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BMR Bulletin

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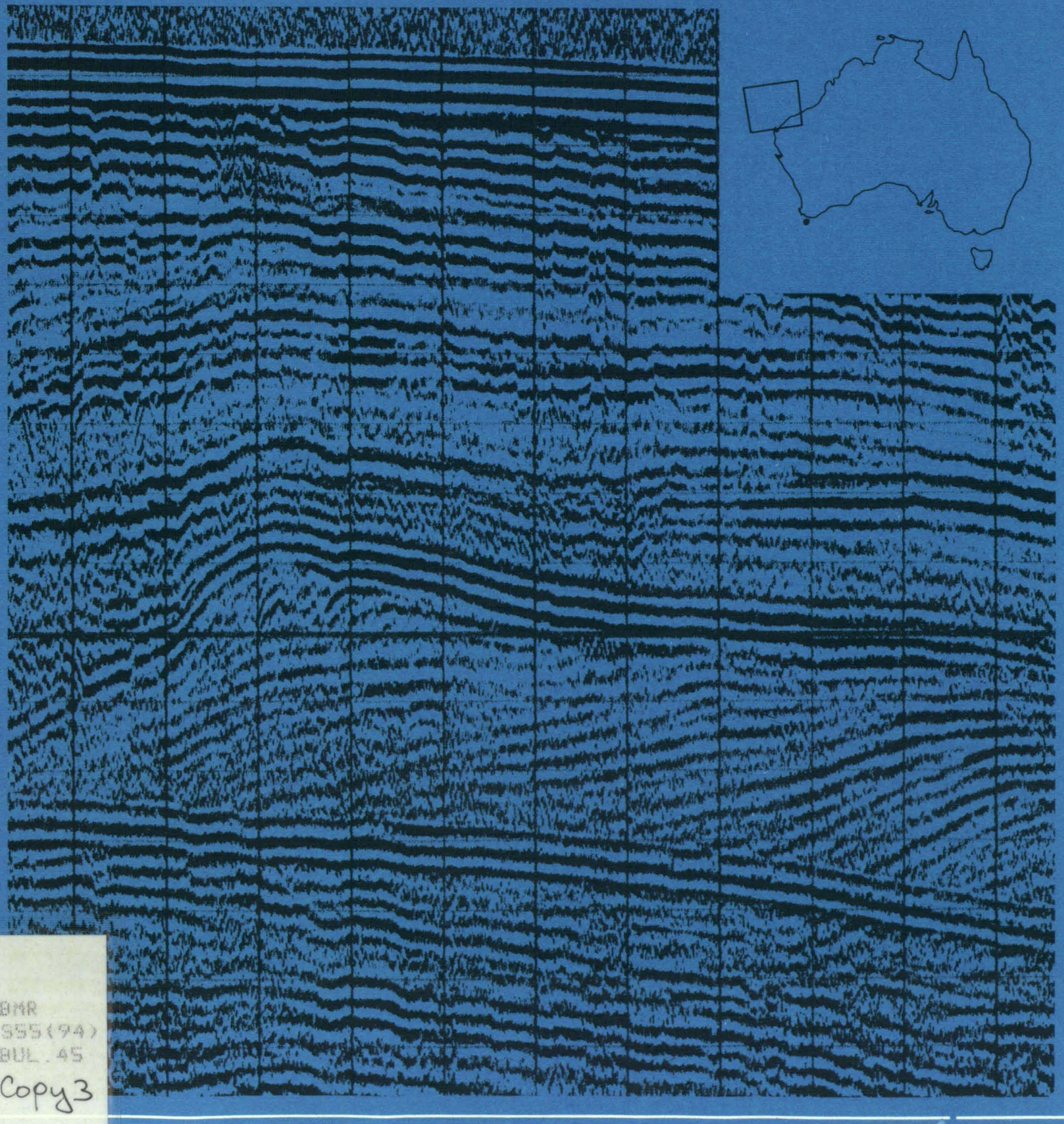

DEPARTMENT OF NATIONAL DEVELOPMENT & ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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The Exmouth Plateau: Stratigraphy, structure, and petroleum potential

N. F. EXON AND J. B. WILLCOX

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ABSTRACT

The Exmouth Plateau and the adjacent lower continental slopes lie in water depths ranging from 800 to 5000 m and cover an area of 300 000 km^2 oceanward of Australia's Northwest Shelf petroleum province. The crust is estimated to be about 20 km thick in the region, and to consist of 5 km of Palaeozoic and 5 km of Mesozoic and younger strata, overlying Precambrian basement. The Phanerozoic sequence forms part of the Carnarvon Basin.

A major Late Triassic unconformity separates block-faulted older sediments from gently warped younger ones in this part of the Carnarvon Basin. During the Palaeozoic and most of the Mesozoic the area was a southern embayment of Tethys, in which deposition of paralic and shallow marine terrigenous clastic sediments predominated. In the Late Cretaceous and Cainozoic, carbonate deposition was dominant.

Potential petroleum source rocks, reservoir rocks, and numerous structural traps are believed to be present on the plateau, and the area has considerable petroleum potential.

Note: This text was completed during 1977 and represents the authors' understanding of the Exmouth Plateau before commercial exploitation.

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SUMMARY

The Exmouth Plateau lies oceanward of Australia's Northwest Shelf petroleum province, in water depths of 800 to 2000 m, and is flanked by the abyssal plains of the Wharton Basin. Its area is 150 000 km^2 and the adjacent lower continental slopes, also considered in this study, cover another 150 000 km^2. The southwest and northwest margins of the plateau are fault-bounded escarpments, but the northern margin consists of spurs and subplateaux separated by deep troughs. Our interpretation of the area is based on 12 000 km of BMR seismic reflection, magnetic, and gravity profiles, and 6000 km of seismic reflection profiles provided by petroleum exploration companies.

Initially, eight major seismic horizons were identified over the profile network. They were then related to the nearest known stratigraphy by means of seismic tie-lines to wells on the Northwest Shelf. Additional information came from magnetic and gravimetric studies and deep-sea drill holes on the adjacent abyssal plains.

Magnetic basement is about 10 km below sea level over much of the plateau but crystalline basement and igneous bodies are at shallow depths around its seaward margins. Interpretation of seismic profiles indicates that up to 5000 m of Palaeozoic strata and 5000 m of younger strata overlie basement. A crustal thickness of about 20 km, similar to that under the Northwest Shelf, is suggested by the gravity data. The outer limit of continental crust roughly coincides with the 4000-m isobath.

The plateau is dominated by the northeast-trending Kangaroo Syncline and Exmouth Arch. These lie 100 km and 220 km, respectively, northwest of the Rankin Platform of the Northwest Shelf. Antithetic normal faults are characteristic of the Palaeozoic and Early Mesozoic sequences; these trend northeast on most of the plateau, and blocks are generally downthrown to the west and tilted to the east. Easterly and northerly cross-trends are present in the north, and northwest cross-trends in the south.

The sediments of the Exmouth Plateau are considered to constitute part of the Carnarvon Basin. Until the Early Cretaceous, this area was probably a north-facing embayment in Gondwanaland, which received terrigenous sediments from the south. Up to 3000 m of paralic and shallow marine terrigenous sediments of Triassic age is believed to overlie the Palaeozoic sequence, unconformably in some areas. Rifting probably commenced in the Permian but culminated in the Late Triassic. In the early Late Jurassic, seafloor-spreading about northeast-trending ridges formed the plateau's northern margin by transform faulting. Its northwest margin formed by rifting either in the early Late Jurassic or in the Early Cretaceous. The average displacement on the numerous normal faults is about 100 m, but some displacements are much larger.

Unconformably overlying the faulted surface is an average of 1000 m of probable Jurassic and Early Cretaceous shallow marine and deltaic terrigenous sediment which was derived from the south and east. A major delta in the south appears to have advanced northwards from a landmass situated where the Cuvier Abyssal Plain is now, before faulting started to form the plateau's southwest margin in the Early Cretaceous.

About 200 m of mid-Cretaceous shallow marine terrigenous sediments overlies the older Cretaceous sediments, and these are overlain, in turn, by 500 to 1000 m of Late Cretaceous and Cainozoic carbonates. The distribution of Late Cretaceous carbonates is very patchy, with thick banks in the east and little or no sediment in the north and west. An Eocene sequence unconformably overlies the Late Cretaceous and older rocks, and probably consists largely of shelf limestones. A scoured unconformity locally present in the Eocene sequence may have developed in subaerial conditions. Unconformably overlying the Eocene sequence are Miocene to Recent calcareous sediments which probably range from shelf carbonates to bathyal oozes. There is a substantial amount of evidence to suggest that much of the area sank to bathyal depths only in Plio-Pleistocene times, at the time when the Exmouth Plateau Arch and Kangaroo Syncline took up their final form by differential subsidence.

Potential petroleum source rocks, especially Palaeozoic to Cretaceous shales and siltstones, and reservoir rocks, especially Triassic and Early Cretaceous sandstones, appear to exist beneath the plateau. In some places depth of burial of mid-Cretaceous source rocks has probably been adequate for petroleum to form. Obvious exploration targets include the numerous Triassic fault-blocks, and the large Early Cretaceous delta in the south.

INTRODUCTION

Since the discovery of the Kingfish and Halibut Fields in the Gippsland Basin during 1967, the most significant discoveries of Australian petroleum have been the gas fields in the Rankin area of the Northwest Shelf. The initial successes on the Northwest Shelf, particularly the discovery of oil on Barrow Island, led to a surge in exploratory drilling during 1970. Drilling has declined since then despite several further gas and minor oil discoveries.

Although regional seismic data off northwest Australia indicated that the prospective section and the types of structures underlying the Northwest Shelf also extend beneath the Exmouth Plateau, until recently the considerable water depths and lack of petroleum exploration permits have discouraged exploration beyond the shelf break. The nearby wells have been drilled in water depths of less than 140 m. However, with the rapid advances being made in drilling, well completion, and recovery technology, the development of fields in more than 1000 m of water will be possible in the early 1980s. Exploration permits over the plateau were granted in 1977. Drilling vessels such as the *SEDCO-445* (Anderson, 1974) which are equipped with blowout prevention stacks, can drill commercial wells in water depths of about 650 m, and *SEDCO-470* is designed to operate in water as deep as 1800 m (Ocean Industry, 1975). Lockheed Petroleum Services Ltd offer a subsea well completion and production system which can be operated in a water depth of 366 m (Lockheed, 1973). If the discovery of deepwater fields

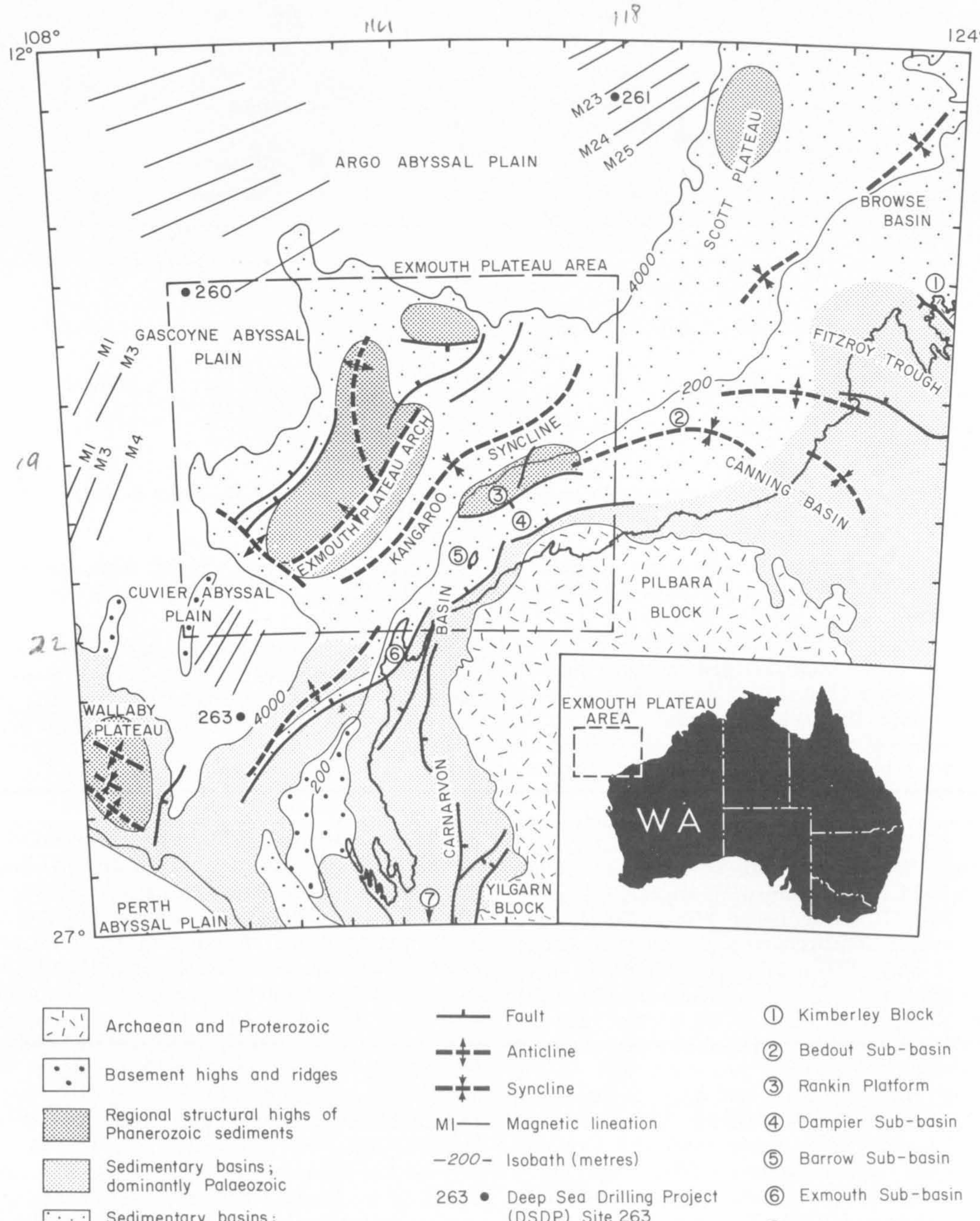


Fig. 1. Regional setting. Based in part on Tectonic Map of Australia and New Guinea, Geological Society of Australia, 1971; Larson, 1975, 1977; Symonds & Cameron, 1977.

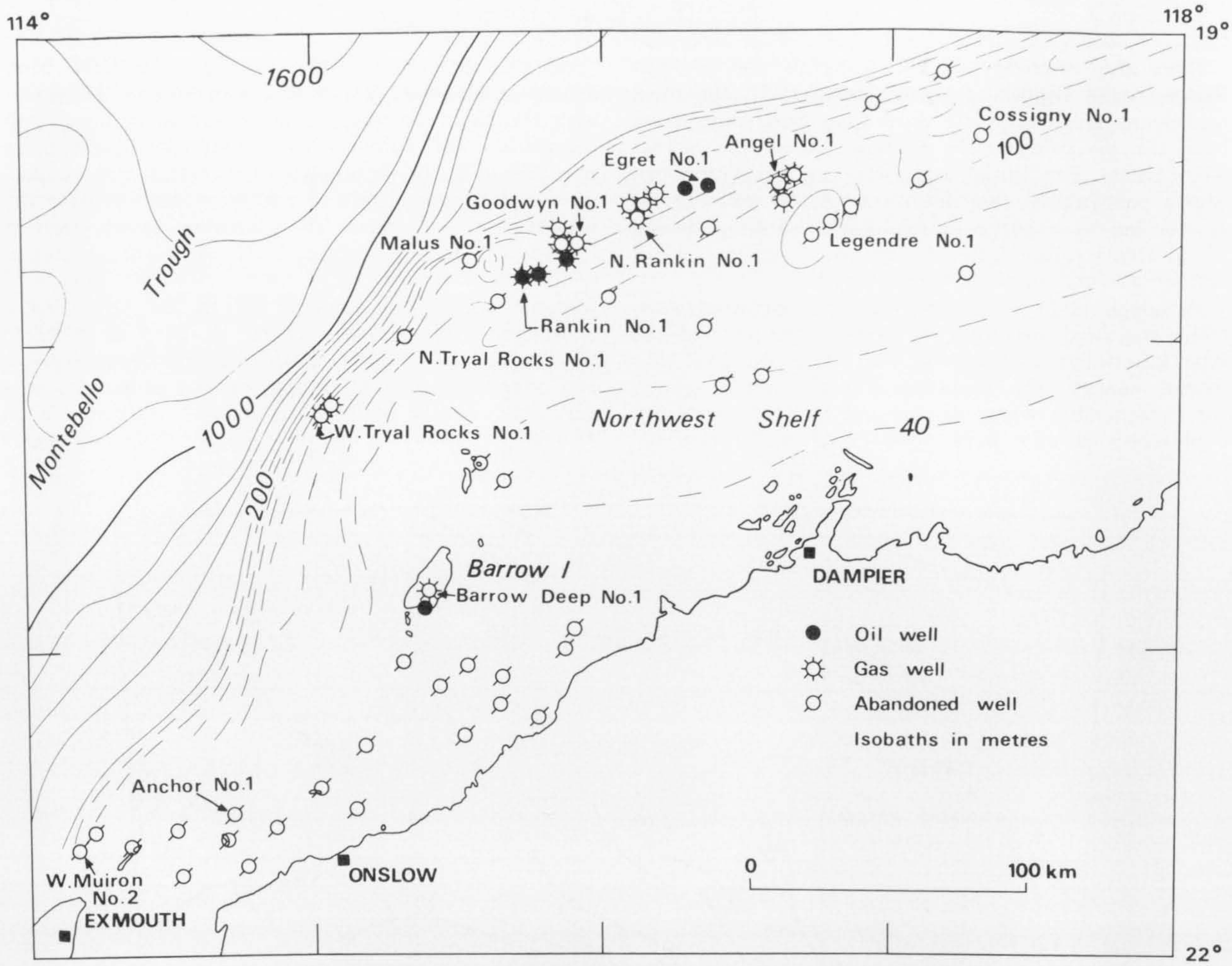


Fig. 2. Petroleum exploration wells on the Northwest Shelf. Labelled wells relate to text.

creates a demand, Lockheed and other companies could readily develop their systems to cope with several times this depth.

The Exmouth Plateau lies adjacent to the Northwest Shelf and is the second-largest marginal plateau of offshore Australia (Fig. 1). It covers 150 000 km² (Falvey & Veevers, 1974), half the size of the Northwest Shelf but ten times larger than the Gippsland Basin. It forms a broad dome centred 250 km offshore, with a minimum water depth of 815 m.

This Bulletin outlines the geology and petroleum potential of the Exmouth Plateau. The principal sources of data are 12 000 km of reflection seismic profiles obtained in 1972 by the Bureau of Mineral Resources (BMR) as part of its Continental Margin Survey, and 6000 km obtained by petroleum exploration companies between 1971 and 1973 and lodged with BMR under the requirements of the Petroleum (Submerged Lands) Acts 1967-1974. The locations of the profiles used are shown in Plate 1. Our interpretation also makes use of seismic refraction data from sonobuoys, and gravity and magnetic profiles and contour maps. Seismic data obtained by the MS *Gulfrex* (Gulf, 1973) have enabled tentative ties to be made from the Exmouth Plateau to wells on the Northwest Shelf (Fig. 2). A preliminary report on the plateau was made by Exon, Willcox, & Petkovic (1975). The geology and petroleum potential of the central area have been discussed by Willcox & Exon (1976), and that of the Exmouth Plateau as a whole by Exon & Willcox (1978). The occurrence of outcrops on the southwest margin of the Plateau was documented by Exon & Willcox (1976).

The seismic results are presented largely in two series of structure contour and isopach maps: one of the entire area (Pls. 11-13, 15-17), and the other for the central area (Pls. 18-27); the two areas are related in Plate 3.

Previous investigations

Falvey & Veevers (1974) made an exhaustive study of the Wharton Basin (West Australian Basin) and the Exmouth and Scott Plateaux. Veevers, Falvey, Hawkins, & Ludwig (1974) made a regional study of the stratigraphy and structure of Exmouth and Scott Plateaux and adjacent deeps, using seismic data collected by Lamont-Doherty Geological Observatory and the Royal Australian Navy (Pl. 2), supplemented by seismic data from BMR's 1968 sparker survey of the Northwest Shelf (Whitworth, 1969; Veevers, 1973).

The geology of the onshore Carnarvon Basin (Fig. 1) was discussed by Condon (1968) and that of the offshore portion by Thomas & Smith (1974). The geology of the onshore and offshore Canning Basin was described by Veevers & Wells (1961) and Challinor (1970), respectively. A review of the geology of the northwest continental margin of Australia was presented by Powell (1976). Geophysical data in the offshore Canning Basin and the northernmost part of the

Carnarvon Basin were collected by Burmah Oil Company of Australia Ltd (BOCAL) and associated companies, and by BMR (Whitworth, 1969). Most of the Carnarvon Basin has been explored by West Australian Petroleum Pty Ltd (WAPET) and its predecessors.

