and intra-Triassic plays

In all the wells drilled to test sub-unconformity and/or intra-Triassic plays, the Late Triassic Mungaroo Formation equivalent contained sands of variable, but at all locations, adequate reservoir quality.

In the southeastern area ('Exmouth Sub-basin' trough), point bar and thick braided-stream sequences were encountered at Zeewulf No. 1 and Resolution No. 1. The reservoir sands in Zeewulf No. 1 are described (Esso, 1979a) as consolidated, medium to coarse-grained feldspathic quartz sandstone with porosity and permeability reduced by kaolinitic clay matrix, and pyrite and siderite cement. In the gas-bearing interval (sub-unconformity), porosity averaged 12 percent, and at deeper levels ranged from 18 to 21 percent.

Similarly at Resolution No. 1, porosity in the sub-unconformity sands is estimated at 11 percent, and in the intra-Triassic sands as ranging from 18 to 24 percent (Esso, 1980b).

In the central area at Mercury No. 1 (Phillips, 1980b) sands within the area of drape closure at the top of the fault block were only 0.5 to 3 m thick, mainly very fine-grained, calcareous and argillaceous, with estimated porosities of about 22 percent. Deeper in the Mungaroo Formation equivalent, sandstone units up to 60 m thick were intersected. For the formation generally, average porosities range from about 27 percent in the upper part (2500 - 3000 m) to about 17 percent near total depth (3812 m).

At Jupiter No. 1 (Phillips 1980a) the sandstones in the upper part of the Mungaroo Formation equivalent are also characteristically thin, with clay matrix. In the gas-bearing zone the average porosity is estimated at 10 percent, and maximum porosity at 28 percent. Porosity generally ranges from an estimated 34 percent in the upper part of the formation to less than 6 percent at total depth (4946 m). Reservoir sands in the much smaller thickness of Late Triassic section penetrated by Investigator No. 1, are interpreted as possible interdistributory bay deposits, and were very fine to fine-grained, sparsely carbonaceous, and contained siliceous and carbonate cement. Estimated porosities range up to a maximum of 16 percent.

At Eendracht No. 1 (Esso, 1981a) the most westerly well drilled, the 372-m thick marine section at the top of the Mungaroo Formation equivalent includes only three sands in which the estimated porosity is greater than 10 percent. The underlying section has a net sandstone content of 30 percent. The sandstone units are 5 to 25 m thick, and are interpreted as being distributory mouth bars, point bars, and channel-fill sands. To the south, at Vinck No. 1, the most westerly well in the southernmost permit WA-97-P, the Mungaroo Formation equivalent contains potentially good reservoir sands in the upper part, but a continuous decrease in porosity is evident with increasing depth. Estimated porosity-ranges decrease from 16 - 25 percent in the upper part of the sequence to 0 - 10 percent at total depth. Loss of porosity is attributable to quartz overgrowths, authigenic minerals, and compaction of lithic grains in pore spaces (Esso, 1981b).

<u>Seals - sub-unconformity and intra-Triassic plays</u>

Appraisal of drilling results in the Esso permits has indicated that, although the unconformity is overlain by good sealing units, a lack of seal across the bounding faults of the Late Triassic structures is a likely reason for the lack of significant hydrocarbon accumulations in some of the wells, and a problem of general significance to the prospectivity of the sub-unconformity and intra-Triassic plays (Esso, 1979b; 1981a). In the eastern area ('Exmouth Sub-basin' trough) the throws on some of the major faults exceeds the thickness of the sealing units; at Zeewulf No. 1, the small size of the hydrocarbon accumulation is attributed (Esso, 1979a) to -

1) reduced vertical trap closure due to the juxtaposition of permeable strata in the lower Main Delta sequence on the downthrown side of the southeast bounding fault; and/or

2) partial leakage of hydrocarbons upwards along the plane of the southeast bounding fault.

In the Zeepaard structure, hydrocarbon entrapment appears most likely to be related to anticlinal closure independant of faulting, which is also the case at the Vinck structure in the central area. In the west at Eendracht No. 1, hydrocarbon accumulations occur only where Late Triassic reservoirs are juxtaposed against the Neocomian or Jurassic section, and not where Late Triassic abuts Late Triassic, when leakage appears likely.

In the Phillips permit, a company study of the Jupiter and Mercury structures has indicated that the Early Cretaceous claystone seal overlying the unconformity is possibly ruptured as a result of late movement on the bounding faults.

Source rocks-sub-unconformity and intra-Triassic plays

As previously stated, Late Jurassic to Early Cretaceous marine claystone and marl and shale-prone prodelta sequences, and fine-grained intra-Triassic units are potential source rocks for the sub-unconformity and intra-Triassic plays. Selected source rock data from studies carried out on the wells are given in Tables 4 and 5.

Source rocks evaluation of the Late Triassic Mungaroo Formation equivalent in the Esso and Phillips permits has indicated that the formation equivalent contains source rocks that are predominantly gas-prone, although some oil-prone kerogen was detected, and that the source potential, in terms of total organic carbon (TOC) content, is higher than that of its correlative on the adjacent shelf (Table 3).

Details of studies carried out on individual wells are summarised in the following.

In the eastern area, at Zeewulf No. 1, vitrinite reflectance measurements (Plate 2) indicate that the Late Triassic section at total depth was in the zone of very early or marginal thermal maturation.