Stratigraphic information in the deep ocean basins adjacent to the Exmouth Plateau comes from holes drilled on Leg XXVII of the Deep Sea Drilling Project (Veevers, Heirtzler, et al., 1974). A bibliography of papers dealing with deep sea drilling in Australasian waters was compiled by Veevers (1975).

Analyses of marine magnetic anomalies off Western Australia, on the Perth Abyssal Plain and in the Wharton Basin, have been used in reconstructions of Gondwanaland and in attempts to explain the structures of the western and northwestern margins of Australia (Veevers, 1971; Veevers, Jones, & Talent, 1971; Sclater & Fisher, 1974; Markl, 1974; Veevers & Heirtzler, 1974; Larson, 1975 and 1977).

Geophysical data

The reflection seismic data used in the preparation of this Bulletin come from five surveys:

- BMR Continental Margin Survey, 1970-1973 (CGG, 1975)
- BMR geophysical survey of the northwest continental shelf, 1968 (Whitworth, 1969)
- Esso Australia Ltd marine seismic survey of the Indian Ocean, offshore Western Australia, E71A, Dec. 1971-Jan. 1972 (Esso, 1972)
- Gulf Research and Development Co. and Australian Gulf Oil Co. regional geophysical reconnaissance off the north coast of Western Australia, conducted with the MS *Gulfrex* from 28 May to 6 July 1972 (Gulf, 1973)
- Shell Development (Australia) Pty Ltd marine geophysical survey offshore Australia, conducted with MV *Petrel* from 7 June to 25 August 1971 (Shell, 1972).

Seismic data collected on board HMAS *Diamantina,* RV *Vema,* and RV *Conrad* (see Veevers et al., 1974), whose tracks are shown in Plate 2, have also been considered in critical areas.

The seismic energy sources used on the Esso, Gulf, and Shell surveys were Maxipulse, Aquapulse, and airguns, respectively. Twenty-four channels were recorded digitally on these surveys. On the Continental Margin Survey the seismic energy source was a single-electrode sparker with a discharge energy of 120 kilojoules. Six channels were recorded in analogue form. Seismic penetration in these various surveys ranges from 2 to 6 s reflection time below the sea-floor, and is generally greatest on the Esso and Gulf profiles.

The gravity and magnetic data used herein were derived from the BMR surveys for which corrected data tapes containing one-minute values were available. The regional reliability of the gravity and magnetic data can be gauged from the standard deviations of the misties at line intersections, given by Hogan & Jacobson (1975) for Continental Margin Survey lines off northwest Australia; these values are 4.1 mGal and 23.4 nT, respectively.

Primary navigational control for most of these surveys was given by satellite-Doppler systems. The ship's position between satellite fixes was computed by linear adjustment of the dead-reckoned track for the Esso, Gulf, and Shell surveys, and by VLF navigation and linear adjustment of the sonar-Doppler track for the BMR 1968 and 1970-73 surveys. We consider the navigational accuracy in waters beyond the shelf for all the surveys to be about 2 km. The absence of major bathymetric and seismic misties at the intersections of seismic lines from different surveys supports this assumption. Further post-survey processing of the BMR navigational data is expected to lead to greater accuracy along Continental Margin Survey lines.

Presentation of seismic profiles and maps

The reflection seismic profiles used in this interpretation have been processed and displayed as follows:

Esso and Gulf sections: 12-fold and 24-fold Common Depth Point (CDP) stack with deconvolution and time variant filtering after stack; variable area display.

Shell sections: 2-fold CDP stack without corrections for moveout, produced on-line by an optical method; variable-area display.

BMR 1968 data: Single-channel monitor sections produced on-line using EG & G electro-chemical recorders.

BMR Continental Margin Survey data: Single-channel monitor sections produced on-line using EPC electrosensitive recorders. Also a 6-fold CDP stack of line 18/069, digitally processed by Geophysical Service Inc. for WAPET.

The water-depth data presented in Plate 3 are derived from Elac fathometer records, recorded during the Continental Margin Survey and hand-digitised by Compagnie Générale de Géophysique (CGG, 1975), and directly from company seismic records. Recent studies have indicated that water depth measurements made using the Raytheon fathometer during the Continental Margin Survey are consistently smaller than the Elac values, the difference increasing almost linearly from about 0 to 100 m for water depths from 0 to 6000 m. The studies indicate that the Raytheon measurements are generally more reliable than the Elac, so a correction graph for adjusting Elac measurements was prepared (Exon et al., 1975, appendix II).

Free-air, Bouguer, and magnetic anomaly contour maps at 1:2 500 000 scale (Pls. 4, 5, & 6) were produced from half-hourly values (equivalent to about 8-km spacing along lines) by machine contouring, using linear interpolation on a surface of minimum curvature fitted to the data points (Briggs, 1974). Profile maps (Pls. 7, 8, 9, & 10) were prepared by machine-plotting from the one-minute data tapes.

Two sets of structure and isopach maps are presented: one at 1:2 500 000 scale for the entire area (110°-118°E, 16°-22°S) (Pls. 11-13, 15-17), and the other at 1:1 000 000 scale for the central area of the Exmouth Plateau (112°-115°E, 19°-21°S) (Pls. 18-27). The interpreted seismic reflectors were hand-digitised, and depths to horizons and thicknesses of sequences were calculated by computer, using the velocities shown in Table 4. The maps were hand-contoured using approximately linear interpolation. The orientation of faults was determined in places where major fault-blocks could be traced from line to line and where several lines intersect, but the spacing of lines is generally too great to allow small faults to be mapped. The faults shown on the maps of the whole area are essentially the major fault zones; subsidiary fault cross-trends probably exist but were not detected. Somewhat more detail is shown on maps of the central area, where there is a greater density of lines. Maps in this area were originally drawn at 1:250 000 scale and then reduced.

All maps are presented on a Simple Conic Projection which has standard parallels at 18° and 36°S. This projection is generally regarded as standard for 1:2 500 000 scale maps of the entire continent. Although this conic projection does not preserve angular relationships as do Mercator projections, it permits exact matching between adjacent maps of the series. The choice of 18° and 36°S as standard parallels leads to a small amount of distortion in the Exmouth Plateau area.

ACKNOWLEDGEMENTS

We wish to acknowledge the assistance gained from discussions with Prof. J. J. Veevers of Macquarie University, Dr D. A. Falvey of the University of Sydney, and employees of BOCAL and WAPET, which helped formulate our ideas. Drafting was carried out by the Cartography Section, BMR.

REGIONAL SETTING

PHYSIOGRAPHY

The Exmouth Plateau is a marginal plateau projecting into the Wharton Basin (West Australian Basin). To the north (see Falvey & Veevers, 1974; also Fig. 1) lies the Argo Abyssal Plain (North Australian Basin) (average depth 5700 m); to the northwest the Gascoyne Abyssal Plain (Exmouth Abyssal Plain) (average depth 5700 m); and to the southwest the Cuvier Abyssal Plain (average depth 5070 m). The Argo and Gascoyne Abyssal Plains are separated by the Roo Rise. The Cuvier Abyssal Plain is bounded on three sides by the relatively shallow Exmouth Plateau, Carnarvon Terrace, and Wallaby Plateau, and in the west by deep submarine ridges. The lower continental slope along the northwest margin of the Exmouth Plateau merges with foothills and swales of the complex continental rise (Falvey & Veevers, 1974), but along the steep southwest and northern margins of the slope dips steeply down to the abyssal plains.

Falvey & Veevers (1974) subdivided the plateau area by using changes of slope. Below the shelf break they defined an upper (continental) slope with an inclination of 1°-2°, and a lower (continental) slope with an inclination of 3°-5°. The inner Exmouth Plateau, referred to as the 'plateau proper', lies below the upper slope and has gradients of less than 0.5°, and the outer Exmouth Plateau, referred to as the 'plateau edge zone', lies above the lower slope and has gradients of up to 3°. If the plateau is defined in this manner, its landward margin lies between 800 and 1400 m, and its seaward margin between 1300 m and 3100 m, depending on the depths of slope breaks; the area of the plateau is 200 000 km^2.

Because our interests are not primarily physiographic we have used a simpler definition, and regard the Exmouth Plateau as lying between about 800 and 2000 m (see Pl. 3). We follow Falvey & Veevers in defining the eastern limit of the Exmouth Plateau as lying immediately east of Swan Canyon, but differ from them in excluding the northern deeper water area from the plateau. To the northeast of the Exmouth Plateau, the continental slope progressively widens, forming the Scott Plateau. Landward of the plateau is the broad, largely featureless Northwest Shelf, with the shelf-break at a depth of about 200 m.

According to our definition, the Exmouth Plateau has an area of about 150 000 km^2. However, the area dealt with in this Bulletin lies between the shelf-break and the foot of the lower continental slope, and totals about 300 000 km^2.

GEOLOGY OF CARNARVON AND CANNING BASINS

The Exmouth Plateau (Fig. 1) is a northwest prolongation of Australia's continental crust and probably consists of up to 10 km of Precambrian metamorphic basement rocks and possibly sediments, overlain by as much as 10 km of Phanerozoic sediments. The basement rock types are probably similar to those of the Pilbara Block, and we regard the Phanerozoic sedimentary sequence as part of the offshore Carnarvon Basin.

The Phanerozoic sediments are laterally continuous with those of the Exmouth Sub-basin to the south, Barrow Sub-basin to the southeast, Dampier Sub-basin to the east, and Canning Basin. Pre-Late Jurassic sediments terminate at the northern, western, and possibly southwestern margins of the plateau, and the oceanic basement of the surrounding abyssal plains is overlain by Cretaceous and Cainozoic deep-ocean deposits. Typical offshore Carnarvon Basin sequences of the Northwest Shelf are illustrated in Figure 3, and the sequence in the Tryal Rocks area is shown in Figure 4. A lithostratigraphic correlation from Legendre No. 1 to DSDP 260 showing inferred lithology of the Exmouth Plateau sequence is illustrated in Figure 12.

The Exmouth Plateau sedimentary sequence appears to be generally similar to that of the *Carnarvon Basin.* The Carnarvon Basin proper is about 300 000 km^2 in area, to which the Exmouth Plateau region adds a further 300 000 km^2.

The *Carnarvon Basin* was described by Thomas & Smith (1974) as an elongate crustal depression which straddles the central Western Australian coast between the towns of Geraldton and Dampier. It is a large, complex structure containing sediments ranging in age from Silurian to Recent, which lap eastward onto the Precambrian Shield. The southern part of the basin consists largely of Palaeozoic sediments veneered by Cretaceous and Tertiary sediments, but the northern part contains thousands of metres of Triassic, Jurassic, and Neocomian sediments. In the offshore part of the northern area, between the coast and the Exmouth Plateau, thick post-Neocomian Cretaceous, Tertiary, and Quaternary shelf sediments overlie the older rocks. The northern Carnarvon Basin consists of three sub-basins—Exmouth, Barrow, and Dampier (Fig. 3)—which flank the Exmouth Plateau. There is no structural break between the Exmouth and Barrow Sub-basins and the Exmouth Plateau.

The north-northeast-trending *Exmouth Sub-basin* was interpreted by Thomas & Smith (1974) as a Mesozoic

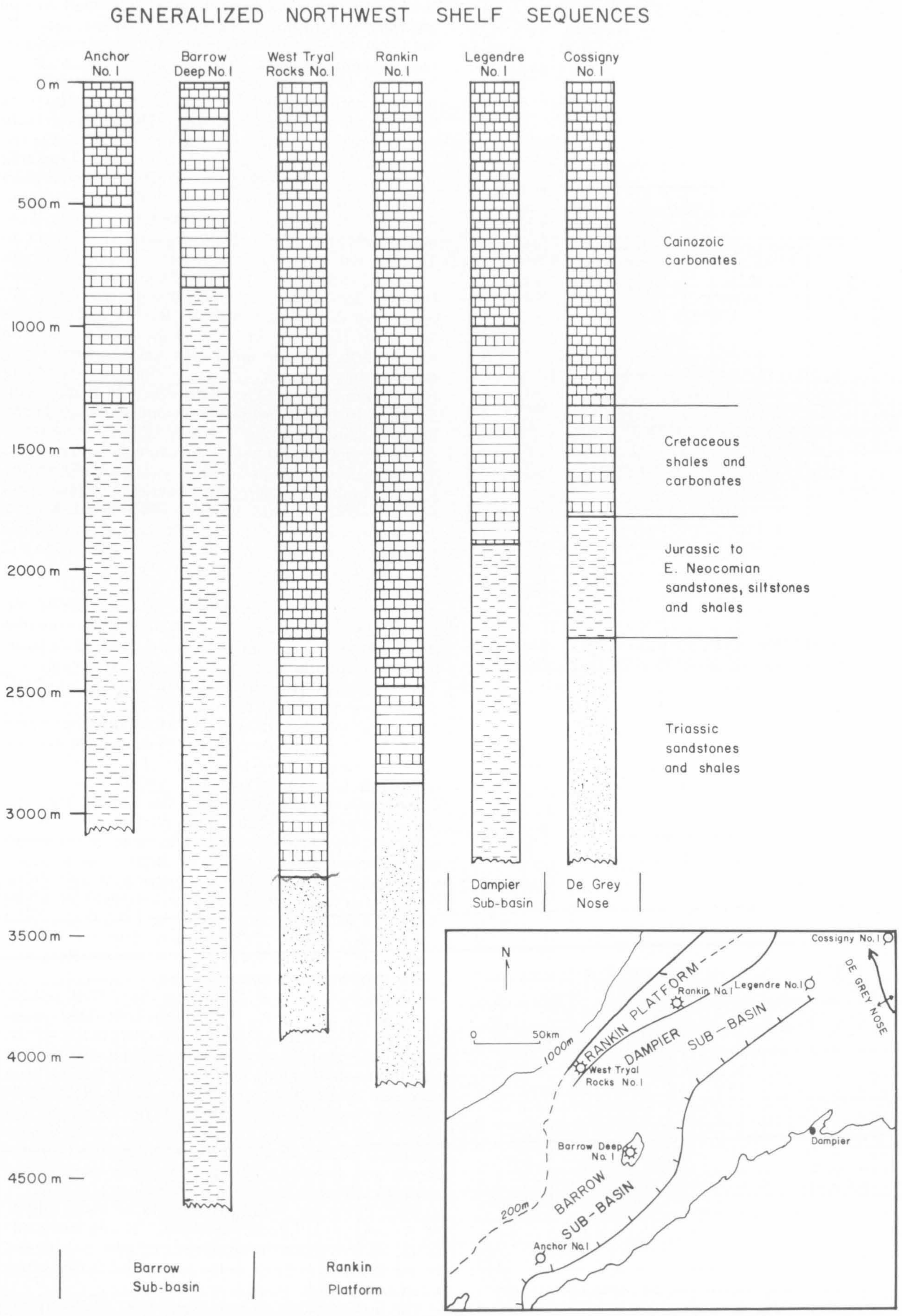
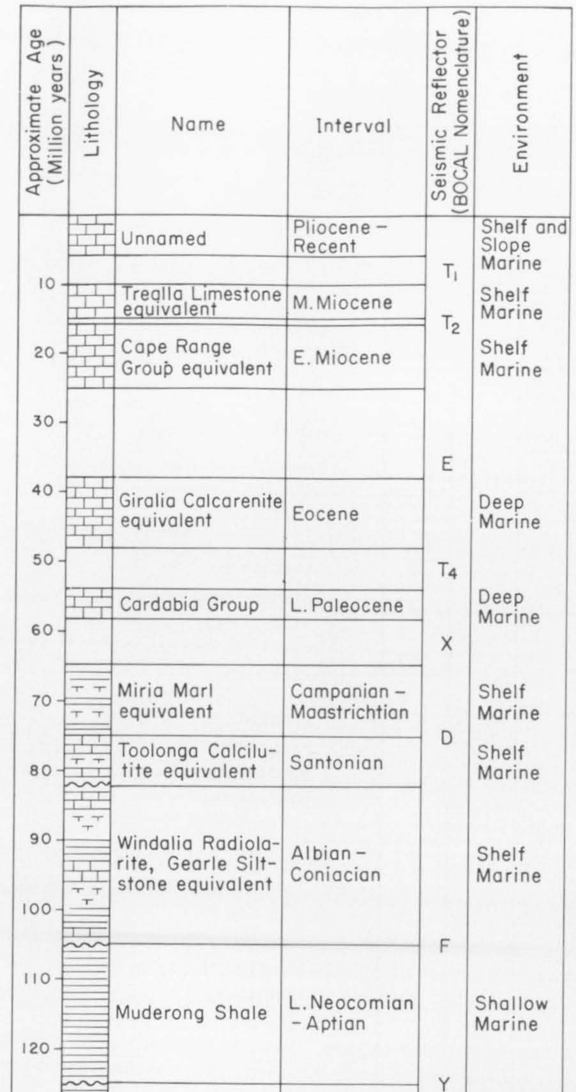


Fig. 3. Generalised stratigraphic sequences for selected wells in the Barrow and Dampier Sub-basins.



NOTES:

True time breaks known for Cainozoic sequence only

Lithological key from Figure 8

Fig. 4. Generalised stratigraphy in the Tryal Rocks area.

half-graben containing possibly 5000-7000 m of marine and fluviatile sediments of mainly Jurassic age. The pre-Cretaceous structure is dominated by a strong pattern of faults trending north-northeast. The southeast boundary of the sub-basin is the Rough Range Fault, a major normal fault with a pre-Cretaceous throw of up to 3000 m down-to-the-west. The Exmouth Sub-basin grades northeastward into the Barrow Sub-basin.

Thomas & Smith stated that the northeast-trending *Barrow and Dampier Sub-basins,* between which there is no clear division, form a Jurassic-Cretaceous downwarp bounded to the east by major down-to-the-basin faults and to the west by a regional high trend in Triassic and Early Jurassic rocks (Rankin Platform and its southern extension). The Exmouth, Barrow, and Dampier Sub-basins were probably a depositional entity throughout the Jurassic, with the Barrow and Dampier Sub-basins remaining linked into the Neocomian. The Barrow and Dampier Sub-basins are bounded to the east by the complex Enderby, Flinders, and Long Island Fault Systems. The faults generally trend north-northeast in the Barow Sub-basin and northeast in the Dampier Sub-basin.

The Exmouth-Barrow-Dampier trough is considered by Thomas and Smith to have formed early in the Jurassic by block-faulting in a tensional regime, possibly related to the break up of Gondwanaland. At least 5000 m of marine, deltaic, and fluvial sediments accumulated in the trough from the Middle Jurassic to the Early Cretaceous (Neocomian). These are underlain by faulted Permian, Triassic, and Early Jurassic sediments which have been penetrated in wells only on the structurally high eastern and western flanks of the trough. Seismic data indicate over 15 000 m of sedimentary section in parts of the Barrow Sub-basin.

The *Rankin Platform,* a northeast-trending structural high consisting of a number of horsts of Triassic and Jurassic sediments, separates the Exmouth Plateau area from the Dampier Sub-basin and much of the Barrow Sub-basin (Fig. 1). Up to 3000 m of Cretaceous, Tertiary, and Quaternary sediments (Figs. 3 & 5) are draped over the platform, which lies beneath the edge of the continental shelf. The platform is cut by numerous en-echelon normal faults with predominant trends varying from northeast to north, and displacements of as much as 1000 m. Thomas & Smith (1974) indicate that fault movement in the northern Carnarvon Basin as a whole continued from the Late Triassic into the Jurassic. Powell (1976) showed that the faulting culminated in the Callovian on the Rankin Platform.

The intracratonic *Canning Basin* covers 600 000 km^2, of which 165 000 km^2 lies inside the 200-m isobath offshore. It is a gentle downwarp containing about 6000 m of Palaeozoic sediments over much of its extent. The geology of the offshore Canning Basin, in which structural trends are largely westerly, has been described by Challinor (1970) and by the BMR Sedimentary Basins Study Section (1974). Onshore the basin is dominated by the northwest-trending Fitzroy Trough, a graben which developed during the Carboniferous and Permian. The graben, whose depth may reach 19 000 m in some places, contains up to 8000 m of Late Palaeozoic sediments overlain by about 700 m of Triassic and Jurassic sediments. It continues offshore, in a west-northwest direction, and is bounded by the Beagle Bay Fault to the north, and the Dampier Fault to the south (Challinor, 1970).