Geochemical analysis of the gas/condensate recoverd from the Triassic sequence showed that it was generated in more thermally mature sediments beyond the depth penetrated by the well. In nearby Resolution No. 1, vitrinite reflectance data indicate a sharp increase in reflectance at about the level of the Jurassic/Triassic unconformity; reflectance values of more than 2.0 percent indicating an overmature Triassic section. Thermal alteration index studies of the kerogen and geochemical analyses also indicate a sharp increase in the organic maturation profile in the Triassic section, but of lesser magnitude. It was concluded (Esso, 1980b) that the sharp increase is due to an ancient heating event, of probably restricted areal influence, since it was not recorded in Zeewulf No. 1. Studies of kerogen types indicate that the source rocks are potentially and predominantly gas sources.

In the central area, vitrinite reflectance data from Investigator No. 1 indicate that the Late Triassic section is within the mature zone for hydrocarbon generation. The results of organic extraction and liquid chromatographic analyses show that although the Late Triassic shales are rich in organic carbon, they are not comparably rich in liquid hydrocarbons, and would rate as predominantly gas sources. The results also indicate the presence of migrated hydrocarbons in the Triassic section. The results of source rock studies are broadly similar for Jupter No. 1 and Mercury No. 1; vitrinite reflectance data indicating that the Late Triassic section is mature for hydrocarbon generation below about 3600 m in Jupiter No. 1, and below total depth, at about 3900 m, in Mercury No. 1. For comparison, spore colouration in sidewall core samples from Jupiter No. 1 indicates the following maturation levels:

1410 - 1865.5 m	Immature
1872 - 3448.5 m	Marginally mature
3450 - 4058.5 m	Marginal to mature
4113 m- T.D.	Mature

In both wells, the kerogen type in the Triassic section is predominantly gas-prone.

In the southwest, at Vinck No. 1 (Esso, 1981b), vitrinite reflectance data (Plate 2) indicate that the onset of thermal maturation in the Mungaroo Formation equivalent occurs at about 3200 m, some 500 m below the top of the formation. The data provided no evidence of the postulated

Neocomian heating event referred to previously with the consequence that the mature zone occurs in the section with lower porosity and permeability, reducing the possibility of significant hydrocarbon accumulations. The gas/condensate-bearing zones are mainly located below 3200 m, which is suggestive of local generation with minor migration. Oil-prone kerogen (exinite) is common to abundant in the Late Triassic source rocks, but the comparatively greater abundance of vibrinite is suggestive of a high gas-to-oil ratio.

Source rock evaluation of the Late Jurassic and Early Cretaceous sequences in the Esso and Phillips permits indicates that the best potential oil source for the sub-unconformity and intra-Triassic plays is the late Jurassic (Kimmeridgian to Oxfordian) claystone sequence encountered by Resolution No. 1 and Zeepaard No. 1 in the 'Exmouth Sub-basin' trough. However this sequence seems to be restricted to the eastern trough. In Resolution No. 1, the source rocks had TOC values between 2.6 and 3.2 percent and up to 50 percent of the kerogen is classified as oil-prone. Maturation levels, as determined by vitrinite reflectance measurements and spore colouration, indicate that mature Late Jurassic-Early Cretaceous source rocks occur in the 'Exmouth Sub-basin' trough and in the central area within the thick Main Delta sequence.

In individual wells the main results of source rock evaluation are as follows.

In the eastern area at Zeewulf No. 1, the Early Cretaceous sequence, which provides the seal on the structure, was shown to have a very poor source potential in the samples tested, which had an average TOC content of 0.44 percent. The potentially oil-generative Late Jurassic claystone in Resolution No. 1 has reached a thermal maturation level slightly below peak generation stage.

In the central area at Investigator No. 1, vitrinite reflectance measurements indicate that the Late Jurassic and basal Cretaceous section is in the mature zone for oil generation. The average TOC content of samples tested from the Early Cretaceous deltaic sequence was 0.94 percent. Shales in the lower part of this sequence have been given a tentative oil-source rating. The Early Cretaceous marine section in Jupiter No. 1 and Mercury No. 1 contains oil-prone kerogen but is immature at the well locations.

Geochemical reports are not yet available for the western wells (Zeepaard No. 1 and Vinck No. 1). However, the Early Cretaceous section at Vinck No. 1 is described (Esso, 1981b) as a 'potentially good source with a high proportion of disseminated amorphous material, dinoflagellates and laminar herbaceous material' and rated as a potential oil source if at a deeper burial depth.

DELTA CREST PLAY

Tests

Investigator No. 1 was the first test of the Delta Crest Play. It was located on a large closure mapped at the front of the Main Delta, the largest closure mapped in the play; delta front sands being the primary objective. Sirius No.1, located some 60 km south-southwest of Investigator No. 1, also had the Delta Crest Play as a primary objective in an anticlinal closure mapped on the top of the Main Delta.

Hydrocarbons

There were no significant indications of hydrocarbons in the Delta Crest Play in either test.

Reservoirs

Both wells encountered good quality reservoir sands in the objective interval at the top of the Main Delta. At Investigator No. 1, the unit (Unit IB) was 93 m thick and consisted of unconsolidated quartzose sandstone, predominantly fine-grained, but ranging from fine to very coarse-grained. Porosity averaged 21.9 percent, and ranged from 12.9 to 30 percent. At Sirius No. 1, a preliminary report (ESSO, 1981a) describes the objective interval as 825 m thick, consiting of sandstone with minor siltstone.

Seals

At both well locations, basinal claystone units could be expected to provide effective seal for the Delta Crest Play.

Source rocks

Vitrinite reflectance measurements in Investigator No. 1 indicate that source rocks mature for hydrocarbon generation occur only in the lower part of the Main Delta sequences, below about 3000 m. An average TOC content of 0.94 percent indicates relatively lean source rocks by comparison with the 2.56 percent (TOC) average measured for the Late Triassic sequence. Esso attributes the absence of hydorcarbons in the delta front sand unit to the immaturity of the adjacent source rocks and the lack of adequate vertical migration pathways for hydrocarbons generated at deeper levels.

In Sirius No. 1, preliminary data suggest that no mature source rocks occur in the Early Cretaceous and Jurassic section, and that the Triassic section penetrated is immature to early-mature.

INTRA-DELTA PLAYS

Deepwater turbidite sandstone reservoir

Tests

Scarborough No. 1 was the only well drilled to test the deepwater turbidite sandstone reservoir play as a primary objective. The well was located on a north-northeast-trending, gently domed structure in the central part of the Plateau, about 54 km north-northeast of Investigator No. 1. The objective was an interpreted Neocomian turbidite sandstone unit deposited basinwards of the youngest delta sequence in the Main Delta. A flat lying seismic event across the structure at the level of the objective horizon was interpreted as a direct hydrocarbon indicator (DHI).

Interpreted intra-deltaic turbidite sandstone units were secondary targets at Investigator No. 1, Vinck No. 1, and Zeepaard No. 1.

Hydrocarbons

Scarborough No. 1 was a gas discovery in the objective interval (Plate 2). The gas-bearing reservoir was 34 m higher than predicted on the DHI, probably due to an error in the velocity conversion factor. The gas column had a gross thickness of 59 m between 1867 and 1926 m, and formation interval testing at 1904.5 m produced 5 cubic metres of gas.

There were no significant indications of hydrocarbons in turbidite sandstone units encountered within the Main Delta in Investigator No. 1 and Vinck No. 1. In Zeepaard No. 1 minor hydrocarbon shows were recorded during drilling of the Early Cretaceous Main Delta sequence below 2835 m. However formation tests recovered no hydrocarbons, and the shows are interpreted in a preliminary report (Esso, 1981a) to represent stratigraphically-trapped hydrocarbons within low permeability sandstones and siltstones. The more permeable sandstones are interpreted as water-wet.

Reservoirs

The reservoir sands in Scarborough No. 1 (Unit SB) have been interpreted (Esso, 1980c) as submarine fan and turbidite deposits. A net sand thickness of 40 m is estimated in the 59-m thick gas-bearing interval. The porosity of the sands ranges from 5.7 to 30.9 percent with an average of 23 percent. The sands occur in massive beds 10 to 20 m thick; thinner sands occur immediately below the gas-water contact with porosity reduced by clay matrix.

In Investigator No. 1, the turbidite unit (Unit ID) is a sequence of interbedded sandstone, siltstone, and claystone in which the percentage of sandstone is approximately 57 percent. Log analysis indicates that the sandstone beds may average only 1 to 2 m thick. The sandstone is medium to coarse-grained, typically unconsolidated, but with some thin zones containing calcareous cement. The average porosity, estimated from electric log interpretation, is 19.4 percent, and maximum porosity 28.5 percent.

In Vinck No. 1, predicted turbidite sands in the basal part of the Main Delta did not occur. However, sands at the top of the Main Delta sequence (Unit VB), which have a total net thickness of 13.5 m, are interpreted as probable turbidite deposits (Esso, 1981b). The two sandstone beds in Unit VB consist of unconsolidated, medium-grained quartzose sandstone with porosities of the order of 30 percent.

Seals

At Scarborough No. 1, the gas-bearing reservoir is sealed by prodelta claystone deposited by both the Main and Upper Deltas. Similarly, prodelta shale and siltstone deposits at Investigator No. 1 and Vinck No. 1 could be expected to provide an effective seal for the turbidite sand-prone units.

Source Rocks

Vitrinite reflectance data suggest that source rocks within the section penetrated by Scarborough No. 1 are immature for hydrocarbon generation. Extrapolation of the reflectance data suggests that a mature source rock section could be expected some 500 m below the Rhaetian unconformity at the Scarborough location. The TOC content in the Early Cretaceous source rocks was 2 to 3 percent and in terms of kerogen type, equally oil or gas-prone. The source of the gas accumulation in the well has not been identified but the company regards the gas as possibly immature, and sourced from within the Early Cretaceous section (Esso, 1980c).

The source rock potential of the deltaic and older sequences in Investigator No. 1, Vinck No. 1, and Zeepaard No. 1 have been discussed in previous sections.

FUTURE PROSPECTS

Exploration activity in the Esso and Phillips permits is currently suspended pending detailed evaluation of all data obtained to date by the companies.

Drilling results from the southern half of the Exmouth Plateau, of particular significance to the prospectivity of the area and future exploration, are summarised as follows:

In the Esso permits, possible lack of lateral seal across the bounding faults of the Late Triassic structures is recognised as a significant problem, and the delineation of prospects with anticlinal closure, independent of faulting, will be important for further exploration of the sub-unconformity and intra-Triassic plays (Esso, 1981a). Similarly, in the Phillips permit, the possibility of a ruptured top seal on the Late Triassic horst blocks underlying the Exmouth Plateau Arch is now recognised, and studies are being undertaken to identify prospects where the top seal is unbreached (Phillips, 1981).

In the central and western areas, the fact that the predominantly gas-prone source rocks of the Late Triassic Mungaroo Formation were the only mature source rocks of significant thickness encountered, has downgraded the prospects for a major oil discovery in all exploration plays.

The eastern parts of the Esso permits must be rated on the available source rock data as having the best prospects for oil discovery in all plays. The Late Jurassic claystone sequence, which seems to be confined to the northeasterly trending deep trough in this area, contains mature source rocks with good oil-generative potential. The lack of liquid hydrocarbons in the wells drilled is possibly attributable to the overpressured nature of the Late Jurassic and Late Triassic sequence, which may have inhibited migration into the adjacent (Late Triassic) or overlying (Delta complex) reservoir sands. Esso has carried out a major detailed velocity study in this area with the objective of predicting the presence of the abnormally pressured zones.