The east-trending Bedout Sub-basin, which forms the western part of the offshore Canning Basin, is

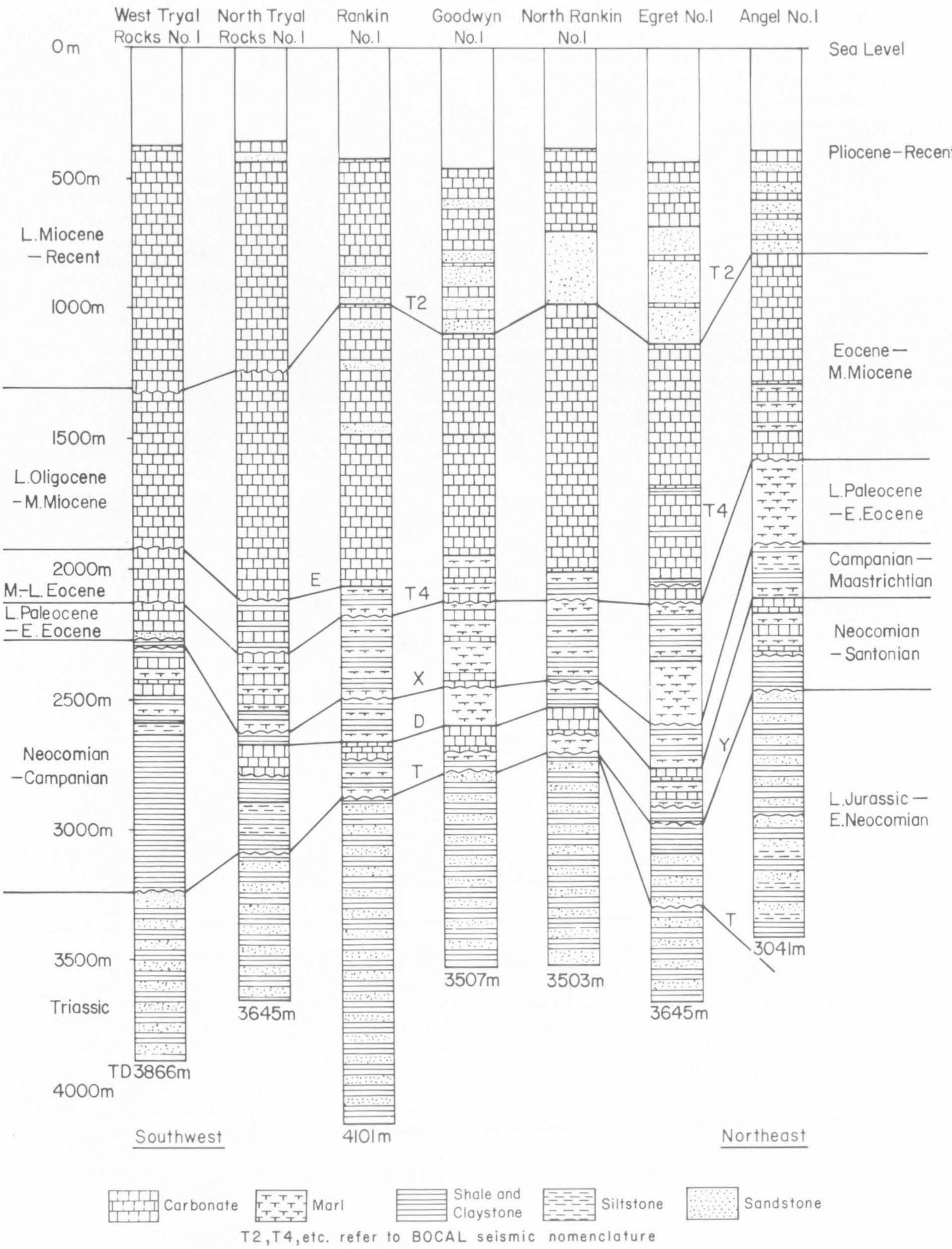


Fig. 5. Well correlations along the Rankin Platform.

separated from the Rankin Platform and the Beagle Trough of the Dampier Sub-basin by the northeast-trending North Turtle Arch. However, farther north no strong structural division between the Canning Basin and the Exmouth Plateau area is apparent. In the Bedout Sub-basin up to 1500 m of Early Jurassic non-marine sediments rests unconformably on older sedimentary and volcanic rocks, and is overlain by about 2000 m of marine Late Jurassic, Cretaceous, and Cainozoic sediments.

The stratigraphic relations between sediments in oceanic areas around the Exmouth Plateau and sediments of the Carnarvon and Canning Basins have been discussed by Veevers & Johnstone (1974). At DSDP Site 263 in the Cuvier Abyssal Plain southwest of the Exmouth Plateau (Fig. 1), the lower part of the section penetrated consisted of about 700 m of neritic claystone of Aptian-Albian age. Basement was believed to be at shallow depth below the base of the hole. The claystone is believed to be part of the Winning Group of the Carnarvon Basin and to have sunk to abyssal depths during Late Cretaceous and Cainozoic times. It is overlain by about 100 m of Late Cainozoic turbidite ooze. At DSDP Site 260 (Veevers, Heirtzler, et al., 1973) northwest of the Exmouth Plateau, about 150 m of Albian and Late Cretaceous deep-sea clay and ooze rests on oceanic basement. At DSDP Site 261 northeast of the Exmouth Plateau, about 400 m of Late Jurassic and Cretaceous deep-sea clay and ooze overlies oceanic basement. At both sites (260, 261) about 170 m of Late Cainozoic turbidite ooze overlies the Cretaceous sequence. At all three sites most of the Cainozoic is not represented (see Davies, Luyendyk, Kidd, & Weser, 1975, for discussion).

The *Exmouth Plateau* is considered to have been part of the Carnarvon Basin until Cainozoic times, and a Palaeozoic and Mesozoic sequence of continental and shallow marine sediments probably underlies the younger sequences. The plateau probably sank to its present depth during the Cainozoic and was covered by shallow marine to bathyal carbonates.

Petroleum geology of northern Carnarvon Basin

As a petroleum province, the Exmouth Plateau appears to be a natural extension of the northern Carnarvon Basin, including the Rankin Platform. The northern Carnarvon Basin contains a number of gas, gas-condensate, and oil fields, gas predominating on and near the Rankin Platform and oil at Barrow Island.

The major gas fields of the Rankin Platform area—North Rankin, Goodwyn, West Tryal Rocks, and Angel—are large by world standards (wells located in Fig. 2 and Pl. 3). Most of the hydrocarbons are trapped in horst blocks in highly porous and permeable sandstones of the late Triassic Mungaroo Formation, which are capped by Cretaceous shales. The horst blocks formed in Late Triassic to Middle Jurassic times and petroleum probably migrated into them from laterally juxtaposed Jurassic shales in the Late Cretaceous and Cainozoic. Kaye et al. (1972) stated that other possible reservoir rocks in the area are Early Triassic, Jurassic, Early Cretaceous, and basal Tertiary sandstones, and Late Cretaceous carbonates. No production facilities had been established on the fields of the Rankin Platform by 1977, although planning of such facilities was under way.

Barrow Island was declared a commercial oilfield in 1966. Initial oil reserves in this small field are estimated to have been 40 x 10^6 m^3 (BMR Petroleum Newsletter No. 60). According to Crank (1973) almost all production comes from the Aptian-Albian Windalia Sand Member of the Muderong Shale, which is of high porosity and low permeability. Structural trapping occurs in a faulted anticline in which the reservoir is capped by siltstones of the Windalia Radiolarite. Other oil and associated gas shows have been encountered in sandstones in the Early Cretaceous and Late Jurassic sequences. Sandstones in the Jurassic Dingo Claystone produced large quantities of gas in Barrow Deep No. 1 well. The major source beds are believed to be shales in the Jurassic and Cretaceous sequences. Crank (1973) states that the Barrow Island anticline started to form in Aptian times, that major arching occurred very late in the Cretaceous or early in the Paleocene, and that much of the migration of oil into the Windalia Sand Member must have occurred in the Tertiary.

The depositional history of the Exmouth Plateau seems to be similar to that of the onshore northern Carnarvon Basin, at least until the Late Cretaceous, and thus it is appropriate to make use of information from the Northwest Shelf in considering the petroleum prospects of the plateau.

PHYSIOGRAPHY

The Exmouth Plateau is a marginal plateau beyond the Australian Northwest Shelf, and is elongated northeast, parallel to the coast (Pls. 3 & 7). We regard the plateau proper as being bounded by the 800-m isobath to the east and by the 2000-m isobath to the north, south, and west, and as extending eastwards to the Swan Canyon. Its total area is about 150 000 km^2 (Pl. 3). The continental slopes around its margins extend from about 200 to 800 m and from 2000 m to 4500 or 5000 m, and have an area of 150 000 km^2. The physiography of the Exmouth Plateau region is largely structurally controlled, but has been modified by submarine canyons, and by other relatively recent erosional and depositional processes.

The Northwest Shelf generally dips northwest away from the land towards the shelf-break at a depth of about 200 m and about 200 km offshore. The shelf has formed by prograding of Cainozoic carbonate sands away from the continent, but at present it is a zone of non-deposition (Jones, 1971).

The upper continental slope has an average dip of 1° toward the northeast and north-trending Montebello Trough (Falvey & Veevers, 1974). The Montebello Trough has a northerly gradient of about 0°20′ and debouches into the northeast-trending Montebello Canyon (new name). Falvey & Veevers (1974) considered that there is no evidence of large-scale sediment transport in the trough, which tends to follow a broad depression in the Middle Jurassic unconformity (compare Plates 3 and 23). They suggested that the trough is caused by sagging of the crust under a thick load of prograded sediments beneath the shelf edge zone.

The trough is probably a Cainozoic feature as Jurassic and Cretaceous sediments do not thicken beneath it (Pls. 11 & 12).

About 250 km west-northwest of Barrow Island, and 100 km west of Montebello Trough, is the north-northeast-trending culmination of the Exmouth Plateau, about 8000 km^2 of which lies above the 1000 m isobath. The shallowest point is about 815 m deep and is located at about 20°S 113°E. This culmination, called the Exmouth Plateau Arch, can be traced for nearly 400 km and, together with Montebello Trough, dominates the physiography of the plateau. The feature closely reflects and is probably controlled by the deep structure (compare Plates 3 and 23).

The margins of the plateau are linear and steep, suggesting that they were formed by faulting. The southwest margin (Pls. 3 & 7) is a straight northwest-trending escarpment with an inclination of 3-5°. The northwest margin is a complex arcuate structure in which downfaulted blocks have formed several deep terraces and ridges. Its average gradient is about 3°. The northern margin is also complex, being dissected into spurs and troughs whose trends vary from east to north. The overall trend of the outer edge of this margin is west-northwest and the slope is as steep as 17° in places (Falved & Veevers, 1974).

The major features along the northern margin are Platypus Spur, Wombat Plateau, Montebello Canyon, Echidna Spur, Emu Spur, and Swan Canyon; all these are new names (Pl. 3). Platypus Spur forms an extension of the Exmouth Plateau which can be traced northward for more than 200 km into water deeper than 3000 m. Wombat Plateau (North Exmouth Plateau) rises to 1620 m below sea level and is separated from the Exmouth Plateau by a trough, the Wombat half-graben, which is more than 2600 m deep. The Wombat Plateau is oval-shaped, elongated latitudinally, and measures about 100 km by 50 km above the 2000-m isobath. It is separated from Platypus Spur to the west and Echidna Spur to the east by north-trending depressions. Montebello Canyon, which separates Wombat Plateau from Echidna Spur, is an extension of Montebello Trough. Echidna Spur and the adjacent Emu Spur are extensions of the Exmouth Plateau which can be traced northwards for more than 100 km into water depths of around 3000 m. Farther east is the north-northeast-trending Swan Canyon, which is depressed by some 1500 m relative to Emu Spur.

The largest canyons on the Exmouth Plateau are along the northern margin, but there are also several canyons along the eastern part of the southern margin. Falvey & Veevers (1974) consider that most of the canyons are inactive at the present time.

GRAVITY AND MAGNETIC INTERPRETATION

The definitions of the free-air (FAA), 'marine Bouguer' (BA), and magnetic anomalies as used in this text are given in Appendix I.

Hogan & Jacobson (1975) have discussed Bouguer and magnetic anomaly contours over offshore northwest Australia, making use of data from the Continental Margin Survey. The magnetic, free-air, and Bouguer anomaly contour maps at 2 500 000 scale accompanying this text (Pls. 4, 5, & 6), were drawn using hourly values from the Continental Margin Survey and Lines 04/144, 04/146, 04/092, and 04/099 of the 1968 sparker survey (Whitworth, 1969), by machine contouring the surface of minimum curvature (Briggs, 1974). Free-air, Bouguer, and magnetic anomaly profile maps derived from one-minute data values are presented in Plates 8, 9, and 10.

Geodetic parameters describing the Earth's gravity field have been computed by Gaposchkin & Lambeck (1971) using satellite and terrestrial gravity data. These results indicate that in the Exmouth Plateau area the height of the geoid ranges linearly from about +10 m in the northeast to about −10 m in the southwest, and the regional free-air anomaly field has values between zero and about −10 mGal. It is generally considered that these regional variations of the gravity field observed from satellite data result from density differences in the mantle; thus the negative free-air anomalies over the Exmouth Plateau may reflect a slight mass deficiency in the mantle. Such density variations must be taken into account if average free-air anomaly values are used as an indication of the degree of isostatic compensation.

On the continental shelf and on marginal plateaux where the gradient of the seabed is relatively small, Bouguer and free-air anomalies have similar contour patterns. However, where the gradient is steep, free-air anomalies show a local correlation with water depth, whereas Bouguer anomalies show little correlation except across the continental slope where the increase in values oceanwards is due to rapid thinning of the crust. Generally, free-air anomalies provide more useful geological information than Bouguer anomalies over the continental slope because the opposing gravity effects due to increasing water depth and crustal thinning are partly cancelled out, and regional gradients are less intense than for Bouguer anomalies. Theoretically, free-air anomalies average zero over features in isostatic equilibrium, and can be used as a measure of the degree of isostatic compensation. However, this is is not true over the margins of a feature, or over a feature which is narrower than about ten times the depth of compensation (Bott, 1971). The minimum width of features which are compensated is about 200 km; narrower features are supported by the crust.

On the continental slopes the free-air anomalies show a marked 'edge effect', consisting of a gravity ridge along the top of the slope and a trough along the foot. It arises from differences in the rates of change of two opposing influences on free-air anomaly values as the continental margin is crossed; namely, the gravity effects at sea level due to variations in depth to the sea-floor, and variations in crustal thickness.

GRAVITY AND MAGNETIC ANOMALY MAPS (Pls. 4, 5, 6 and 8, 9, 10)

The free-air anomalies (Pls. 4 & 8) are regionally positive over the continental shelf, which suggests that slight subsidence of the shelf is required for the crust to be in isostatic equilibrium. The isostatic imbalance is possibly caused by the rapid accumulation of Late Cainozoic sediments within the Exmouth, Barrow, and Dampier Sub-basins and over the Rankin Platform, without compensating subsidence of the crust (Symonds

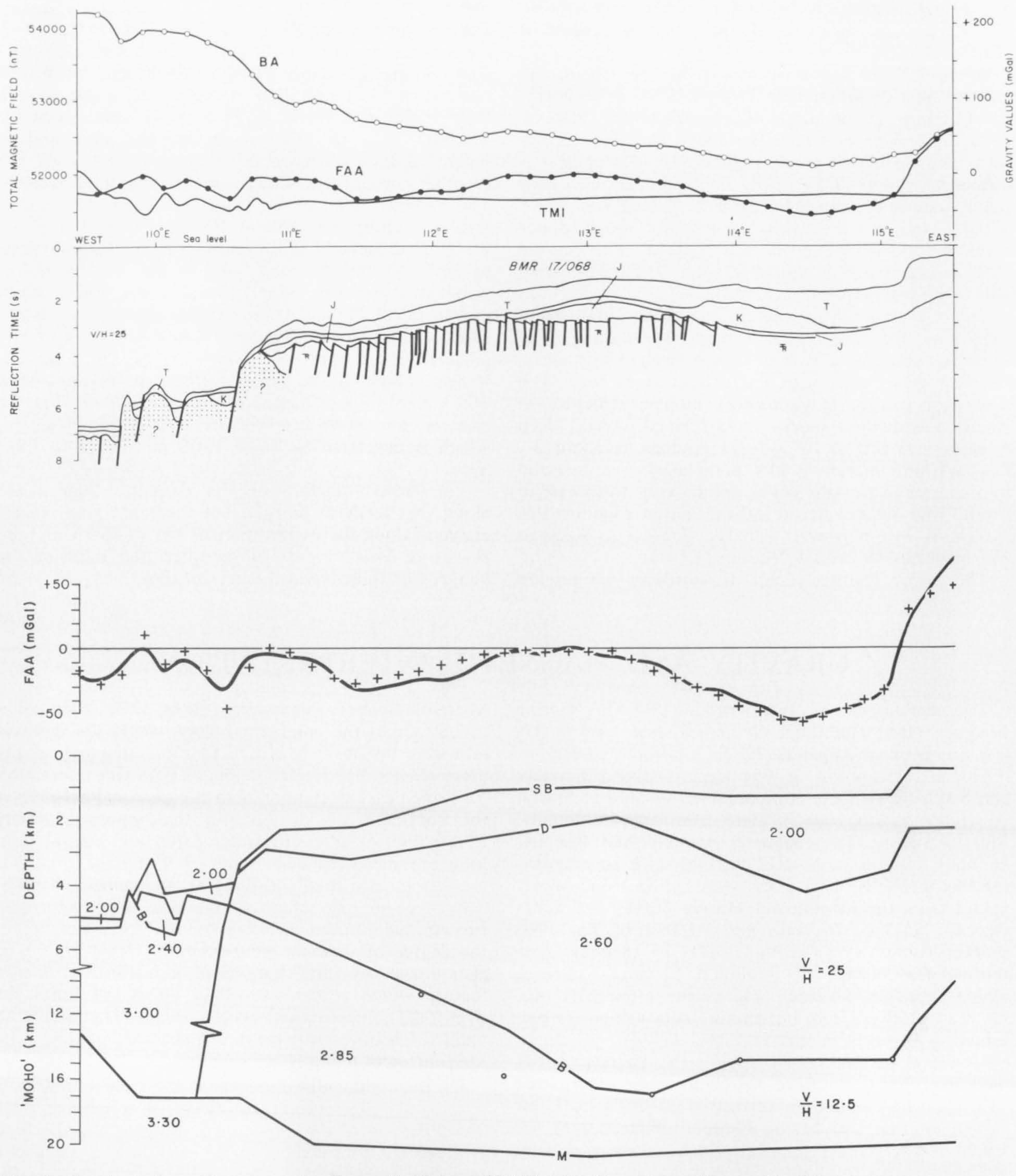


Fig. 6. Geophysical profiles across the Exmouth Plateau (BMR 17/068) with gravity model. BA = Bouguer anomaly (Bouguer density 2.2 t.m^{-3}); FAA = free-air anomaly; TMI = total magnetic intensity. Legend as shown in Fig. 7.

& Willcox, 1976). The northeast-trending belt of gravity highs over the outer continental shelf is attributed partly to an inferred Proterozoic mobile belt, peripheral to the interpreted offshore extension of the Pilbara Block (Fraser, Darby, & Vale, 1977), and partly to a Middle Jurassic horst—the Rankin Platform.

Free-air anomalies over the Exmouth Plateau average approximately zero, indicating that the crust is close to isostatic equilibrium. Individual structural and physiographic elements, generally less than 100 km in width and principally along the northern margin of the plateau, are reflected in the gravity field, which indicates that they are not fully compensated. The gravity ridge and adjacent trough along the southwest margin are due mainly to the 'edge effect', although the gravity ridge may be partly caused by an anticline, and by departures of the shape of the Moho from its theoretical shape if in perfect isostatic equilibrium (see Worzel, 1965; Bott, 1971, fig. 3.14).

Bouguer anomalies (Pls. 5 & 9) increase sharply across the lower continental slopes around the plateau, because of thinning of the crust. The relatively low regional gradient between the continental shelf and the plateau, however, indicates only a small change in crustal thickness, as demonstrated by gravity modelling studies using data from BMR Line 17/068 (Fig. 6). The actual crustal thickness under the Exmouth Plateau has not been determined from seimic data, but a rough estimate can be made by comparing the measured gravity values with values for a 'standard crust' (for examples of standard crusts, see Finlayson & Cull, 1973). If it is assumed that a standard crust 33 km thick, with densities of 2.85 and 3.30 $t.m^{-3}$ for crust and mantle, gives zero free-air anomaly, a crustal thickness of about 20 km is indicated for the outer continental shelf and Exmouth Plateau. Crust of typically 'oceanic' thickness, ranging from 9 to 13 km, lies oceanward of about the 4000 m isobath.

In general, gravity features in the area reflect the main pre-Cretaceous structural features—the north to northeast-trending Exmouth Plateau Arch and Kangaroo Syncline, and the northwest-trending anticline along the southwest margin. The gravity expressions of horsts and grabens along the northern margin of the plateau are also prominent in the free-air anomaly contour pattern. They form a major west-trending gravity lineament which cuts across the area at about 18°S and may reflect an old line of weakness which was reactivated during formation of the plateau margin in the Jurassic. Other west to northwest-trending gravity features, which are associated with the Canning Basin and mobile belts flanking the Pilbara and Kimberley Blocks, extend across the continental shelf but cannot generally be discerned beyond the shelf-break (BMR, 1976a).