REFERENCES

APTHORPE, M.C., 1979 - Depositional history and palaeo-geography of the Upper Cretaceous of the North West Shelf based on foraminifera APEA Journal, 19 (1), 74-89.

CHANEY, M.A., 1978 - The petroleum geology of the northern Carnarvon Basin. Hudbay Oil (Australia) Limited; Bureau of Mineral Resources, Australia, Special Studies Report SS 415 (in confidence).

CHANEY, M.A., 1980 - Enclosure 2. In - Update of the petroleum geology of the Exmouth Plateau area. Hudbay Oil (Australia) Limited; Bureau of Mineral Resources, Australia, Special Studies Report SS483(2) (in confidence).

COPE, R.N., & PIPPET, A.H., 1975 - The West Tryal Rocks Field: A preliminary estimate of Petroleum reserves as at 30.6.1975. Department of Mines Western Australia, Petroleum Branch Record No. 1975/2.; Bureau of Mineral Resources, Australia, Special Studies Report SS 209 (in confidence).

DUKE, R.W., 1978 - Geophysical interpretation report of the Exmouth Plateau area, Western Australia. Hudbay Oil (Australia) Limited; Bureau of Mineral Resources, Australia, Special Studies Report SS 414 (in confidence).

ESSO (Australia Ltd), 1978 - Permits WA-96-P and WA-97-P. Annual report for first permit year (November 19, 1977 to November 18, 1978). Bureau of Mineral Resources, Australia, Special Studies Report SS 418 (in confidence).

ESSO, 1979a - Zeewulf No. 1 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 79/85 (in confidence).

ESSO 1979b - Permits WA-96-P and WA-97-P. Annual report for second permit year (November 19, 1978 to November 18, 1979) Bureau of Mineral Resources, Australia, Special Studies Report SS 489(1) (in confidence).

ESSO, 1980a - Investigator No. 1 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 78/1326 (in confidence).

ESSO, 1980b - Resolution No. 1 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 79/581 (in confidence).

ESSO, 1980c - Scarborough No. 1 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 79/769 (in confidence).

ESSO, 1981a - Permits WA-96-P and WA-97-P. Annual report for third permit year (November 19, 1979 to November 18, 1980). Bureau of Mineral Resources, Australia, Special Studies Report SS 489(2) (in confidence).

ESSO, 1981b - Vinck No. 1 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 79/1011 (in confidence).

EXON, N.F., WILLCOX, J.B., & PETKOVIC, P., 1975 - A preliminary report on the geology of the Exmouth Plateau. Bureau of Mineral Resources, Australia, Record 1975/158 (unpublished).

EXON, N.F., & WILLCOX, J.B., 1978 - Geology and petroleum potential of Exmouth Plateau area off Western Australia. Bulletin of the American Association of Petroleum Geologists, 62 (1), 40-72.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1975 - Geology of Western Australia. Geological Survey of Western Australia Memoir 2, 269-318.

GORTER, J.D., RADIDI, J.S., TUCKER, D.H., BURNE, R.V., PASSMORE, V.L., WALES, D.W., & FORMAN, D.J., 1979 - Petroleum geology of the Canning Basin. Bureau of Mineral Resources, Australia, Record 1979/32 (unpublished).

LARSON, R.L., MUTTER, J.C., DIEBOLD, J.B., CARPENTER, G.B., & SYMONDS, P., 1979 - Cuvier Basin: a product of ocean crust formation by Early Cretaceous rifting off Western Australia. Earth and Planetary Science Letters, 45, 105-14.

PHILLIPS (Australian Oil Company), 1980a - Jupiter No. 1 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 79/317 (in confidence).

PHILLIPS, 1980b - Mercury No. 1 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 79/746 (in confidence).

PHILLIPS, 1981 - Quarterly exploration and production report, fourth quarter - year 3, Exploration Permit WA-84-P. Bureau of Mineral Resources, Australia, File 77/1449 (in confidence).

RIESZ, E.J., 1978 - SIMULAT, a computer program for the 'prospect by prospect' method of estimating petroleum resources using Monte Carlo simulation. Bureau of Mineral Resources, Australia, Record 1978/2 (unpublished).

ROBERTSON RESEARCH INTERNATIONAL LIMITED, 1979 - Petroleum geochemistry of the Australian North-West Shelf, V. 1 & 2. Robertson Research International Limited. Bureau of Mineral Resources Special Studies report SS 477, Part 1 & 2 (Part 2 in confidence).

SMITH, Eugene, L., in prep - WILDCAT: A computer program for the prospect-by-prospect method of estimating hydrocarbon resources using Monte Carlo simulation. Bureau of Mineral Resources Australia Record (unpublished).

THOMAS, B.M., & SMITH, D.N., 1974 - A summary of the petroleum geology of the Carnarvon Basin. APEA Journal, 14 (2), 66-76.

VON STACKELBERG, U., EXON, N.F., VON RAD, U., QUILTY, P., SHAFIK, S., BEIERSDORF H., SEIBERTZ, E., & VEEVERS, J.J., 1980 - Geology of the Exmouth and Wallaby Plateaus off northwest Australia: sampling of seismic sequences. BMR Journal of Australian Geology & Geophysics, 5, 113-140.

VOS, R.G., 1978 - Triassic environmental analysis northern Carnarvon Basin/Exmouth Plateau. Phillips Australian Oil Company; Bureau of Mineral Resources, Australia, Special Studies Report SS 439 (in confidence).

WAPET (West Australian Petroleum Pty Ltd), 1973 - North Tryal Rocks No. 1 well completion report. Bureau of Mineral Resources, Australia, File 72/2069.

WAPET, 1976 - West Muiron No. 2 well completion report. Bureau of Mineral Resources, Australia, Petroleum (Submerged Lands) Act report, File 75/157 (in confidence).

WILLCOX, J.B., & EXON, N.F., 1976 - The regional geology of the Exmouth Plateau. APEA Journal, 16 (1), 1-11.

WISEMAN, J.F., 1979 - Neocomian eustatic changes - biostratigraphic evidence from the Carnarvon Basin. APEA Journal, 19, 66-73.

WRIGHT, A.J. & WHEATLEY, T.J., 1979 - Trapping mechanisms and the hydrocarbon potential of the Exmouth Plateau, Western Australia. APEA Journal, 19 (1), 19-29.

APPENDIX 1.

RESOURCE ASSESSMENT

Sub-unconformity and intra-Triassic plays

Pre-drill assessments were made of hypothetical resources in the Triassic plays in Jupiter No. 1, Vinck No. 1, and Zeewulf No. 1 using a computer program SIMULAT (Riesz, 1978; Smith, in prep.). The parameters necessary for the calculation of the volume of oil and gas resources are input as ranges of weighted values, and the estimates produced in the form of cumulative probability curves. The mean values obtained, and the hydrocarbons actually encountered, are shown in Table A.

A company estimate of 23.8 billion cubic metres (0.84 trillion cubic feet) for the gas discovered in the Jupiter prospect compares with a pre-drill risked mean estimate of 37.2 billion cubic metres (1.3 trillion cubic feet). There are no company estimates available for the gas resources discovered in the Vinck structure, but the pre-drill assessment made in BMR indicates that the structure has the potential to contain a gas accumulation in the 'giant' (28.3 to 99.1 billion cubic metres (1 to 3.5 trillion cubic feet)) category. For the risked estimates in both the Jupiter and Vinck prospects, the application of an 80 percent chance that the wells would discover gas rather than oil, was justified by the drilling results.

In assessing the Zeewulf structure, the first prospect drilled on the Exmouth Plateau, the highest risks were thought to be those associated with the petroleum source potential of the area and the character of the interpreted Triassic Mungaroo Formation equivalent, in terms of the possible occurrence of good reservoir sands. A more optimistic view was taken of the adequacy of trap and seal, because of the high quality of the seismic control, and from comparison with similar structures on the Rankin Trend. The possibility that vertical trap closure might be significantly reduced by a substantial thickness of permeable deltaic strata downthrown against the bounding faults, was not foreseen.

Delta Complex plays

Pre-drill assessments were made of hypothetical resources in the Delta Complex plays in the Investigator structure, and an assessment of gas resources in the Scarborough prospect was made in the latter stage of drilling, when the presence of gas in the structure had been determined.

In Investigator No. 1 it was concluded (ESSO, 1979b) that the lack of hydrocarbons in the delta front sands (Unit IB), which were the primary objective, was due to the thermal immaturity of potential source rocks in the adjacent sequence, and the absence of effective migration pathways for hydrocarbons generated at depth to move up into the delta sequences. Both of these possibilities were recognised and taken into account when the undiscovered resources of the Investigator prospect were assessed. For the delta play (delta front sands), the risked estimates were derived on the basis of two hypotheses (Table A):

Existence risks	Hypothesis 1	Hypothesis 2
oil versus gas	0.8	0.8
gas versus oil	C.2	0.2
source	0.8	0.8
thermal history	0.85	0.01
reservoir	1.0	1.0
trap and seal	1.0	1.0
timing	0.1	1.0
flushing	1.0	1.0
overall gas existence risk	0.01	0.001
overall oil existence risk	0.05	0.006

Hypothesis 1 assumed that any hydrocarbons in the delta play would have been generated in the Triassic or older section, because the younger sequence would probably be immature. Fairly optimistic existence risks were applied to 'source' and 'thermal history', but because of the long vertical migration path involved, a high risk was applied to 'timing'.

Hypothesis 2 assumed a later Jurassic and/or Early Cretaceous source, because of the favourable source potential of this section the Barrow and Dampier sub-basins. In this case, a low existence risk was applied to 'timing' but a very high risk to 'thermal history'.

In both hypotheses, the play was given a better chance of containing oil then gas for several reason. Above the major unconformity, the basal part of the sequence was expected to be within the oil generation zone but immature for the major phase of gas generation. There was also the possibility that the depositional environment of the Late Triassic sequence below the main unconformity would become more marine in a northwesterly direction, and consequently more likely to contain oil-prone source rocks.

The following range was estimated for the gas resources in the Scarborough structure:

20 percent probability	-	2.3 TCF
mean estimate	-	1.9 TCF
80 percent probability	-	1.5 TCF

An estimate of 3.0 TCF has been obtained from the company (Table A). The difference between the company and BMR estimates is probably due to a more conservative view of the areal closure being taken for the BMR assessment.