The continuity of Bouguer anomaly pattern between the continental shelf and the Exmouth Plateau suggests that the shelf-break is a limit of major sedimentary deposition rather than a tectonic feature, and this is consistent with the seismic profiles which show the shelf to be underlain by a thick wedge of prograded sediment. A broad northeast-trending Bouguer anomaly low over the Montebello Trough is interpreted as indicating that the sediment above the Horizon D unconformity is about 1 km thicker than post-unconformity sediment on the Exmouth Plateau Arch.

Magnetic and free-air anomalies are broad and of low amplitude over most of the plateau, suggesting that sediments are uniformly thick. The shortest-wavelength magnetic anomalies have widths of 20 km, which indicates a depth to magnetic basement of about 7 to 10 km. Magnetic anomalies of relatively short wavelength over the northwest margin have shallow sources in the crystalline basement, which is probably composed of altered and intruded continental crust. Several high-amplitude anomalies at the foot of the continental slope southwest of the plateau (e.g. Fig. 7) may be the expressions of igneous bodies intruding along faults parallel to the slope, which were active during the formation of the Cuvier Abyssal Plain in the Late Cretaceous.

Along the northern margin of the Exmouth Plateau are several dipole-like magnetic anomalies. The positive parts of the dipolar anomalies lie mainly between latitudes 16° and 17°S, and are situated over probable crystalline basement cropping out on the northern side of Wombat Plateau and on the lower continental slope to the north of the plateau. Eastward from 118°E the anomalies trend northeast, then north, following the lower continental slope, and farther north extend over the western part of the Scott Plateau (BMR, 1976b). The largest dipolar anomaly has a maximum positive value of 800 nT, and its positive and negative peaks are displaced 30 km north of Wombat Plateau and the Wombat half-graben, respectively (Fig. 8). The total field profile shows that it consists of a long-wavelength component, probably related to a change in crustal structure across the continental margin, and a short-wavelength component derived from a source at 5 to 10 km depth. The short-wavelength component appears to be related to outcrops of probable igneous basement on the northern edge of the Wombat Plateau and to structures deep within the half-graben. The easterly elongation of the magnetic trough along latitude 17°20'S coincides with the axis of the half-graben. Farther east, on Shell Lines N209 and N210, two other elongated magnetic lows also show an approximate correlation with grabens. On the magnetic anomaly map the three troughs appear to form a regional trough which has been offset along northerly-trending transcurrent faults on meridians 115°30', 116°30', and 117°00'E. The regional trough can be clearly traced eastward to the Rowley Shoals area on the 1:2 500 000 map described by Hogan & Jacobsen. Other transcurrent faults may occur across the western end of the Wombat half-graben and along meridians 113°30'E and 112°00'E.

The general trends of the gravity contours on the Plateau are consistent with the fault patterns interpreted from seismic sections. The southwestern edge of the Plateau is formed by steep northwest-trending fault scarps; the northwest margin by numerous basement blocks downthrown to the west along north-northeast-trending faults; and the northern margin by several grabens and sub-plateaux which resulted from interaction between north-northeast and east-trending faults.

Gravity models (Figs. 6, 7, & 8)

Gravity models along traverse lines over the Exmouth Plateau (BMR 17/068) and its northern and southwestern margins (BMR 18/008; BMR 18/004 & 17/063) have been computed to test the consistency of the seismic intrepetation with the gravity observations, and to roughly determine the shape of the crust/mantle interface. Sediment densities, determined from Neutron and Sonic Logs (Schlumberger, 1966, pp. 42, 43) for wells on the Northwest Shelf and in the southern Carnarvon Basin, are given in Table 5. The densities of the main sedimentary intervals are assumed to apply in the Exmouth Plateau area; they are listed in Table 1. The densities shown for the basement complex and the mantle are values which are commonly assumed in gravity modelling studies of crustal structure.

TABLE 1. DENSITIES USED FOR GRAVITY MODELS

Layer	$t.m^{-3}$
Water	1.05
Late Cretaceous to Recent (post-Horizon D)	2.00
Triassic to Mid-Cretaceous	2.40
Palaeozoic	2.60
Basement complex	2.85
Mantle	3.30

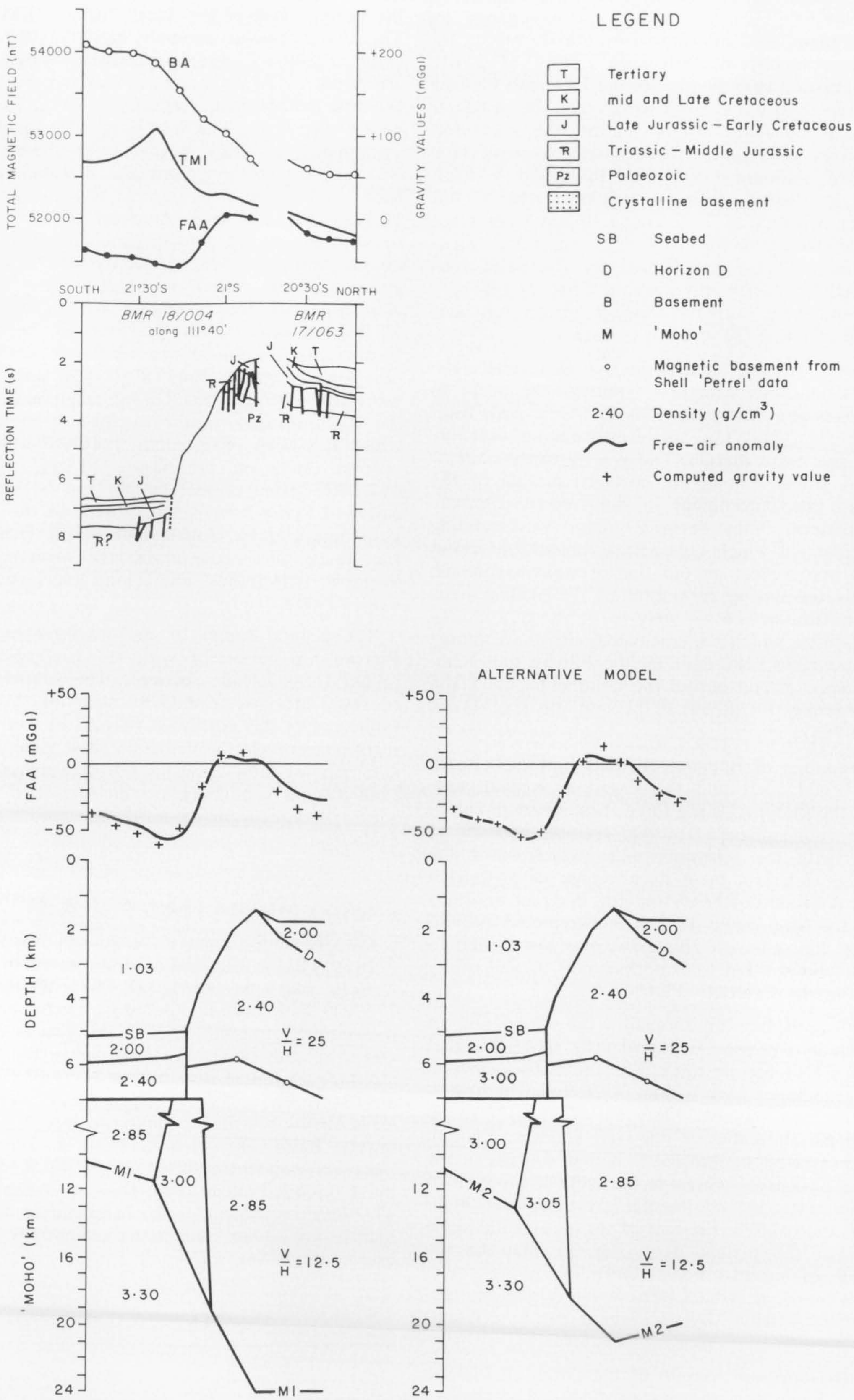


Fig. 7. Geophysical profiles across the southwest margin (BMR 18/004 and 17/063) with gravity models. BA = Bouguer anomaly (Bouguer density 2.2 $t.m^{-3}$); FAA = free-air anomaly; TMI = total magnetic intensity. Models indicate intrusion along marginal transform fault.

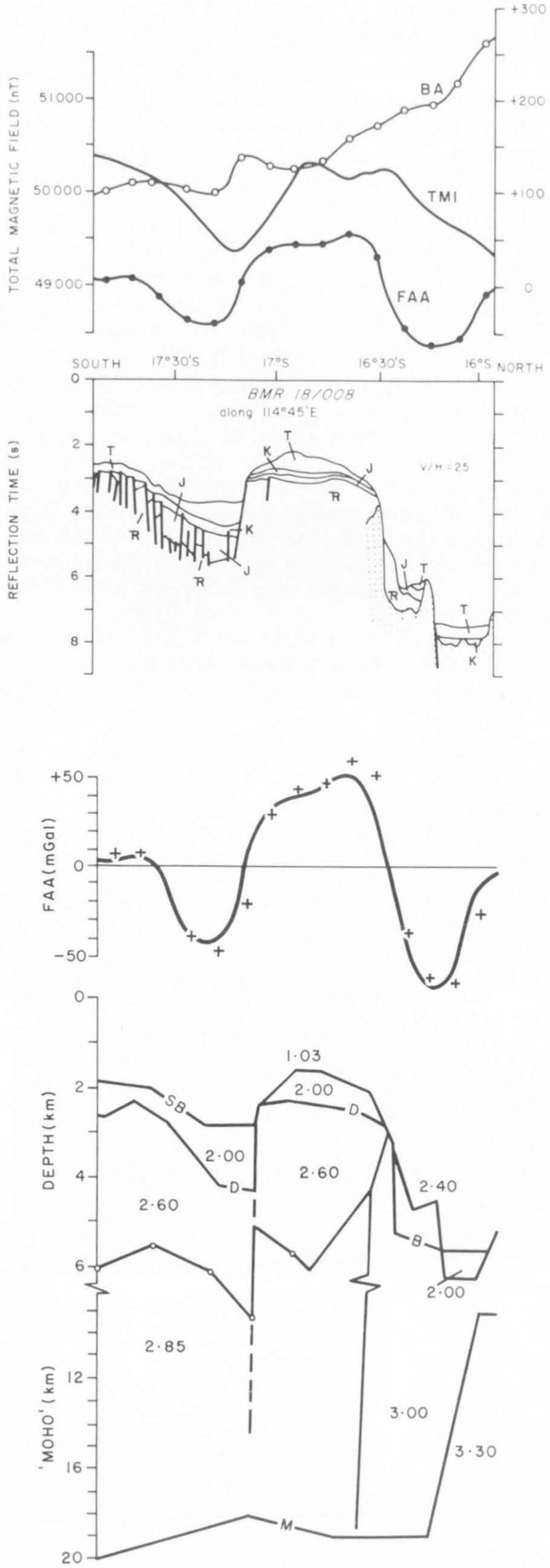


Fig. 8. Geophysical profiles across the northern margin (BMR 18/008) with gravity model. BA = Bouguer anomaly (Bouguer density 2.2 $t.m^{-3}$); FAA = free-air anomaly; TMI = total magnetic intensity. Legend as shown in Fig. 7.

The basement depths assumed in the models are depths to magnetic basement computed by Shell from data collected aboard the *Petrel* (Shell, 1972). The depth of the crust/mantle interface used as a starting point in the gravity modelling studies was computed from differences between the regional gravity values and those of a standard crust 33 km thick, of density 2.85 $t.m^{-3}$, overlying mantle of density 3.30 $t.m^{-3}$. The chosen thickness of the standard crust is not critical and variations of about ± 5 km have little effect on the computed gravity values except in areas where the crustal thickness varies abruptly.

The gravity model along line BMR 17/068 (Fig. 6) assumes that Late Cretaceous to Recent sediments are relatively thick within the Kangaroo Syncline, and that a depression in the basement beneath the Exmouth Plateau Arch may have existed in Palaeozoic times. The crust is interpreted as being of uniform thickness under most of the plateau, but becoming thinner beneath the lower continental slope. The gravity modelling indicated that the density of the basement complex increases from 2.85 to about 3.00 $t.m^{-3}$ under the margin. Such a density increase is attributable to a transition from continental to oceanic crust.

The seismic interpretation of the northwest margin (Fig. 25; also Powell, 1976, fig. 4) as consisting of blocks of dense crystalline basement at shallow depth is not consistent with the gravity observations, which suggests that at least some of the blocks are of low density, and probably composed of fractured Palaeozoic or Triassic sedimentary rocks, representing the original rift valley.

Models across the steep, linear, southwest margin of the plateau are derived from data on BMR 18/004 and 17/063 (Figs. 7 & 24). Two seismic horizons beneath the northern margin of Cuvier Abyssal Plain have similar acoustic and structural characteristics to Horizons C and F on the Exmouth Plateau, indicating that pre-Late Jurassic sediments may be present (Exon & Willcox, 1976). These sediments are older than the ocean floor and, if present on the Cuvier Abyssal Plain, must overlie continental basement which has sunk to abyssal depths. Two gravity models were computed: one with continental crust of density 2.85 $t.m^{-3}$ extending from the Exmouth Plateau to the northern margin of the Cuvier Abyssal Plain; the other with a change to oceanic basement of density 3.00 $t.m^{-3}$ at the foot of the lower continental slope. Although these models were not a satisfactory test of the alternatives as both gave acceptable fits with the observed gravity data, both models require that a high-density body be placed beneath the continental slope/abyssal plain boundary; this implies that a large intrusive body, probably associated with a major fault, is present beneath the southwest margin of the plateau. This body is considered to be the cause of a 500 nT magnetic anomaly (Fig. 7), and diffractions observed on the seismic profile (Fig. 24).

On the northern margin, the computed and observed gravity are in good agreement (Fig. 8). Here too, a zone of transitional crust is interpreted. Abrupt thinning of the crust by about 10 km along the margin suggests that the margin may have formed as a transform fault.

SEISMIC HORIZONS AND INTERVALS

Characteristics and Nomenclature

Stratigraphic control in the Exmouth Plateau area is based on tentative seismic ties to the Rankin Platform of the Northwest Shelf, where WAPET and BOCAL have drilled several exploration wells, and on a comparison of the structural style of the plateau with that of the northern Carnarvon, offshore Canning, and Browse Basins (Fig. 1). The Tryal Rocks area, leased to WAPET and at the southwestern end of the Rankin Platform, is the nearest area in which the stratigraphy is known (Fig. 3).

WAPET's stratigraphic scheme is similar to that of BOCAL (e.g. Kaye et al., 1972) although the ages assigned to some particular stratigraphic units are different in the two schemes. For example, BOCAL regard the Barrow Formation as of Late Jurassic to Neocomian age, whereas WAPET consider it to be entirely Neocomian; also the ages assigned to the various Cainozoic units differ considerably. A tentative correlation of seismic horizons in the Exmouth Plateau area with those of BOCAL was presented by Exon et al. (1975, table 1).

The Late Cretaceous and older sequences of the Northwest Shelf and Exmouth Plateau appear to be similar, allowing reasonable correlations to be made, but the Cainozoic sequences differ considerably, and correlations are rather tentative.

The main characteristics of the seismic horizons and intervals, which are typical of those in most of the Exmouth Plateau area, can be seen in a profile from Esso Line 1 (Fig. 9; location shown in Pl. 1). These characteristics and the ages assigned to horizons are summarised in Table 2. The nomenclature which we adopted for the Permian to Recent sequences, together with the general age ranges of the unconformities, inferred lithologies of intervals, and environments of deposition, are given in Table 6 (p. 20).

Horizon F is the most prominent unconformity in the Exmouth Plateau area. It is readily identified on the Exmouth Plateau Arch where the discordance between beds within fault-blocks below the unconformity and overlying ponded sediments is considerable (Fig. 9). The unconformity deepens and the discordance diminishes eastward across the eastern limb of the arch into the Kangaroo Syncline (Fig. 10C). On the northeast Exmouth Plateau Horizon F appears to lie within the fault-blocks.

Horizon F has been tentatively tied to the Rankin Platform (Figs. 10A & 10B) via Gulf lines AU11-24. The tie-points generally lie within a conformable

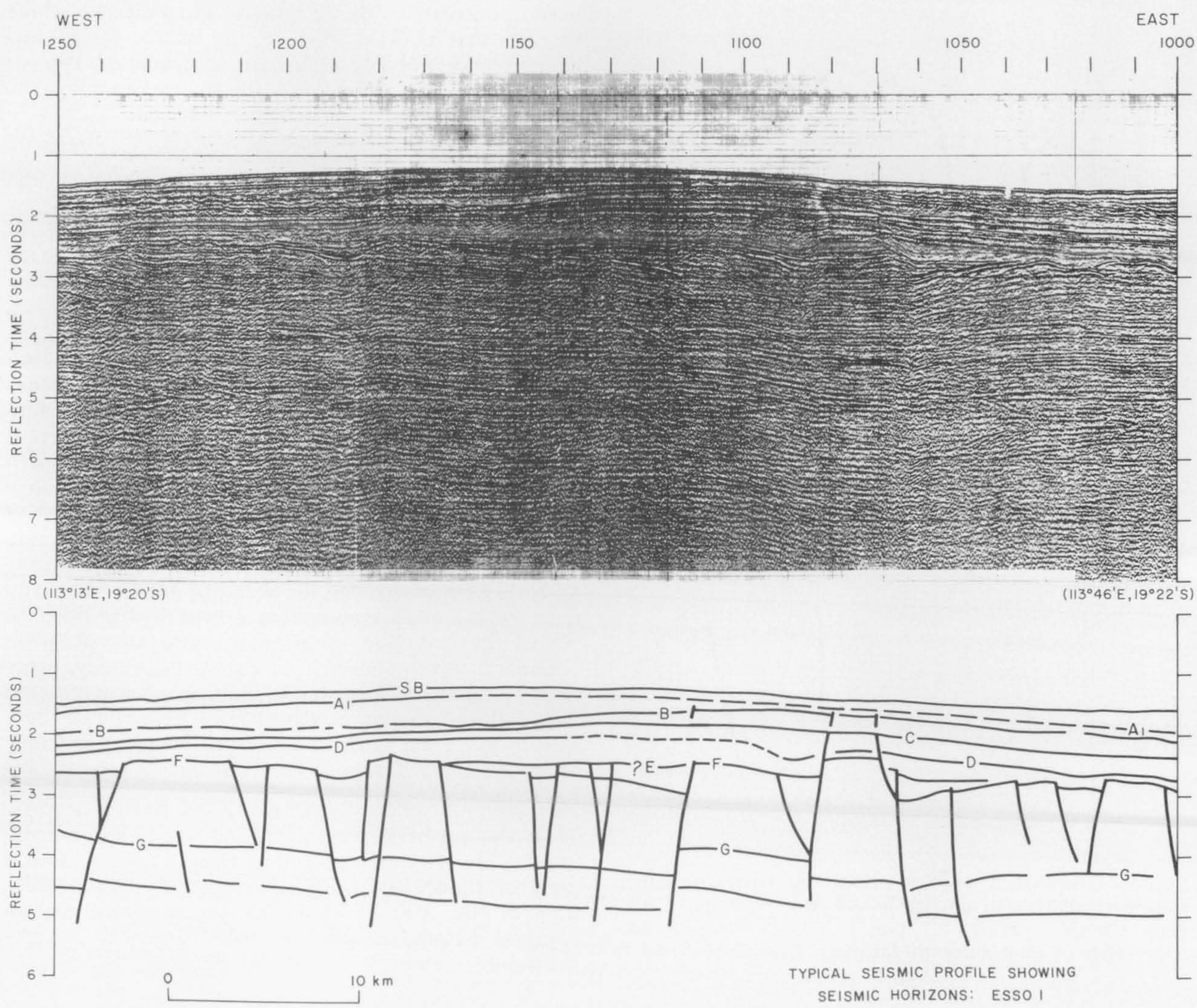


Fig. 9. Typical seismic profile and its interpretation: Esso 1. Location given in Pl. 1.