TABLE A

PRE-DRILL ESTIMATES OF HYPOTHETICAL PETROLEUM RESOURCES IN EXMOUTH PLATEAU PROSPECTS, AND DRILLING RESULTS

Well No.	UNRISKED MEAN ESTIMATES GAS $X10^{12}ft^3$	OIL $X10^6$BBL	GAS $X10^9m^3$	OIL $X10^6m^3$	RISKED MEAN ESTIMATES GAS $X10^{12}ft^3$	OIL $X10^6$BBL	GAS $X10^9m^3$	OIL $X10^6m^3$	RESULTS
Investigator No. 1 (Delta play)	20.6	6214.0	584.6	988.0	*0.881 **0.03	338.0 36.0	8.0 0.8	54.0 6.0	Gas shows in Mungaroo Fm. equivalent
Jupiter No. 1	2.3	459.0	64.5	73.0	1.3	66.0	37.2	11.0	Company estimate about 0.84 $X10^{12}ft^3$
+Scarborough No. 1	1.9	-	54.4	-	-	-	-	-	Company estimate 3. $X10^{12}ft^3$ gas in Ma: Delta (turbidite reservoir)
Vinck No. 1	4.0	550.0	112.5	87.0	2.2	77.0	63.0	12.0	Gas/condensate discovery in Mungaroo Fm. equivalent
Zeewulf No. 1	4.8	645.0	136.8	103.0	0.82	109.0	23.1	17.0	Gas shows in Mungaroo Fm. equivaler

Company estimates from D.J. Forman, BMR, personal communication

* Hypothesis 1
** Hypothesis 2
\+ Assessment made in latter stage of drilling, when presence of gas and absence of oil had been established.

TABLE 1 - GEOPHYSICAL SURVEYS, EXMOUTH PLATEAU, 19.11.77 - 18.11.80

Permit	Survey name	Operator	Start	Finish	Line kilometres
WA-96-P	X78A Marine Seismic	ESSO Exploration and Production Australia Inc.	March, 1978	June 1978	5164
WA-96-P	" " "	" " "	24 Nov 1978	2 Jan 1979	1439
WA-97-P	" " "	" " "	March 1978	June 1978	5072
WA-97-P	" " "	" " "	24 Nov 1978	2 Jan 1979	1486
*WA-25-P	" " "	" " "			114
WA-96-P	X78A Ext "	" " "	1978	1978	1347
WA-96-P	" " "	" " "	19 Nov 1978	23 Nov 1978	889
WA-97-P	" " "	" " "			833
WA-97-P	" " "	" " "	19 Nov 1978	23 Nov 1978	133
WA-96-P	X80A " "	" " "	9 July 1980	17 July 1980	52
WA-97-P	" " "	" " "	9 July 1980	17 July 1980	99
**	" " "	" " "	9 July 1980	17 July 1980	297
WA-93-P	Exmouth Dampier	Hudbay Oil (Australia) Ltd	18 July 1978	24 Jan 1979	3657
	Marine Seismic	Phase 1	18 July 1978	31 Aug 1978	
		Phase 2	3 Jan 1979	24 Jan 1979	
		Phase 3	27 Dec 1978	3 Jan 1979	
***WA-84-P	Expeau 78 Seismic	Phillips Australian Oil Co.	7 Sept 1978	18 Dec 1978	5344
WA-84-P	Expeau 79 Seismic	" " " "	26 Sept 1979	2 Nov 1979	3716
WA-90-P	Project 78E Hermite Barton Marine Seismic	Woodside Petroleum Ltd	July 1978	July 1978	1011.45
WA-90-P	Project 79K & part of Project 79L of Woodbine - Victoria Marine Seismic	" " "	1979	1979	1072

* 114 km were shot in the adjacent permit in order to tie the X78A survey to Wapet wells Tryal Rocks No. 1 and West Muiron NO. 2

** Shot inadjacent permits

*** plus 1421 km of magnetic recordings

TABLE 2 - PETROLEUM EXPLORATION WELLS, EXMOUTH PLATEAU, TO 31-12-80

COMPANY & well name	P(SL)A file no.	Permit	Latitude South Longitude East ° ' "	Elevation (m) WD/KB/RT	Date spudded T.D. reached	T.D. (m)	Status and results
ESSO AUSTRALIA LIMITED							
Eendracht No. 1	80/518	WA-96-P	19 54 25.590	WD 1363.8	8 5 80	3410	PA
			112 14 38.686	KB 10.4	30 5 80		Gas show
Investigator No. 1	78/1326	WA-96-P	20 21 06.59	WD 841.2	7 5 79	3745.6	PA Small gas
			112 58 01.46	KB 10.4	12 7 79		shows
Resolution No. 1	79/581	WA-97-P	21 17 56.97	WD 1086.3	25 7 79	3883.8	PA
			113 41 24.90	KB 10.5	2 11 79		Gas shows
Scarborough No. 1	79/769	WA-96-P	19 53 06.59	WD 925.4	13 11 79	2360	PA Wireline testing found considerable reserves of gas at 1904.5m but due to water depth is presently classed as non-commercial
			113 08 44.53		10 12 79		
Sirius No. 1	80/1296	WA-97-P	20 55 04.04	WD 1176.5	18 10 80	3500	PA
			112 41 21.34	KB 10.4	26 11 80		
Vinck No. 1	79/1011	WA-97-P	20 35 04.393	WD 1362.8	20 12 79	4600	PA Gas and oil
			112 11 33.936	KB 10.4	17 3 80		shows
Zeepaard No. 1	80/929	WA-96-P	20 44 13.910	WD 739.5	8 6 80	4215	PA Hydrocarbons
			114 25 22.010	KB 10.4	10 10 80		show
Zeewulf No. 1	79/85	WA-96-P	21 06 32.527	WD 1194	3 3 79	3500	PA Gas shows
			113 37 13.205	KB 10.4	28 4 79		

(cont) TABLE 2 - PETROLEUM EXPLORATION WELLS, EXMOUTH PLATEAU, TO 31.12.80

COMPANY & well name	P(SL)A file no.	Permit	Latitude South Longitude East ° ' "	Elevation (m) WD/KB/RT	Date spudded T.D. reached	T.D. (m)	Status and results
PHILLIPS AUSTRALIAN OIL COMPANY							
Jupiter No. 1	79/317	WA-84-P	19 34 53.374	WD 959.8	19 5 79	4946	PA Gas shows
			113 31 58.334	RT 9.5	14 10 79		
Mercury No. 1	79/746	WA-84-P	19 33 52.8	WD 1142.1	29 10 79	3812	PA Dry
			113 52 46.1		20 12 79		
Saturn No. 1	79/1047	WA-84-P	19 54 35.605	WD 1177.5	1 12 80		Drilling ahead
			114 56 40.753				

WELL NAME	AGE	DEPTH (m)	TOC %	EOM ppm	SATS ppm	AROM ppm	VITR. R. Ro Mean max
North Tryal Rocks No. 1	L. Cret.	2629	0.64				
	L. Cret.	2763					0.70
	E. Cret.	2933	1.18	2560			
	E. Cret.	3010	0.86				
	E. Cret.	3056	1.94	1720			
	L. Jur.	3086	1.07				
	L. Trias. (Mungaroo Fm)	3104					0.67
	L. Trias. (Mungaroo Fm)	3656					0.72
Rankin No. 1	L. Cret.	2496	0.33	271	46		
	L. Cret.	2518	1.23	1000	322	138	
	L. Cret.	2571					0.73
	L/M Trias.	2768	0.41	3160	513	387	
	L/M Trias.	3493					0.79
	L/M Trias.	3993	1.4	1388	92		
	L/M Trias.	4110					0.94
Barrow No. 1	L. Jur.	2597	2.1	80	71		
Barrow Deep No. 1	L. Jur.	3124-216	2.93	230	177		
Dampier No. 1	L. Jur.	3487	1.92	100	78		
	L. Jur.	3856-4069	2.18	530	445		
	L. Jur.	4135	3.31	1080	907		
Madeleine No. 1	L. Jur.	3856	1.07	225	189		
	L. Jur.	4162	2.46	465	386		
Angel No. 1	L. Jur.	3224	1.61	70	34		
	E. Jur.	4130-313	2.05	160	98		
Legendre No. 1	M. Jur.	3384	2.11	100	47		

TABLE 3. Geochemical and vitrinite reflectance data, Dampier & Barrow Sub-basins (Robertson Research International Limited, 1979).

WELL NAME	DEPTH (m)	TOC %	EOM ppm	SATS ppm	AROM ppm	POLAR ppm	VITR. R. Ro. Mean max.
Investigator No. 1	3410	1.78	612	9	22	450	0.81
	3528	-	-	-	-	-	0.73
	3530	1.67	401	14	64	198	-
	3610	-	-	-	-	-	0.84
	3620*	7.64	2064	27	326	811	-
	3735.7	2.93	614	23	164	32	-
	3742.5	2.82	677	20	131	61	-
	3744.0	-	-	-	-	-	0.86
Jupiter No. 1	1870-95	0.46	120	58	32	30	-
	2400	5.44	2000	104	710	1186	-
	2950	-	-	-	-	-	0.50
	3600	6.33	3460	438	1958	1062	0.70
	4200	-	-	-	-	-	1.00
	4815	2.35	330	75	149	105	-
	4900	-	-	0	-	-	1.3
Mercury No. 1	2600	1.51	410	60	178	173	0.44
	2900	2.23	690	70	500	120	0.43
	3150	-	-	-	-	-	0.50
	3500	2.54	1260	106	843	291	0.57
	3800	3.93	1460	164	825	472	0.65
Resolution No. 1	3765	2.43	1902	320	162	569	-
	3795	3.22	2140	475	400	355	0.73
	3840	-	-	-	-	-	1.71
	3845	2.32	-	-	-	-	-
	3860	1.60	755	124	231	146	2.11
	3877	-	-	-	-	-	2.23
Zeewulf No. 1	3090	1.12	-	-	-	-	-
	3156	-	-	-	-	-	0.46
	3180	1.71	-	-	-	-	-
	3300	-	-	-	-	-	0.51
	3375	3.54	-	-	-	-	-
	3450	-	-	-	-	-	0.53
	3500	10.82	-	-	-	-	-

*Coal

TABLE 4. Geochemical and vitrinite reflectance data, Triassic Mungaroo Formation equivalent (Esso, 1979a; 1980a, b, Phillips, 1980a, b).