TABLE 2. CHARACTERISTICS AND PROPOSED AGES OF SEISMIC HORIZONS

Seismic Horizon	*Characteristics*	*Basis of age determination*	*Proposed Age*	*Comments*
A1	Unconformity separating upper acoustically semi-transparent zone from a lower zone of contorted reflectors or diffraction	Analogy with unconformities in the Tryal Rocks area, on S extension of Rankin Platform (Quilty, 1974). A1, A2, & B cannot be traced across upper continental slope	Tertiary; probably Oligocene	Can be traced throughout area. Interval (A1-seabed) has prograded westward to form the continental shelf. In places on the continental shelf it incorporates dune-like structures (Fig. 17)
A2	Unconformity marking bed of channel-like features in some places		Tertiary; possibly early Eocene	Channels very apparent on N part of plateau (Fig. 13) but also present farther S
B	Mild unconformity near base of zone of contorted reflectors or diffractions, which contains enormous lenticular bodies		Tertiary; probably early Paleocene	Probably occurs over most of area but has not been identified on N Exmouth Plateau Arch. In some places Horizon B is possibly a decollement surface along which slumping has occurred. Coincides with Horizon C in many places
C	Strong reflector at base of thin well-stratified zone. A mild angular unconformity under S Exmouth Plateau	Reliable seismic ties to several wells on the Rankin Platform	Early Late Cretaceous	Mapped throughout area. Few major faults penetrate the horizon except in NE Kangaroo Syncline. Compaction of Jurassic and Cretaceous sediments has caused some draping of Horizon C. Coincides with Horizons D & F on some horst blocks
D	Reflector marking top of zone of northerly prograded sediment beneath S Exmouth Plateau. Can be traced N as a weak reflector within an acoustically semi - transparent zone. On NE Exmouth Plateau Horizon D coincides with a 'top of blocks' unconformity (E)	Tentative seismic ties to Tryal Rocks No. 1 and West Muiron No. 2 (Barrow Sub-basin)	Early Cretaceous; Neocomian	Mapped through most of area, but is weak and is located somewhat uncertainly beyond the delta. Coincides with Horizon F on some horst blocks. Shows evidence of draping and compaction
E	Weak reflector. Mild angular unconformity overlying a thin sequence ponded between tilted blocks. Generally marks upward limit of block-faults. Cannot be distinguished from Horizon F in parts of central Exmouth Plateau	Seismic-character tie to wells on the Rankin Platform. In N Rankin area, Callovian sediments have been found below this unconformity which overlies the main fault-blocks	Late Jurassic; Callovian	
F	Strong reflector. An angular unconformity near the 'top of blocks' on central Exmouth Plateau. Largely conformable and within fault-blocks under NE Exmouth Plateau and continental shelf	Tentatively traced to wells on Rankin Platform where it lies within or below the Late Triassic section. Analogy with tensional phase in Browse and Canning Basins (Powell, 1976)	Pre-Callovian; probably Late Triassic	Readily mapped. Faults become more intense towards the outer margin. Blocks are generally tilted landward (Fig. 25)
G	Strong reflector which is an angular unconformity beneath parts of Exmouth Plateau. Under the continental shelf it marks an early episode of block-faulting	Analogy with block-faulting in inner Browse Basin (Powell, 1976)	Possibly Late Permian	Horizon shows the deep structure in parts of Exmouth Plateau Arch. It indicates a large faulted monocline beneath Plateau crest (Fig. 23)
Basement	Envelope of diffraction patterns	Commencement of seafloor spreading (Veevers, Heirtzler, et al., 1974) and occurrence of volcanic rocks in wells	Probably Precambrian Pilbara Block equivalent under plateau; Permian to Cretaceous igneous basement at margins	Transitional basement associated with rift-valley stage of seafloor spreading. Visible on seaward ends of seismic sections (Fig. 20)

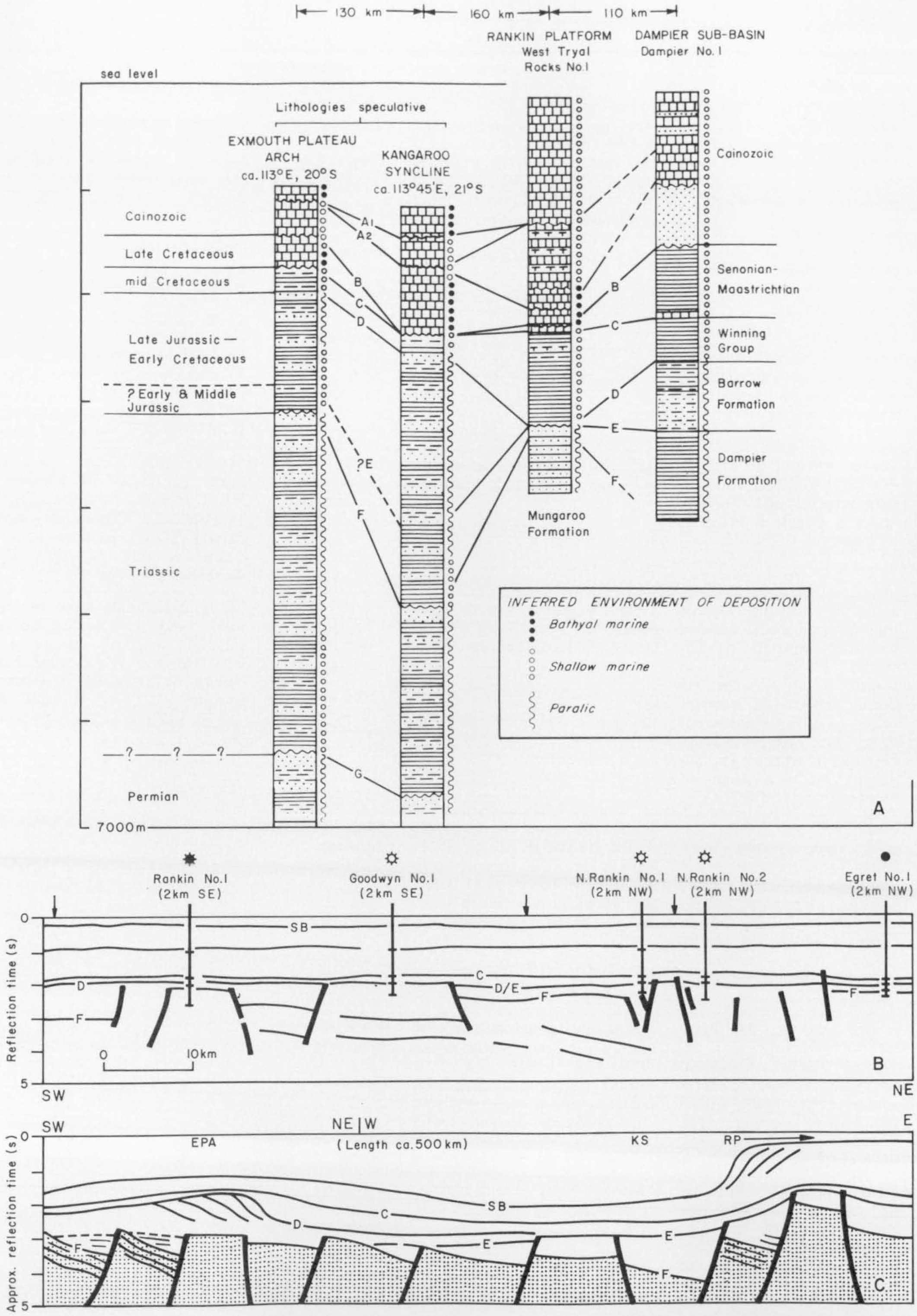


Fig. 10. A. Correlations between the Dampier Sub-basin, Rankin Platform, Kangaroo Syncline, and Exmouth Plateau Arch. B. Profile along the Rankin Platform (Gulf AU 12-13). Arrows show seismic tie-points. Well picks show: Middle Miocene, top Cretaceous, (top Jurassic in Egret), top Triassic, total depth. Seismic profile shown in Pl. 33. C. Schematic profile showing apparent relations of seismic horizons on the Exmouth Plateau and Northwest Shelf. EPA = Exmouth Plateau Arch; KS = Kangaroo Syncline RP = Rankin Platform.

sequence of sediments which flanks the horst-blocks on which most of the wells have been drilled. These sediments are believed to range from Triassic to Middle Jurassic by analogy with data from Cossigny No. 1, Enderby No. 1, and Legendre No. 1 wells (Fig. 2), which were drilled in structurally lower parts of the Dampier Sub-basin. In some areas Horizon F is considered to lie near the surface of horst-blocks which consist of Late Triassic sediments (Mungaroo Formation) and are unconformably overlain by the mid-Cretaceous (Winning Group).

In summary, the Horizon F unconformity on the Exmouth Plateau is probably Late Triassic and is contemporaneous with episodes of block-faulting in the offshore Canning and Browse Basins as discussed by Powell (1976). Strata beneath the unconformity may range from Permian to Late Triassic, and generally appear to be oldest towards the west. The Horizon F unconformity fits the category of a 'rift-onset' unconformity as defined by Falvey (1974). However, an earlier episode of rifting probably occurred in the Late Permian and is indicated by Horizon G.

The Late Jurassic, probably Callovian, age assigned to Horizon E is based primarily on the presence of Callovian sediments beneath the unconformity in the North Rankin area, and on the presence of a thick Tithonian sand section apparently derived from the emergent Rankin Platform (Powell, 1976, based on an amendment to fig. 8). Unconformities of similar age have been identified in the offshore Canning and Browse Basins. These unconformities formed in response to the onset of seafloor spreading north of the Exmouth Plateau, dated by magnetic lineations and drilling results from DSDP Site 261 (Larson, 1975; Veevers, Heirtzler, et al., 1974), and have been termed 'break-up unconformities' by Falvey (1974).

Although Horizon E is an important unconformity which can be mapped on the Northwest Shelf and the northeast part of the Exmouth Plateau, it can only be identified in a few places on the central and southern plateau. Over most of the area it appears to be almost coincident with Horizon F.

Horizon D is another important reflector. It is easily recognised in the southern part of the plateau, where it caps a markedly prograded sequence, but it is not so easily identified in other areas. On the northeast Exmouth Plateau it coincides with the Callovian 'top of blocks' unconformity. Over most of the plateau it is a weak reflector, which in some places lies near the top of sediments lying between the older fault-blocks (Fig. 9). The unconformity has not been dated precisely from well data. It is visible on downthrown blocks on the Rankin Platform where few wells have been drilled, but is absent on upthrown blocks where wells are abundant. Its dating as mid-Neocomian depends on ties to Tryal Rocks No. 1, and West Muiron No. 2 in the Barrow Sub-basin, and on whether the identification of the underlying sequence as the Barrow Formation is correct. The deltaic character and thickness of the sequence are similar to those of the Barrow Formation.

The younger horizons under the plateau were dated by studying their continuity with, or similarity to, known horizons under the Northwest Shelf. Horizon C, a strong reflector at the base of a well-stratified zone, can be traced onto the Rankin Platform along a number of profiles, and its identification as the base of the Late Cretaceous carbonate sequence is quite positive.

Prominent unconformities have been identified within the Late Cretaceous to Recent section, and others may be present but obscured by the complex of channel-like structures, slumps, and synsedimentary faults on the plateau. Across the southern part of the Exmouth Plateau Arch two unconformities are apparent: the lower one, Horizon B, lies within a zone of contorted beds and in places near the base of that zone, and is conformable with the gross structure of the arch; the upper one, Horizon A1, separates the contorted beds from the flat-bedded section above. In a few places an intermediate unconformity, Horizon A2, is apparent at the base of channel-like features; in these places A1 lies on top of the channel fill. Across the northern part of the arch both Horizons A1 and A2 are present.

The ages assigned to the unconformities defined by Horizon A1, A2, and B are speculative. No wells have been drilled in the area, and the thickness of sedimentary section increases abruptly across the upper continental slope to the nearest wells on the continental shelf. However, in the Tryal Rocks area on the southern extension of the Rankin Platform (Quilty, 1974) there are three unconformities, of Oligocene, early Eocene, and Paleocene ages, which we correlate with Horizons A1, A2, and B on the Exmouth Plateau.

Although we consider our interpretation to be substantially correct, other interpretations are possible, such as that given for BMR 17/068 (Fig. 11) by Powell (1976). Powell correlates the main late Middle Jurassic unconformity beneath the Northwest Shelf with our seismic Horizon D, rather than with Horizon E, thus inferring that substantial erosion of the fault-blocks has taken place. He interprets our Horizon F, near the crest of the Exmouth Plateau Arch, as lying deep within the fault-blocks and overlain by a lens of sediment (Interval D-F) of Late Jurassic age. He considers that a predominance of mudstone in the lens of sediment might account for its apparent lack of bedding and faults. We disagree with Powell's interpretation, firstly because we have made (admittedly tentative) seismic ties from the Browse and Barrow Sub-basins, and secondly because there is enough bedding in the sediment lens to enable any faulting to be discerned.

Our interpretation for BMR 17/068 (Fig. 11) takes account of data from BMR 18/069 and several company lines which intersect 17/068, and have more northerly orientations. These lines indicate that the lens of sediment is laterally continuous with a prograded sequence immediately to the south. The prograded structure, sediment thickness, and tentative seismic ties to the Barrow Island area, all indicate a Late Jurassic and Neocomian age for this unit; thus it post-dates most of the block-faulting. We believe the unit to be prodeltaic and equivalent to the Dingo Claystone and/or Barrow Formation on Barrow Island.

Seismic interval velocities for time to depth conversion

Velocities and depths of refracting horizons were determined from an analysis of refraction events on nine BMR sonobuoy records from the Exmouth Plateau area (Tables 3 & 4). It was found that refractors lying within any particular seismic reflection interval had similar velocities, so it was possible to assign a meaningful average refraction velocity to each interval. As a first approximation, these average refraction velocities were regarded as interval velocities for the purpose of time to depth conversion.

The average velocities obtained are in reasonable agreement with those derived from sonobuoy records by Veevers et al. (1974), who calculated velocities from the refractions, and from high-angle reflections using a technique described by Le Pichon et al. (1968). From the Late Jurassic upwards (above seismic horizon F) the velocities derived from sonobuoy data on the Exmouth Plateau are considerably less than those derived from velocity determinations in wells along the edge of the continental shelf. This is probably because pelagic sediments, which have low velocities owing to their high porosity, are more abundant on the plateau than on the shelf. Table 4 shows the rela-

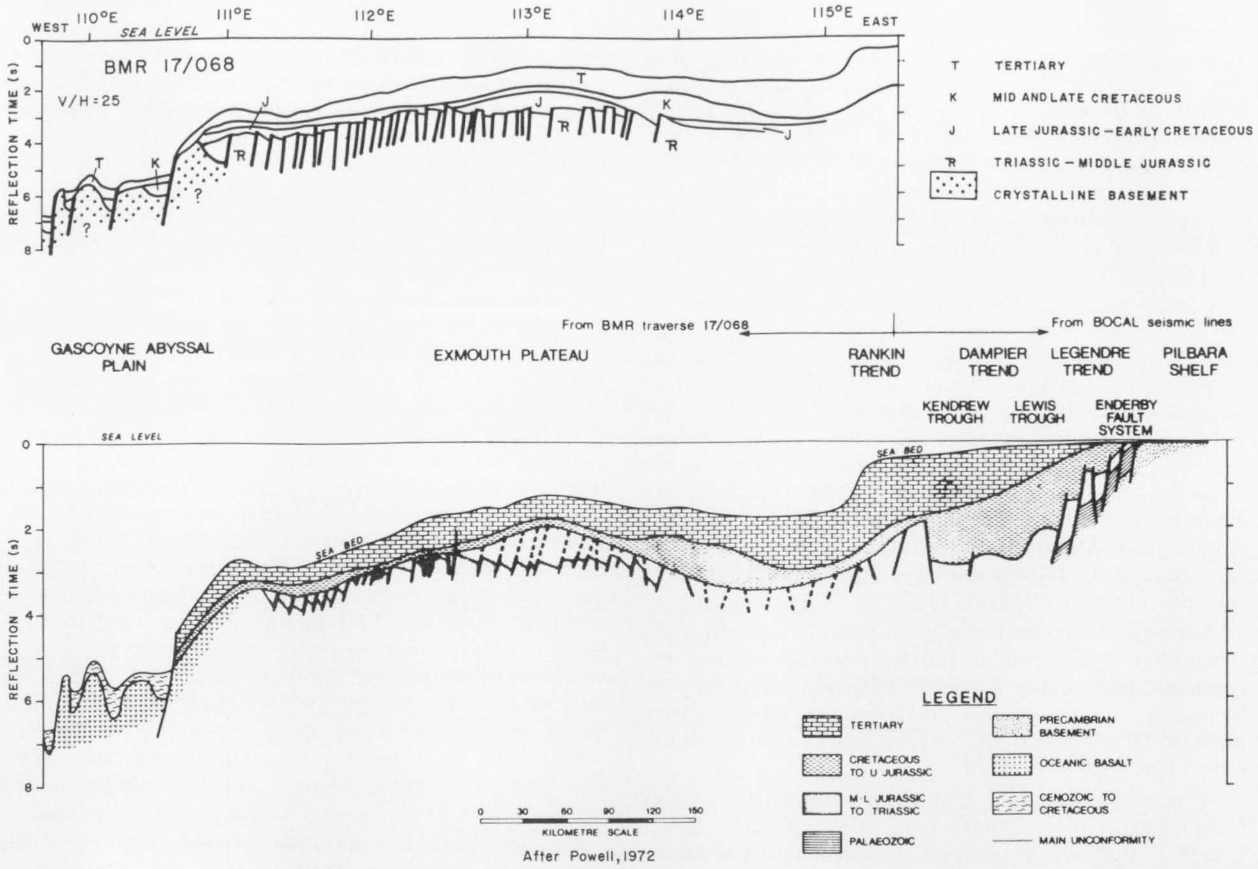


Fig. 11. Interpretations of BMR 17/068: above, by Willcox & Exon (1976) and this text; and below, by Powell (1976). Location given in Pl. 1.

TABLE 3. LOCATION OF BMR SONOBUOYS

No.	*Line*	*Time*	*Approx. location*	
		(DD.HHMM)	*Lat.*	*Long.*
1	17/074	56.0143-56.0250	18°25'S	115°50'E
2	17/093	82.0510-82.0640	17°35'S	117°15'E
3	17/084	75.1403-75.1530	15°50'S	119°25'E
4	17/090	80.2337-81.0051	15°20'S	119°55'E
5	17/089	80.1240-80.1400	14°25'S	121°10'E
6	17/076	59.2244-60.0013	17°25'S	116°25'E
7	17/079	65.2235-66.0103	16°55'S	116°25'E
8	17/072	54.0217-54.0314	18°55'S	144°10'E
9	18/007	07.0547-07.0615	17°55'S	113°30'E

tion between seismic reflectors and interval velocities derived from well velocity surveys and sonobuoy records, together with the velocities chosen for converting times to depths.

The interval velocities determined from well velocity surveys in West Tryal Rocks No. 1, North Tryal Rocks No. 1, and Malus No. 1, on the part of the Northwest Shelf adjacent to the Exmouth Plateau, are related to the stratigraphy in Appendix II, and this information is summarised in Table 4. These figures were redrafted from the well completion reports submitted to BMR and available to the public under the terms of the Petroleum (Submerged Lands) Act, 1967-1974.

Densities determined from wells

Sediment densities were determined from Neutron and Sonic Logs (Schlumberger, 1966, pp. 42-43) for selected wells on the Northwest Shelf and in the southern Carnarvon Basin; the values obtained are given in Table 5. Two major density discontinuities roughly correspond with seismic horizon D and with the top of the Palaeozoic (probably seismic horizon G). In general, the seismic intervals are associated with fairly constant density values. These densities were used in gravity models of the Exmouth Plateau area (Table 1).

STRATIGRAPHY

Seismic reflection profiles, such as those shown in Plates 29 to 33, indicate that many stratigraphic intervals under the Exmouth Plateau are continuous with, and of similar character to, those under the Northwest Shelf. This, together with information on interval velocities obtained from seismic refraction data (Veevers et al., 1974; Exon et al., 1975), has enabled us to infer the lithologies of intervals beneath the Exmouth Plateau (Table 6, Fig. 12). These inferred lithologies are broadly consistent with constraints suggested by our knowledge of the geological history of the plateau region, which is based on the seismic information and on studies of the geology of the Carnarvon and Canning Basins, DSDP drilling results, and the oceanic magnetic lineation pattern.

However, the lithologies inferred for the intervals and illustrated in Figures 10 and 12, will remain speculative until the various sequences have been adequately

TABLE 4. SEISMIC VELOCITIES (m/s) FROM WELL VELOCITY SURVEYS AND SONOBUOYS

Seismic horizons	Wells Seismic velocities from well velocity surveys	Sonobuoys Plateau & edge zone (Veevers et al., 1974)	Sonobuoys Plateau & Continental Slope (BMR Continental Margin Survey)	Seismic velocities chosen for time to depth conversion
Seabed				
	2733 average from Malus, N. Tryal Rocks & W. Tryal Rocks	2200 range 2000-2500; average of 6 interval velocities	2350 range 2020-2570; average of 6 refraction velocities	2300
C				
	2866 average from Malus, N. Tryal Rocks & W. Tryal Rocks	2500 range 2400-2700; average of 3 refraction & 3 interval velocities	2525 range 2480-2570; average of 2 refraction velocities	2500
D				
	3920 average from Malus, Egret, Angel, Dampier & Legendre		3033 range 2840-3220; average of 3 refraction velocities	3500
F				
		3150*	3025**	3500
G	4000 average from Rankin & Goodwyn	3700-4800 refraction velocities	3880 range 3460-4330; average of 3 refraction velocities	4000

*Range 2800-4000; average of 8 refraction and 3 interval velocities

**Range 2900-3460; average of 4 refraction velocities. Value 3850 determined from sonobuoy 6 has been excluded as it probably relates to older ?Triassic section.

TABLE 5. DENSITIES DETERMINED FROM SELECTED WELLS ON THE NORTHWEST SHELF AND IN THE SOUTHERN CARNARVON BASIN

Well	Seismic Interval	Seabed-A	A-B	B-C	C-D	D-F	F+	(?)G+
*Barrow	Depth range					838-4603+		
Deep No. 1	Density					2.3		
**Cossigny	Depth range	113-1063	1063-1318	1318-1633	1633-1784	1784-2282		
No. 1	Density	1.9	2.2	1.9	1.9	2.3		
**Dampier	Depth range			1537-2147	2147-2624	2624-4139+		
No. 1	Density			2.1	1.9	2.4		
**Legendre	Depth range		558-1001	1001-1297	1297-1884	1884-3463+		
No. 1	Density		2.2	1.8	2.0	2.4		
**Rankin	Depth range						2853+	
No. 1	Density						2.4	
**Pendock	Depth range							885+
No. 1	Density							2.6
Average densities		1.9	2.2	1.9	1.9	2.4	2.4	2.6

Depth metres: densities in tonnes per cubic metre
*Density determined from Neutron Log using Schlumberger log interpretation charts
**Density determined from Sonic Log using Schlumberger log interpretation charts

sampled. Some useful sampling of Mesozoic and Cainozoic sequences could be carried out from oceanographic vessels (Exon & Willcox, 1976), but only deep stratigraphic drilling will enable a truly reliable model of the stratigraphic framework to be established.

Precambrian

Gravity data indicate that the crust beneath the Exmouth Plateau is of typical continental thickness (Figs. 6, 7, & 8). The depth to magnetic basement is estimated to range from 7 to 10 km, and the lack of magnetic anomalies indicates that basement consists of continental rather than oceanic rocks.

This evidence suggests that basement may be regarded as an offshore extension of the Precambrian shield and probably consists of Proterozoic granite, gneiss, schist, and sediments.

Palaeozoic

Little is known about the Palaeozoic sequence, which is up to 5000 m thick. Comparison with nearby sequences (e.g. Veevers & Johnstone, 1974) suggests that much of the Palaeozoic is represented in the sequence. The sediments on the Exmouth Plateau may be more marine than elsewhere in the Carnarvon Basin, as the plateau would have been nearer to the

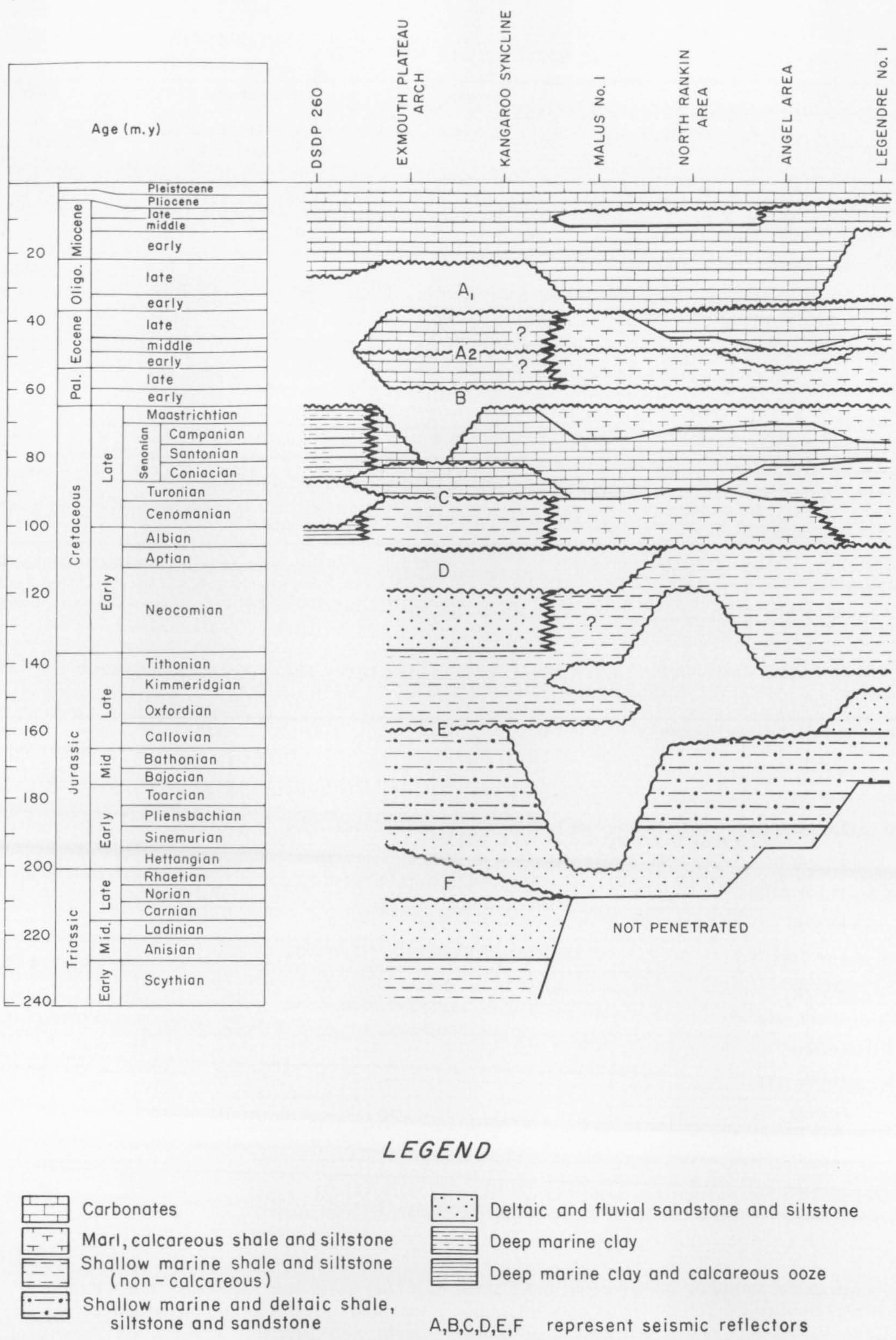


Fig. 12. Lithostratigraphic correlations from the Northwest Shelf to DSDP Site 260, showing inferred lithologies of the Exmouth Plateau sequence.

deep ocean if Tethys lay to the north of Western Australia as suggested by Veevers (1971).

In the Cambrian and Ordovician, shallow marine sediments were laid down in the Canning Basin, whereas non-marine sandstones were laid down in the Carnarvon and Perth Basins (Veevers, 1971). By extrapolating present basin boundaries offshore, it may be inferred that marine shales underlie the northern part of the Exmouth Plateau, and non-marine sandstones the southern part. In the Late Ordovician, Silurian, and Early Devonian, redbeds and evaporites were deposited intermittently in the Carnarvon and Canning Basins (Veevers, 1971), and deposition may have extended to the Exmouth Plateau. Fully marine shales and limestones of these ages could also exist on the plateau. During the Late Devonian and Carboniferous, marine conditions predominated in the northern Carnarvon and Canning Basins (Veevers, 1971), and sandstones, siltstones, shales, and carbonates were deposited in the basins and probably on the Exmouth Plateau. The Late Carboniferous was a period of little deposition in Western Australia and the same probably applies to the Exmouth Plateau.

The Permian sequence of the Carnarvon and Canning Basins, and probably of the Exmouth Plateau, consists of paralic and marine sandstone, siltstone, and shale. The Early Permian Lyons Group, consisting of marine siltstone and lithic sandstone, and containing numerous glacigene boulder beds, is about 2000 m thick in parts of the Carnarvon Basin (Thomas & Smith, 1974). The remainder of the Permian consists largely of marine sandstone, siltstone, and shale.

Triassic (Interval G-F)

Interval G-F under the Exmouth Plateau is probably largely equivalent to the Early Triassic Locker Shale and the Middle to Late Triassic Mungaroo Formation of the Carnarvon Basin. The Locker Shale is a fine-grained marine unit, whereas the Mungaroo Formation consists of interbedded sandstone and claystone laid down in paralic conditions (Thomas & Smith, 1974). The equivalent sequence on the Northwest Shelf is several thousand metres thick and in the central Exmouth Plateau the interval thickness varies from 1500 to 4000 m (Willcox & Exon, 1976a, fig. 11).

The composition of this well-bedded sequence appears to vary from area to area, as seismic interval velocities determined from sonobuoy records range from 2800 to 4000 m/s (see Table 4).

TABLE 6. EXMOUTH PLATEAU STRATIGRAPHY: PERMIAN TO RECENT SEQUENCES

Age (m.y.)				General range of unconformities	Nomenclature	Exmouth Plateau seismic horizons	CENTRAL EXMOUTH PLATEAU: Inferred Lithology	Inferred environment of deposition	Average thickness (m)
			Pleistocene		Miocene – Recent		Carbonate ooze	Bathyal marine	200 – 400
			Pliocene						
		Miocene	late						
			middle						
20			early			A1			
		Oligo.	late				Limestone, marl	Largely Shallow marine	200 – 600
			early						
40		Eocene	late		Eocene				
			middle			A2			
			early						
		Pal.	late			B			50 – 400
60			early		Late Cretaceous				
	Cretaceous	Late	Maastrichtian						
			Senonian: Campanian						
80			Senonian: Santonian						
			Senonian: Coniacian						
			Turonian			C			
100			Cenomanian		mid Cretaceous		Siltstone, shale		200 – 400
		Early	Albian						
			Aptian			D			
120			Neocomian		Early Cretaceous		Sandstone, siltstone, shale	Deltaic	500 – 2000
140	Jurassic	Late	Tithonian		Late Jurassic		Shale, siltstone, sandstone	Marine	
			Kimmeridgian						
			Oxfordian			E			
160			Callovian		Late Triassic to Middle Jurassic		Sandstone, shale	Fluvial, paralic	0 – 200
		Mid	Bathonian						
			Bajocian						
180		Early	Toarcian						
			Pliensbachian						
			Sinemurian						
200			Hettangian						
	Triassic	Late	Rhaetian						
			Norian						
			Carnian			F			
220		Mid.	Ladinian		Permian to Middle Triassic			Fluvial, deltaic	1500 – 3000
			Anisian						
		Early	Scythian				Shale, siltstone	Marine	
240	Permian	Late	Tatarian						
			Kazanian	?		G	Siltstone, sandstone	Paralic, shallow marine	?
		Early	Kungurian		Permian				
260			Artinskian						
280			Sakmarian						

WA/B8-121 A

Jurassic to Neocomian (Interval F-D)

Interval F-D is probably equivalent to the Jurassic tion of the northern Carnarvon Basin, and unconform-Dingo Claystone and the Neocomian Barrow Forma-ably overlies the block-faulted Triassic to Middle Jurassic sequence. On the Northwest Shelf, the Dingo Claystone is absent in places, and is thousands of metres thick in other places. It consists largely of marine shale and siltstone, with some sandstone intervals (Thomas & Smith, 1974). The Barrow Formation is about 1000 m thick near Barrow Island, thins northward and is absent on the Rankin Platform, but may be present farther northwest. It consists predominantly of deltaic sandstone with thin shale interbeds (Thomas & Smith, 1974). .

On the Exmouth Plateau (Pls. 11 & 18) Interval F-D is thickest in the south, where as much as 2000 m of prograded sediment (Barrow Formation equivalent) overlies about 500 m of parallel-bedded sediment (Dingo Claystone equivalent). The prograded sediments were apparently deposited in a delta which advanced northward over prodeltaic muds. The shape and orientation of prograded beds of the delta indicate that the detritus was derived from the south, where the present-day Cuvier Abyssal Plain is located. Beyond the top of the youngest delta-front the sequence thins rapidly (Fig. 21; Pl. 28, BMR 18/069) to an average of about 500 m; it presumably consists largely of shale laid down in a prodeltaic environment. Most of the deltaic sequence is probably composed of sandstone and siltstone, with a basal sandstone sequence derived from and ponded between upthrown rocks of the Triassic sequence. The upthrown blocks and ponded sediments are apparently covered by muds derived from the southern hinterland, deposited as the water deepened.

Apart from the thick deltaic sequence in the south, there are areas of locally thick Jurassic to Neocomian sediments in the northeast of the Exmouth Plateau (700-2000 m) and in the depression south of Wombat Plateau (1000-2000 m).

Mid-Cretaceous (Interval D-C)

Interval D-C is equivalent to the late Neocomian to Cenomanian Winning Group of the Carnarvon Basin, which reaches a maximum thickness of 1500 m northwest of Barrow Island (Pls. 12 & 19). The interval exceeds 500 m in thickness only in the southeast and northeast of the plateau. It is thin on the western limb of the Exmouth Plateau Arch, where it lies directly on upthrown blocks of Triassic sediments in places, and across Echidna Spur which appears to have been structurally high throughout much of the depositional history of the Exmouth Plateau. The sediments appear to be compacted and faulted in areas where the older sequences have considerable structural relief.

The mid-Cretaceous sequence is everywhere acoustically semi-transparent, which suggests that it is of fairly uniform composition. It probably consists of siltstone and shale as does the Winning Group on the Northwest Shelf and in DSDP hole 263 south of the plateau (Veevers & Johnstone, 1974). As on the Northwest Shelf, the sequence was probably laid down during a marine transgression which commenced in the Aptian. In most of the area it rests on Neocomian sediments with little apparent unconformity, but where it overlies tilted Triassic rocks in the west and north (Pls. 12 & 19) an unconformity is quite apparent.

The mid-Cretaceous sediments are thickest just north of the Neocomian delta, which suggests that sediment was provided from the south or southeast and accumulated near-shore, probably largely below normal wave base. Subsidence caused by the load of the Neocomian delta allowed continuous deposition to occur.

Across the southern margin of the Exmouth Subbasin, beyond the southern boundary of our maps, a complete sequence of Silurian to Jurassic formations subcrops under the Winning Group; near Pendock No. 1 well (113°20′10″E, 23°16′52″S) the Winning Group lies directly on steeply dipping Carboniferous sediments (Geary, 1970, fig. 8). Using BMR lines 17/052 and 17/054, Veevers & Johnstone (1974, figs. 11 & 12) correlated the Winning Group in Pendock No. 1 with a sequence of black pelites from DSDP hole 263 (Veevers, Heirtzler, et al., 1973) which was drilled in 5056 m of water on the Cuvier Abyssal Plain (Fig. 1). The correlation was inferred from a comparison of the distinctive lithology and shallow marine fauna of samples from the two wells, and from structural continuity between the two wells suggested by the seismic sections. Palaeobathymetric studies suggest that the lower half of the pelite sequence was deposited in shallow water, whereas the upper half shows indications of seafloor subsidence 'perhaps below the lysocline' (Veevers, Heirtzler, et al., 1974, p. 284). The age of the sediments is deduced to be either middle to late Albian (from nannoplankton) or Neocomian to early Aptian (from palynomorphs). DSDP 263 did not reach acoustic basement; sparker seismic sections suggest that the well bottom (746 m below seafloor) is about 200 m above the basement.

Unlike Veevers & Johnstone (1974, fig. 12), who indicated that basement below the Cuvier Abyssal Plain is of oceanic origin, we consider it possible that the Winning Group was deposited over continental basement which shortly afterwards underwent metamorphism and dyke injection during formation of an incipient rift zone (Willcox & Exon, 1976a). The basement was continuous with that beneath the Exmouth Plateau. In mid-Cretaceous times the basement and overlying Winning Group sediments subsided along faults in the region of the present Cuvier Abyssal Plain. By the time carbonate deposition commenced in the Santonian (Veevers & Johnstone, 1974, fig. 4) the Winning Group west of Pendock was at bathyal depth. During the Santonian to Maastrichtian the Toolonga Calcilutite and Miria Marl were laid down on the continental shelf and redeposited as turbidite sequences on the abyssal plain.

The change from Mesozoic terrigenous sediments to Late Cretaceous and Cainozoic carbonate sediments

Veevers & Johnstone (1974) showed that with few exceptions 'the Coniacian and part of the Turonian are a regional hiatus along the entire [western Australian] margin, and the underlying dominantly detrital sequence is overlain by Santonian and younger, dominantly carbonate rocks'.

Our work has suggested that essentially the same situation applies on the Exmouth Plateau. Furthermore, the rate of sedimentation declined from about 30-50 m per million years for Early Mesozoic terrigenous sediments to about 10-20 m per million years for Late Cretaceous and Cainozoic carbonate sediments.

The gradual decline in terrigenous sedimentation rates during the Mesozoic, while the environment of deposition remained stable, suggests that the supply of detritus to the plateau was diminishing. This could have been due in part to erosional lowering of source areas or climatic change, but is probably due to the effects of seafloor spreading. Seafloor spreading may have removed source areas to the west in the Late Jurassic, and certainly removed source areas to the south in mid-Cretaceous times (see 'Geological History'). The time of removal of the southerly source area closely precedes the disappearance of dominantly terrigenous sedimentation on the plateau and the Northwest Shelf. Without carbonate sedimentation, very little would have accumulated on the Exmouth Plateau in the Cainozoic.

Veevers & Johnstone (1974) offered three theories to account for the onset of widespread carbonate deposition in the Santonian:

(1) The 'juvenile Indian Ocean attained maturity with the initiation of thermohaline circulation of oceanic waters. The concomitant recycling of organic nutrients increased the production, and hence the accumulation, of shallow-water carbonates'.

(2) 'The Maestrichtian/Campanian interval was a time of rapid accumulation of mainly carbonate sediment in the present tropical Pacific . . . and the Paleocene and Santonian/Coniacian were times of slow sediment accumulation. If these were global events, they would have influenced the distribution of carbonate along the Western Australian margin'.

(3) 'Australia apparently started wandering northward at the beginning of the Late Cretaceous . . . and by the Santonian it may have reached a critically warmer latitude that favoured the deposition of carbonate sediments'.

Veevers & Johnstone noted that the third alternative was the weakest in that the onset of carbonate deposition off Western Australia was synchronous over a great variety of latitudes, rather than starting earliest in the north and latest in the south.

Late Cretaceous to Recent carbonate sequence (Interval C—Seabed)

The inerval overlying Horizon C was probably laid down after the Turonian to Coniacian hiatus (Veevers & Johnstone, 1974) which marks the change from terrigenous to carbonate deposition around the west Australian margin. The age range of the interval is Santonian to Recent in the Tryal Rocks area, but varies somewhat in other areas (Fig. 12). On the Exmouth Plateau the sequence is believed to consist almost entirely of carbonates, and the few surface samples taken are highly calcareous (Academy of Sciences of the USSR, 1975).

The Cainozoic section of the Northwest Shelf consists of monotonous carbonate sequences separated by four unconformities (Quilty, 1974; Powell, 1976), but little has been published about their mode of origin. G. C. Chaproniere (BMR, pers. comm.), who has studied the sequences of Ashmore Reef No. 1 well to the north, considers that there is good evidence of subaerial weathering of the rocks below regional unconformities of Oligocene and post-early Miocene age. Fossil evidence indicates that the Cainozoic carbonate sequences of the adjacent part of the Northwest Shelf consist of Paleocene and early Eocene deep-water sediments, and middle Eocene and younger outer shelf sediments (Quilty, 1974).

Three prominent unconformities have been picked on sections crossing the Exmouth Plateau Arch and Kangaroo Syncline, but others are probably obscured by the complex of channels, slumps, and synsedimentary faults within the section. Correlation with horizons under the Northwest Shelf suggests that their average ages are probably Paleocene (B), early Eocene (A_2), and Oligocene (A_1). They have not been mapped on all sections, but maps of the Paleocene and Oligocene unconformities have been prepared for the central area (Pls. 26 & 27). Across the southern part of the Arch (Pl. 28, BMR 17/068; Pl. 30, Esso 2), only these two unconformities are mappable: the lowermost, Horizon B, lies within a zone of contorted beds and in some places near the base of the zone, and follows the gross structure of the Arch; the uppermost, Horizon A1, separates the contorted beds from parallel beds above. In a few places an intermediate unconformity, A2, marks the base of channel-like features (Fig. 13), and A1 lies on top of the 'channel-fill'. Elsewhere, A1 and A2 seem to be coincident. Across the northern part of the Arch (Pl. 28, BMR 17/074) Horizons A1 and A2 diverge eastward beneath the Montebello Trough; A2 can be traced towards the shelf beneath progressively thicker overburden, whereas A1 fades out.