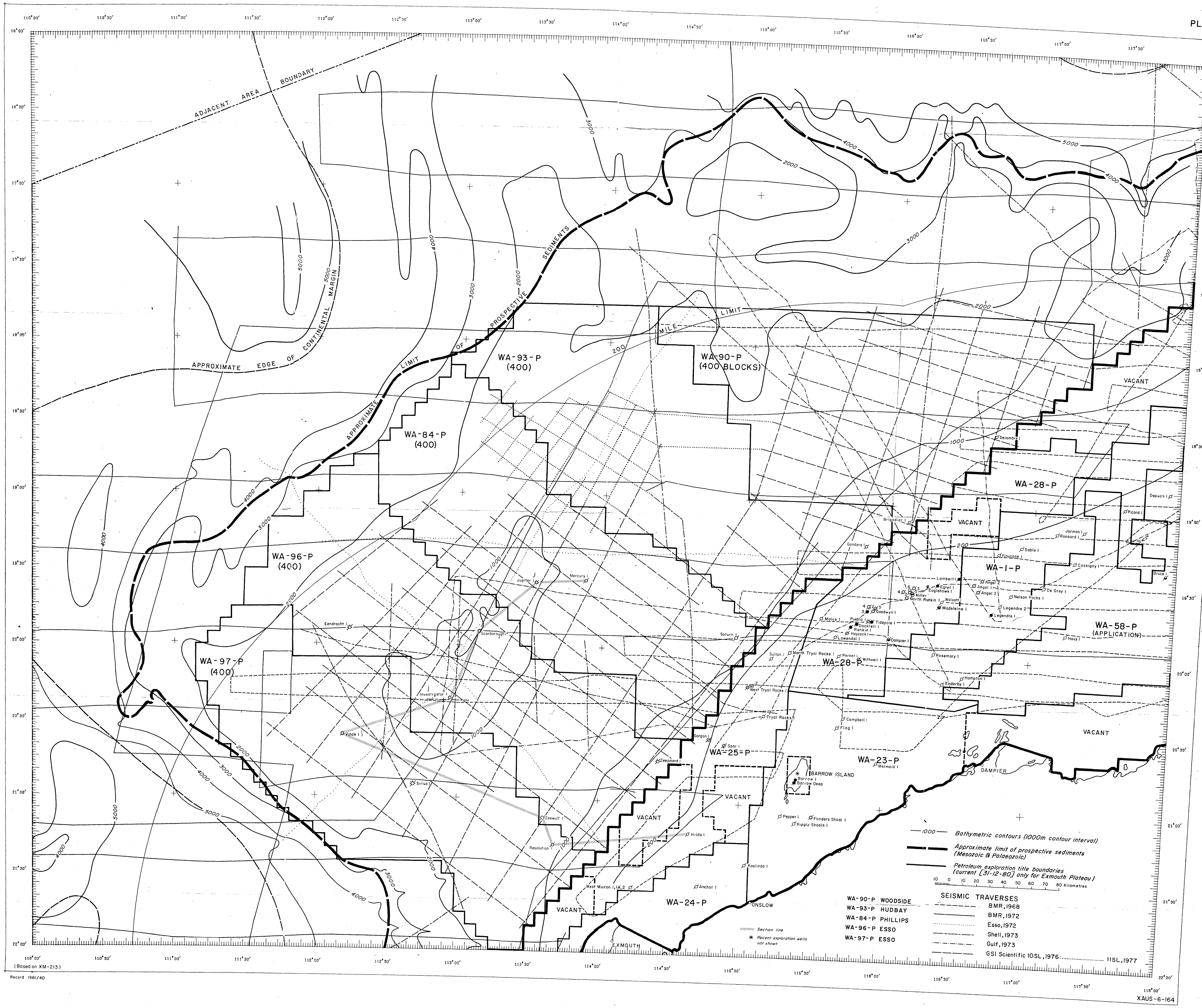
WELL NAME	AGE	DEPTH (m)	TOC %	EOM ppm	SATS ppm	AROM ppm	POLAR ppm	VITR. R. Ro Mean max.
Investigator No. 1	E. Cret.	1690	1.26	-	-	-	-	-
	L. Jur.	3115	1.30	-	-	-	-	0.74
	E. Jur.	3275	-	-	-	-	-	0.62
	L. Trias.	3353	1.07	-	-	-	-	-
Jupiter No. 1	E. Cret.	1575	0.45	1200	480	600	120	-
	E. Cret.	1700	-	-	-	-	-	0.58
	M. Jur.	1862	0.73	230	80	71	79	-
	L. Trias.	1875	1.75	1620	938	515	167	-
Mercury No. 1	L. Cret.	1850	0.15	150	69	48	33	-
	L. Cret.	2000	0.12	120	46	44	30	-
	E. Cret.	2150	0.41	110	41	43	26	-
	E. Cret.	2300	0.86	110	36	26	48	-
	L. Trias.	2450	1.21	150	48	58	45	-
Resolution No. 1	L. Cret.	1720	0.23	368	-	-	-	-
	E. Cret.	1840	0.88	-	-	-	-	-
	E. Cret.	2230	1.17	1155	-	-	-	-
	E. Cret.	2829	0.47	272	-	-	-	-
	L. Jur.	3300	1.86	492	70	54	38	-
	L. Jur.	3480	2.24	886	96	122	82	-
	L. Jur.	3555	2.51	1291	187	45	46	-
Scarborough No. 1	L. Cret.	1410	0.29	691	302	144	115	-
	E. Cret.	1590	0.52	-	-	-	-	-
	E. Cret.	1650	0.12	227	-	-	-	-
	E. Cret.	1765	1.56	721	45	58	141	-
	E. Cret.	2020	2.41	460	12	15	249	-
	E. Cret.	2137	2.75	-	-	-	-	0.32
	E. Cret.	2357	0.98	-	-	-	-	0.37
Zeewulf No. 1	E. Cret.	2965	0.53	813	187	110	136	-

TABLE 5. Geochemical and vitrinite reflectance data, Late Triassic to Late Cretaceous section (Esso, 1979a; 1980a, b, c; Phillips, 1980a, b).

PLOTTED 17/10/74

AUSTRALIA 1 1000000

PLATE 1



APL SPHEROID
SIMPLE CONICAL PROJECTION
WITH TWO STANDARD PARALLELS
AT 18 0 AND 36 0 SOUTH

RESTRICTED

EXMOUTH PLATEAU SEISMIC SURVEYS
1968-1977, AND WELL LOCATIONS
EXMOUTH PLATEAU & BARROW AND DAMPIER
SUB-BASINS TO 31-12-1980

PLATE 2

WELL CORRELATIONS,
EXMOUTH PLATEAU - BARROW SUB-BASIN

RESTRICTED

Record 1981/40