The history of the development of the carbonate sequence on the Exmouth Plateau is not clearly understood because of a lack of stratigraphic information. The oldest core obtained from the plateau is only of mid-Miocene age, and attempts to infer the depositional history by comparing the sequence with that of the Northwest Shelf must be regarded as highly speculative. Veevers et al. (1974) suggested that deep-water depositional environments prevailed over the plateau from the Late Cretaceous onwards, largely from evidence that sonobuoy refraction interval velocities are low, and that the Miocene core sample contains deep-water sediments. The velocities determined by Veevers et al. averaged 2200 m/s (range 2000-2500) which compare with an average of 2350 m/s (range 2020-2700) for BMR sonobuoys, and an average of 2735 m/s for velocity determinations in nearby Northwest Shelf wells (Exon et al., 1975). Although these results do suggest a larger ooze component (deeper water) on the plateau than on the shelf, there is other evidence which suggests that much of the plateau did not sink to its present depth until the Miocene or later.

The carbonate sequence is as much as 2400 m thick in the southeast, and thins toward the outer margins of the plateau (Pl. 13). The sequence is thickest along the edge of the Northwest Shelf where drillhole evidence shows that it consists largely of carbonate sands which have prograded away from the continent. In general the sequence thins gradually away from the shelf, although it is locally thin on structural highs (compare Pls. 13 and 17). The productivity of benthic organisms, which are most abundant in shelf waters, is considerably greater than that of nannoplankton and foraminifera, and we believe that the thinning of the sequence reflects deepening water and a decline in the benthic biota. The local thinning on highs was probably caused by current action.

Approximate sedimentation rates, calculated from the thicknesses and inferred age ranges of the various intervals, are presented in Table 7. These show that the overall sedimentation rate on the plateau is one-half

TABLE 7. EFFECTIVE SEDIMENTATION RATES: SANTONIAN TO CAINOZOIC
(in metres per million years)

Intervals considered (time breaks excluded)	*DSDP Hole No. 260*	*Exmouth Plateau Arch*	*Kangaroo Syncline*	*Barrow Deep No. 1*	*West Tryal Rocks No. 1*	*Rankin No. 1*	*Legendre No. 1*
Late Miocene to Recent		Low	Low	0	210	150	120
Early Miocene to Recent (A_1-seabed)		10	20	10	60	45	25
Late Paleocene to Late Eocene (B-A_1)		30	30	5	70	110	40
Santonian to Maastrichtian (C-B)		Low	20	7	10	10	20
Santonian to Recent (time breaks excluded)	?	15	18	10	40	45	40
Santonian to Recent (time breaks included)	2	10	12	3	30	30	15
Location	Deep Sea *	Exmouth Plateau		Barrow Sub-basin +	Rankin Platform +		Dampier Sub-basin +

*Calculated from Veevers, Heirtzler, et al. (1973)
+Calculated from Table 2, Figure 11, well completion reports

to one-third of that on the Northwest Shelf, whether or not hiatuses are taken into account. In the Late Cretaceous, sedimentation rates were low, and about the same on shelf and plateau (10-20 m per million years). In the Cainozoic, however, average sedimentation rates were much lower on the plateau (less than 30 m per million years) than on most of the shelf (45-210 m per million years). The low Late Cretaceous rates were probably related to low carbonate productivity. Productivity appears to have increased in the Cainozoic on both plateau and shelf, but the shallower water on the shelf was conducive to faster production of carbonates than on the plateau.

Late Cretaceous (Interval C-B)

Interval C-B is correlated with the Toolonga Calcilutite and Miria Marl of the Northwest Shelf, whose ages are Santonian to Maastrichtian. On the shelf the Toolonga Calcilutite unconformably overlies older sequences and consists of argillaceous calcilutite grading to siltstone (Thomas & Smith, 1974). On the Rankin Platform the Toolonga Calcilutite is overlain by the Miria Marl, which consists of marl or shaly calcilutite.

On the Exmouth Plateau the interval C-B is rather patchily distributed and is up to 800 m thick, nearest the shore (Pl. 20) The lower part of the unit contains a number of parallel seismic reflectors, whereas the upper part is acoustically semi-transparent in many places. This is consistent with the interpretation, from regional geological studies, that the lower part of the sequence consists of thickly interbedded calcilutite, marl, and shale, transitional between the earlier terrigenous sediments and the later carbonate sediments, and that the upper part consists of marl. The thicker sequences have the gross form of banks (Pl. 20; Pl. 28, BMR 17/068) and may have formed in an outer shelf environment, largely from benthic organisms. The thin patchy distribution of the Late Cretaceous sequence in other areas suggests that sediments accumulated only slowly, through the deposition of pelagic organisms on the outer shelf and slope, and were swept away in many places by submarine currents. Turbidites consisting of Late Cretaceous carbonates are present in DSDP Hole 212 in the West Australian Basin (Veevers & Johnstone, 1974), indicating that the deep ocean basins were the final repository for a substantial volume of shelf carbonates.

Eocene (Interval B-A_1)

Interval B-A_1 is broadly correlated with the Eocene section of the Northwest Shelf, but probably extends back into the late Paleocene in places. This sequence unconformably or disconformably overlies Middle and Late Cretaceous sediments and is characterised by contorted bedding in many places (Fig. 14). It contains numerous infilled channel-like features, delineated by unconformities A2 at the base of the channels and A1 above the channel fill (Fig. 13).

On the Northwest Shelf the equivalent sequences are the Cardabia Group and the Giralia Calcarenite. These two units consist largely of limestone, with some marl and shale, and are separated by an unconformity (Thomas & Smith, 1974).

On the Exmouth Plateau the Interval B-A_1 is thickest in the east, up to 1200 m, and thinnest around the margins (e.g. Pl. 21). Comparison with the Northwest Shelf sequences (Quilty, 1974) suggests that it consists largely of carbonates, with pelagic organisms probably making up most of the sediment in the west, but with benthic organisms becoming increasingly important eastward, and also with time. The early Eocene unconformity may have formed in shallow water during a fall of sea level.

Contortion and minor faulting of beds are particularly common where the gradient is appreciable (Fig. 14; Pl. 28, BMR 18/069), and appear to have been caused by large-scale low-displacement gravity sliding of semi-consolidated carbonates during the Miocene, when the Exmouth Plateau Arch took up its present form. The contortion of beds over the crest of the arch (Pl. 28, BMR 17/068) is probably caused by local dislocations related to tension on the crest.

Concertina slumping is very characteristic of the Eocene sequences at the plateau margins (Pl. 14); much of this probably occurred during the Miocene. It is especially well-developed on the lower continental slope of the southwest margin (Exon & Willcox, 1976; Fig. 15).

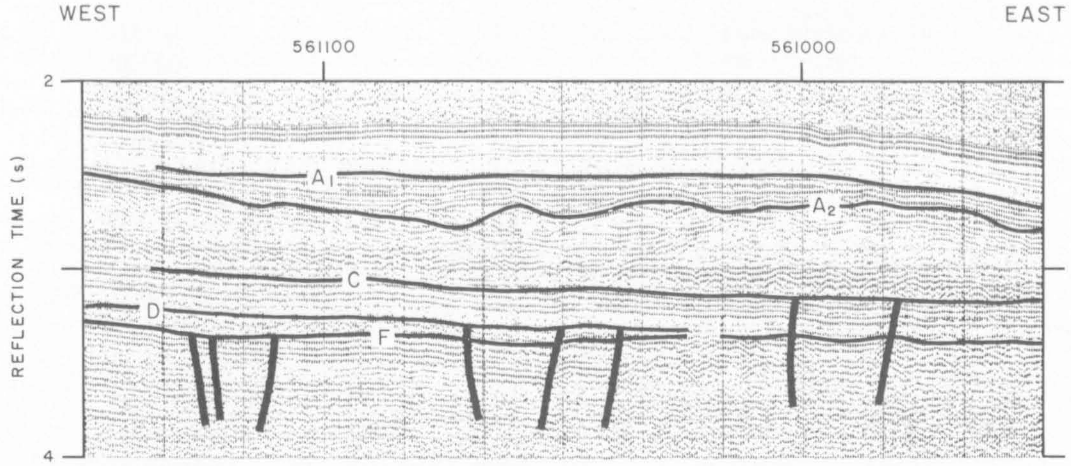


Fig. 13. Channel-like features within the Eocene section (Interval A_1-A_2): BMR 17/074.

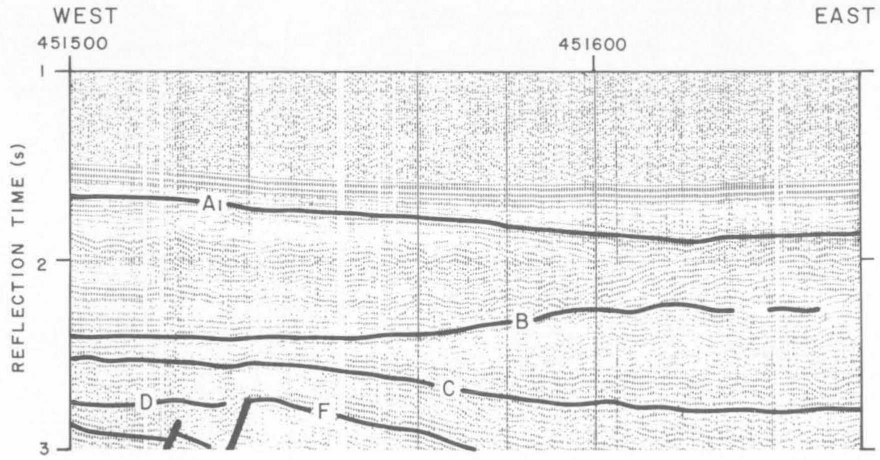


Fig. 14. Contorted bedding within the Eocene section (Interval A_1-B): BMR 17/068.

Differential sinking of the plateau in the Cainozoic may be the cause of normal faulting in the Eocene sequence on the eastern limb of the Kangaroo Syncline near the Rankin Platform (Pl. 28, BMR 17/074). Deposits are thicker in low areas than in high areas, suggesting that ocean currents swept grains from higher to lower areas during Eocene deposition. Such currents may have caused some of the broad channelling which gave rise to the unconformity, Horizon A_2. Channels are particularly common in the northern part of the Exmouth Plateau Arch.

Miocene to Recent (Interval A_1—Seabed)

Interval A_1—Seabed, by correlation with the Northwest Shelf sequence, is believed to consist of early Miocene to Recent sediments. These sediments disconformably overlie the Eocene sequence, and are acoustically semi-transparent on the Exmouth Plateau. The late Miocene-Pliocene unconformity of the Northwest Shelf is not apparent in the seismic profiles over the plateau. The sediments are commonly slumped near the plateau margins, and also along the foot of the upper continental slope (Pl. 14), into characteristic concertina folds (Fig. 16).

On the Northwest Shelf the Miocene-Recent sequence is as much as 1500 m thick and consists of prograded shallow marine carbonates, which include the Cape Range Group, Trealla Limestone, and Yardie Group (Thomas & Smith, 1974).

The sequence thins away from the shelf, and averages only 200 m on the plateau (Pl. 22). This change is probably related to a change from dominantly shelf to dominantly bathyal conditions of deposition. Three surface sediment samples from the area, taken in water depths of less than 5000 m, are composed of nanno-foraminiferal ooze (Academy of Sciences of the USSR, 1975). They contain 65-75% $CaCO_3$ and virtually no amorphous silica, and 55-70% pelitic fraction (less than 10 micrometres). Little is known about the older part of the sequence, although a core of late Middle Miocene sediment described by Veevers et al. (1974) as 'creamy lutite with discoasters and planktonic Foraminifera, which indicate deposition in the open sea away from the direct influence of shelf processes', was obtained from the half-graben south of the Wombat Plateau in a water depth of 2325 m.

The sediments on the plateau are probably dominantly foraminiferal oozes, although shallower water benthic sediments may be widespread in the older part of the section. Oozes are prone to erosion and transport by currents, and currents have created nick-points on the margins of the Montebello Trough (Falvey & Veevers, 1974) and transported sediment into nearby canyons.

Within the sequence is a northeast-elongated field of buried dune-like features, about 150 km long by 20 km wide, which underlies the upper continental slope (Pl. 14) some 50 km northwest of the Rankin Platform. The field lies beneath 400 to 800 m of water, and is elongated parallel to the bathymetric contours. The features are visible on profiles oriented eastward (BMR 17/070, 17/072) and northeastward (BMR 17/093, Fig. 18), but not on profiles oriented northwestward (AU-19, Fig. 17). This suggests that they form long ridges, and that their long axes trend roughly northwest. As their wavelengths appear to be shortest on easterly profiles, their true orientation is probably somewhat north of north-northwest. These features are very regular in shape; they range in wavelength from 700 to 1700 m, and their normal amplitude is about 100 m. The field averages 600 m thick, and the individual 'dunes' have migrated about half a wavelength eastward as the field built upward (Fig. 17). As many as 30 of these features are visible on one profile across the field. The regularity and consistent eastward migration suggests that these features are probably dunes; however, a migrating river distributory system is also a possibility.

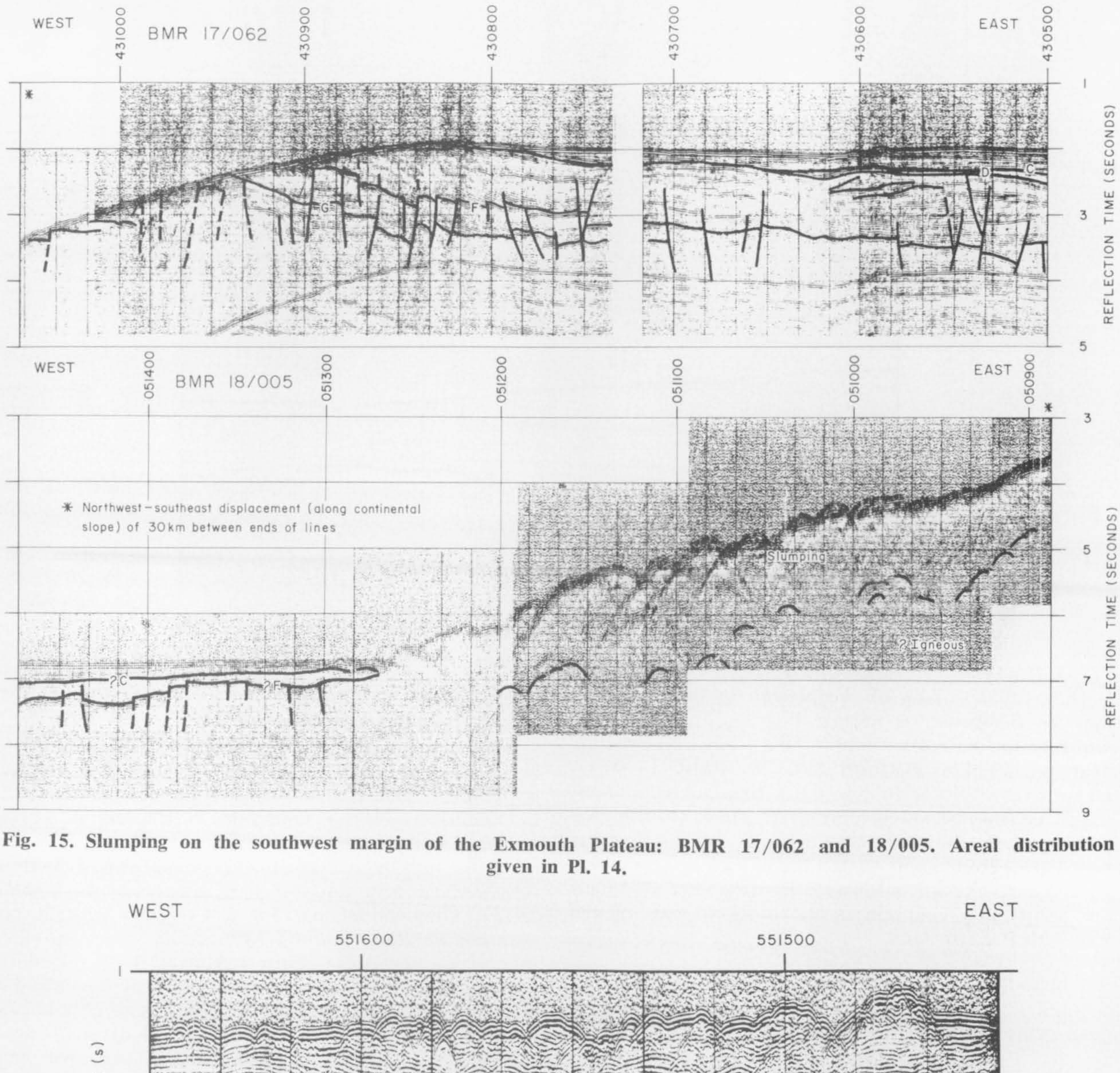


Fig. 15. Slumping on the southwest margin of the Exmouth Plateau: BMR 17/062 and 18/005. Areal distribution given in Pl. 14.

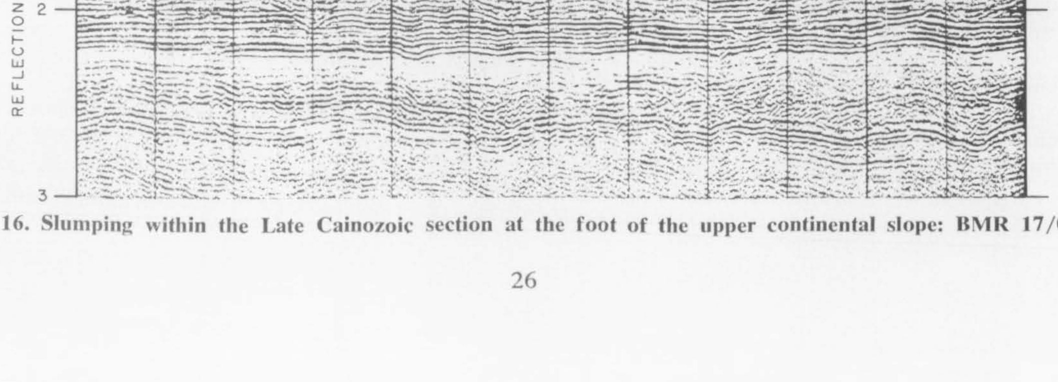


Fig. 16. Slumping within the Late Cainozoic section at the foot of the upper continental slope: BMR 17/074.

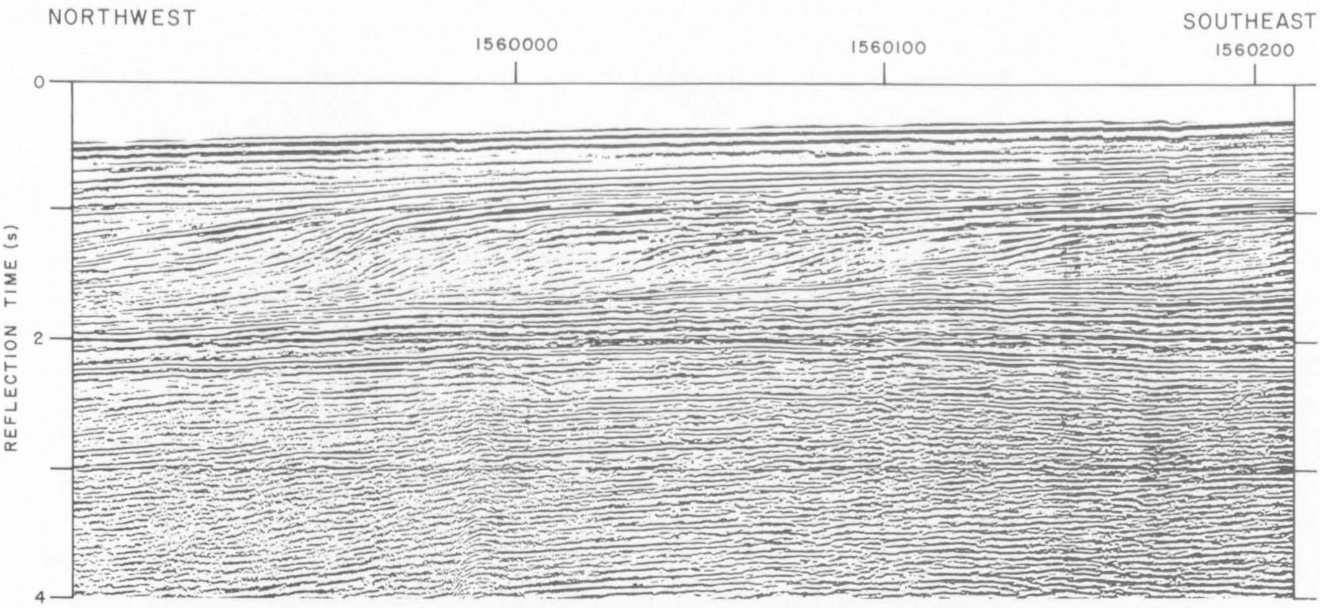


Fig. 17. Sigmoidal prograding wtihin the Miocene section below the outer part of the northwest continental shelf: Gulf AU-19.

The field is overlain by about 100 m of well-bedded sediments believed to be of Quaternary age, and underlain by about 200 m of well-bedded sediments above the Oligocene unconformity (Fig. 18). This suggests that its age could be anywhere in the range Miocene to Pleistocene.

If these features are dunes they are of the right wavelength and amplitude to fit into Wilson's (1972) category of 'draas', which form in many of the world's sandy deserts. They are, however, much higher than similar features formed as beach ridges in South Australia (Cook et al., 1977), on the continental shelf (Jones, 1971; Stride, 1974), or in the deep ocean (Bouma & Treadwell, 1975; Jacobi, Rabinowitz, & Embley, 1975). Draas range in wavelength from 300 to 5500 m, in height from 20 to 450 m, and they may be transverse or longitudinal to the wind direction (Wilson, 1972).

The area lay at about 30°S in the early Miocene (Sclater & Fisher, 1974), and we suggest that the dunes may have formed on the coastal plain, transverse to west-southwest-prevailing winds. The sand may have been derived from sediments of the prograded sequence of the continental shelf (Fig. 17), which was probably above sea level for a short time in the late Miocene or early Pliocene. The general shape of the field suggests that the shoreline extended northeastward, and the dunes must have formed initially just behind the beach.

The only other Cainozoic aeolianites in the Carnarvon Basin are at Shark Bay, 500 km to the south. There the 100 m thick quartzose Peron Sandstone of Plio-Pleistocene age rests unconformably on older rocks, and is conformably overlain by the 300 m thick calcareous Tamara Eolianite of Pleistocene age (Geological Survey of Western Australia, 1975, pp. 305-6). The younger part of the aeolianite sequence northwest of the Rankin Platform may be equivalent to these southern sequences. As all the wells on the Rankin Platform encountered calcareous Cainozoic sediments, there seems no doubt that the dunes consist of calcareous sand.

The importance of this sequence, be it an aeolianite sequence or a shallow water system of channels, is that it indicates subsidence of the order of 1000 m since the Miocene and of 500 m since the early Pleistocene on the eastern flank of the Kangaroo Syncline. Even more subsidence is indicated for the Emu and Echidna Spurs on the northern margin, where Jurassic sediments appear to be unconformably overlain by a thin section of Cainozoic sediments, which are probably Miocene to Recent (Pl. 28, BMR 17/079; Fig. 27). The Jurassic/Cainozoic unconformity is broad and flat, and we interpret this as indicating that it was formed by subaerial erosion, or by wave motion on the continental shelf, probably in the Oligocene. If this is so, the two spurs have sunk more than 2000 m since the Oligocene.

As the Horizon C unconformity (Pl. 13) is at about the same level beneath much of the central part of the plateau, as it is beneath the Emu Spur and the dune-like features (2000-2500 m below sea level), it appears likely that the whole plateau has subsided very considerably since the Oligocene. Thus it is possible that the Oligocene unconformity in the central part of the plateau was formed subaerially or on the continental shelf.

Oceanic areas

The stratigraphy of the oceanic areas around the Exmouth Plateau was compared with continental geology by Veevers & Johnstone (1974), and stratigraphic observations made at three nearby Deep Sea Drilling Project sites (location shown in Fig. 1) were summarised by Veevers, Heirtzler, et al. (1973). All three holes were drilled on abyssal plains in more than 5000 m of water. At DSDP Site 263 on the Cuvier Abyssal Plain, the oldest sequence penetrated consists of about 650 m of Early Cretaceous sediments, mainly claystones. These sediments have been dated as either middle to late Albian (from nannoplankton) or Neocomian to early Aptian (from palynomorphs). Seismic sparker sections indicate that up to 200 m of sedimentary section lies between the well bottom and

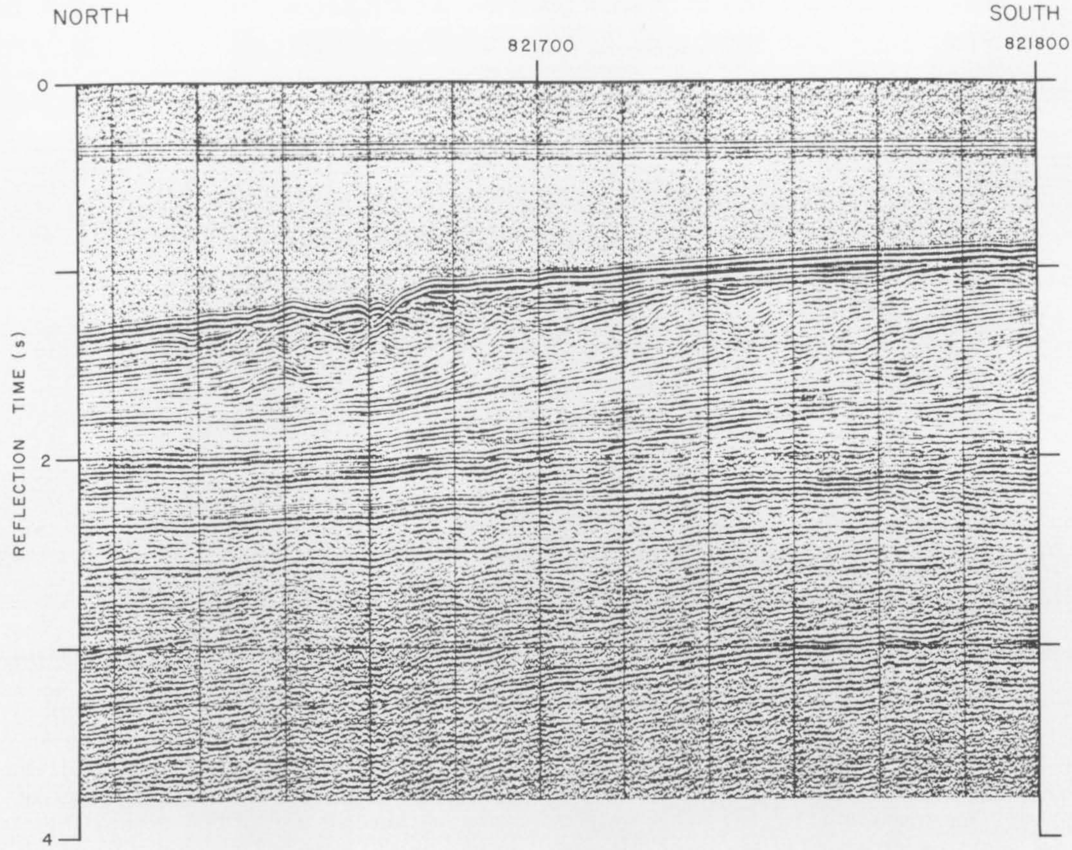


Fig. 18. Dune-like or filled-channel features of probable aeolian or shallow-water origin, within the Miocene section, below the upper continental slope: BMR 17/093. Areal distribution given in Pl. 14.

acoustic basement at the drill site. A study of the palaeo-bathymetry indicates that the lower half of the Early Cretaceous sediments was deposited in shallow water, whereas the upper half shows indications of seafloor subsidence 'perhaps below the lysocline' (Veevers, Heirtzler, et al., 1974, p. 284). The lower sediments must have sunk more than 5000 m since deposition. The sediments are equivalent to the 'mid-Cretaceous' sequence of the Exmouth Plateau, and the Winning Group of the Carnarvon Basin. They are overlain by about 100 m of turbidites consisting of Late Cainozoic carbonate ooze, which were probably derived from the continental margins. At DSDP Site 260 northwest of the Exmouth Plateau, about 150 m of Albian and Late Cretaceous deep-sea clay and carbonate ooze rests on oceanic basement. At DSDP Site 261, northeast of the Exmouth Plateau, about 400 m of Late Jurassic and Cretaceous deep-sea clay rests on oceanic basement. At these two sites, about 170 m of turbidites consisting of Late Cainozoic carbonate overlies the Cretaceous sequence.

At all three sites most of the Cainozoic sequence, including all the Early Cainozoic sequence, is missing. Davies et al. (1975) pointed out that the deep-sea hiatuses can be caused by erosion or non-deposition due to deep-sea currents, or dissolution of carbonate below the carbonate compensation depth. They attempted to relate the regional unconformities in the Indian Ocean carbonate sequence to climatic changes in Antarctica and to break-up of Gondwanaland, which changed the nature of Antarctica bottom water and its flow patterns.

The formation of the unconformities in the carbonate sequence

The older (B) and younger (A_1) unconformities are broad regional hiatuses, which could have formed in a variety of ways at various water depths, but the early Eocene (A_2) unconformity is irregular, and forms channel-like features in places. These channels may have formed by stream erosion in a subaerial environment, by tidal erosion on the continental shelf, or perhaps by current erosion of turbidite fans and fan aprons at bathyal depths. It therefore seems unlikely that this unconformity A_2 could have been formed in deeper water purely by current action, solution, or diagenesis, whereas unconformities B and A_1 could have.

The Deep Sea Drilling Project has shown that unconformities exist in the abyssal sediments of all the oceans, and Rona (1973) suggested that two hiatuses, one in the early Paleocene and one in the Oligocene, were synchronous in all the principal ocean basins. Davies et al. (1975) have shown that these hiatuses are widespread in the eastern Indian Ocean, and suggested that they were caused by vigorous deep-ocean currents, and by solution of carbonate below the carbonate compensation depth (3000-4000 m). They also suggested that both unconformities could be related to climatic changes leading to Antarctic glaciation, which might have increased the amount of Antarctic bottom water entering the Wharton Basin. However, deep-sea drilling near Antarctica (Hayes, Frakes, et al., 1973) has provided no evidence of Paleocene cooling. The results show that extensive glaciation began on the Antarctic continent only in the early Miocene and is therefore not associated with the formation of the Oligocene unconformity.

Kennett, Burns, et al. (1972) pointed out that the interpretation of magnetic anomaly patterns, which suggests that Australia began to separate from Antarctica in the early Eocene, has important implications in the study of palaeo-current patterns. They suggested that the circum-polar current flowed around Australia until the late Oligocene, but thereafter followed its present route between Australia and Antarctica. If this was the case, widespread erosion and non-deposition of deep-sea sediments could be expected until Miocene times. Such erosion of deep-sea sediments is taking place along the present route of the Antarctic current (Watkins & Kennett, 1973).

Both the continental shelf situation, with its shallow marine and subaerial erosion, and the deep-ocean situation may have prevailed on parts of the Exmouth Plateau from time to time and place to place during the Cainozoic. Slumping occurs within the Cainozoic sequence, but is restricted both areally and stratigraphically. It may have played an important role in the formation of the Horizon B unconformity, which lies toward the base of a contorted sequence in some areas.

Currents may have played a major part in producing unconformities on the plateau. Both the pre-Miocene circum-Antarctic current envisaged by Kennett, Burns, et al. (1972), and the present north-flowing West Australian Current could have caused widespread erosion in periods when oceanic circulation speeded up because of colder climatic conditions. Tidal currents of more than 150 cm/s occur on the Northwest Shelf 100 km offshore during spring tides, and maximum rates of about 50 cm/s are common (Jones, 1973). Thus, tidal currents may have caused erosion at depths of several hundred metres in the Exmouth Plateau region.

Internal waves commonly occur at the depth of the thermocline, which in this area probably lies between 100 and 200 m deep. Such waves can cause erosion, but too little is known about the oceanography of the Exmouth Plateau area to be able to predict their position, magnitude, or effect with any degree of certainty today, let alone in the past.

Solution of carbonate is normally restricted to the deep oceans, but Worsley (1971, 1974) suggested that the worldwide Maastrichtian-early Paleocene unconformity was caused by solution, even in shelf depths. He hypothesised that the great plankton bloom which produced widespread Maastrichtian chalk decreased the carbon dioxide content of the atmosphere, leading to worldwide cooling. The cooling increased the solubility of carbon dioxide and hence decreased the level of carbonate saturation in the ocean. At the same time, the amount of $CaCO_3$ entering the ocean declined steadily because the base level of erosion on the continents was being approached. Eventually even shallow waters became undersaturated in $CaCO_3$ (i.e. the carbonate compensation depth was zero) and widespread solution occurred, causing the worldwide hiatus. Conditions were then unfavourable to the plankton, whose numbers declined sharply; carbon dioxide was released to the atmosphere, and conditions returned to normal. This mechanism would be capable of producing a hiatus of perhaps 1 million years, but not the longer unconformities which we see.

There is reasonable evidence to suggest that the northern margin of the plateau, and the eastern side of the Kangaroo Syncline, lay near sea level in Oligocene times (see earlier). By analogy, much of the central part of the plateau may also have lain in shallow water during the Oligocene, and hence much of the unconformity A_1, as well as unconformity A_2, may have developed on the continental shelf or even subaerially.

In conclusion, it seems unlikely that all the plateau lay in deep water throughout the Late Cretaceous and Cainozoic as suggested by Veevers et al. (1974). Much of the sinking probably occurred in post-Oligocene times, and the unconformities A_2 and A_1 and possibly B, may have formed in shallow water in some places at least. In outer, deeper areas current activity was probably the major cause of unconformities.

STRUCTURE

Veevers & Johnstone (1974) broadly divided the region (Fig. 1) into the onshore continental areas, the continental margin, and the deep ocean.

Northwest trends predominate over much of Western Australia, occurring within the Yilgarn Block and the tightly folded Proterozoic sequence between the Yilgarn and Pilbara Blocks, and forming the margins of the Yilgarn, Pilbara, and Kimberley Blocks. These trends are Precambrian, and Palaeozoic and Mesozoic structures in the intracratonic Canning Basin presumably reflect the grain of underlying Precambrian rocks.

Structural lineaments on the continental margin are, on the other hand, generally parallel to the coastline, and northeast-trending structures predominate in the Exmouth Plateau, Rankin Platform, and Browse Basin. The marginal structures presumably formed during rifting preceding and during the Mesozoic break-up of Gondwanaland. D. J. Forman (BMR, pers. comm.) has pointed out that there are, in fact, three major fault directions on the Northwest Shelf: north, northeast, and east. He suggests that the Shelf may be represented by a strain ellipsoid with an axis of maximum extension trending northwest, and an axis of maximum shortening trending northeast. If this hypothesis is correct, the northeast-trending faults are normal faults, and the north-trending and east-trending faults are strike-slip faults.

Falvey (1972) discovered northeast-trending magnetic lineations (Fig. 1) in the Gascoyne and Argo Abyssal Plains. A physiographic study by Falvey & Veevers (1974) revealed that most abyssal hills are elongated northeast or north-northeast, and appear to be abruptly terminated by fracture zones normal to the hills. Falvey & Veevers interpreted the magnetic lineations, hills, and fracture zones as the results of seafloor spreading. A well-defined north-northeast structural grain is also apparent on the Cuvier Abyssal Plain (Willcox & Symonds, 1976).

On the Exmouth Plateau the spacing of seismic lines is too broad to define all fault-directions accurately, but the major direction appears to be northeast. However, north-trending strike-slip faulting is suggested by offsets in the magnetic trough across the northern part of the area (Pl. 6), and east-trending faulting is suggested by the shape of the half-graben south of Wombat Plateau, and by trends in gravity and magnetic maps in the vicinity of 18°S (Pls. 4, 5, & 6).

Structural cross-sections based on east-west and north-south BMR seismic profiles are presented in Plate 28. These show the extensive normal faults which affect the pre-Jurassic section, except in the northeast Kangaroo Syncline where they extend into the Late Cretaceous (Pl. 28, BMR 17/074; Figs. 22 & 23). They also show the Jurassic-Early Cretaceous delta (Pl. 28, BMR 18/069; Fig. 21) on the southern part of the plateau, and the regional warping of the area which probably took place in the Miocene. The relative sparseness of faults on BMR 18/069 is consistent with a northeast trend. Northwest-trending faults, probably associated with formation of the southwest plateau margin, appear on BMR 18/004 and 17/063 (Pl. 28). The subplateaux, spurs, and grabens along the northern margin are illustrated by BMR 17/079 and BMR 18/008 (Pl. 28). The grabens contain relatively thick Jurassic to mid-Cretaceous sediments (Interval F-C), indicating that they must have been structural lows during the time represented by this interval, or that sediment has been stripped from the adjacent blocks at a later time.

Representative seismic profiles of Shell, Esso, and Gulf lines (Pls. 29-32) show the regional structure of the Exmouth Plateau area. Gulf seismic profile AU12-13-13B-14 links the North Tryal Rocks, Rankin, Goodwyn, and North Rankin petroleum exploration wells (Fig. 2) and illustrates the somewhat discontinuous character of seismic horizons D, F, and G and the tentative nature of the well ties (Fig. 10).

The structures of horizons F, D, and C over the Exmouth Plateau area are shown in Plates 15, 16, and 17. Horizon F is considered to be the Late Triassic unconformity, D the Early Cretaceous horizon, and C the Late Cretaceous horizon. More detailed maps of the central area (Pls. 23-27) also show horizons B and A_1 which are considered to be of Paleocene and Oligocene ages.

Horizon E is a weak reflector which is a gentle angular unconformity overlying a thin sequence ponded between the tilted Triassic blocks. It cannot be distinguished from Horizon F in parts of the central Exmouth Plateau, and has not been mapped because of its uncertain presence in many areas. Seismic character ties suggest that Horizon E represents the Callovian break-up unconformity (see Figs. 9 & 10C).

The Late Triassic unconformity (Pl. 15), the main unconformity in the area, is cut by complex faulting, most of which is believed to have developed during rifting before seafloor spreading off the northern and possibly northwestern margins. Prominent high areas are the Exmouth Plateau Arch, the anticline along the southwest margin, fault-blocks on the northern margin, and the Rankin Platform. The same general features are reflected in maps of the Early and Late Cretaceous horizons (Pls. 16 & 17), but significant faulting of these horizons is confined to the plateau margins. Because of thick Late Mesozoic sedimentation in the southeast of the plateau, the Kangaroo Syncline is shallower, and its axis is farther west than it was during the Triassic.

Assuming that deposition took place near sea level throughout the Mesozoic, average rates of subsidence for various periods can be calculated. Subsidence was rapid in the Jurassic to Early Cretaceous and the Cainozoic (20-40 m/m.y.) and generally slow in the mid and Late Cretaceous (10-20 m/m.y.). Rapid subsidence on the plateau coincided with rapid sedimentation in the Mesozoic, but not in the Cainozoic, perhaps because a large proportion of the Cainozoic sequence was laid down slowly in deep water.

The Exmouth Plateau is formed over two major north-northeast-trending structures, the Exmouth Plateau Arch and the Kangaroo Syncline, which parallel the Rankin Platform and lie 220 and 100 km respectively northwest of it. The arch and syncline are apparent throughout the Triassic to Recent section (Pls. 15, 16, 17, 23-26) and probably started to form during the Late Triassic episode of normal faulting. Differential subsidence and Miocene warping have accentuated these features in the upper part of the section. Both features have bathymetric expression: the culmination of the Exmouth Plateau Arch is the shallowest part of the Exmouth Plateau, and the Kangaroo Syncline roughly coincides with the Montebello Trough for most of its length.

The entire Exmouth Plateau area is sliced by numerous normal faults which have a predominant north-northeast or northeast trend, except along the southwestern and northern margins. Most faults affect only the Late Triassic and older sequence, although Cretaceous faults probably occur along the southwest margin. In the northeastern Kangaroo Syncline, normal faults which moved as late as the Late Cretaceous appear to be present. The Jurassic to Recent section is generally characterised by gentle warping although synsedimentary faults and rejuvenated Late Triassic faults are apparent, particularly along the oceanward margins.

The deepest stratigraphic horizon which can commonly be picked in the region, Horizon G, is believed to lie near the top of the Permian. On the arch it is the uppermost of a pair of strong reflectors about 2000 m (1 s) apart (Pl. 30, Esso 2) and appears to be a mild angular unconformity. It is correlated with a single strong reflector on the northern part of the arch (Pl. 28, BMR 17/074) and in the Dampier Sub-basin, southeast of North Rankin No. 1 (e.g. Pl. 31, Gulf AU19-20), although only a few direct ties from line to line are possible.

About 20 km northeast of the plateau crest, the horizon lies about 6000 m below the plateau surface and is incorporated in a faulted monocline (Fig. 19). There are vague indications of sediment onlap above the monocline, suggesting that it may have existed in Triassic time. However, most of the 2000 m increase in thickness of the Triassic (i.e. Interval G-F) section across the monocline is due to Late Triassic faulting and subsequent erosion.

At the northern end of the arch, Permian sediments probably lie within the core of a faulted anticline which forms the foundation of Platypus Spur and has an east-west closure of 1000 m (Fig. 26). The crest of the anticline at Horizon G (top Permian) lies about 3000 m below sea level and underlies 1600 m of younger sediments. There is no evidence to suggest that this structure existed in the Permian, and it may have formed as late as the Miocene.

The Permian probably lies at a depth of 6000-7000 m in the Kangaroo Syncline and shallows eastward to about 5000 m in the Dampier Sub-basin.

A few faults extend upward only as far as Horizon G, indicating that there was a period of Late Permian faulting on the plateau. Faulting was probably accom-

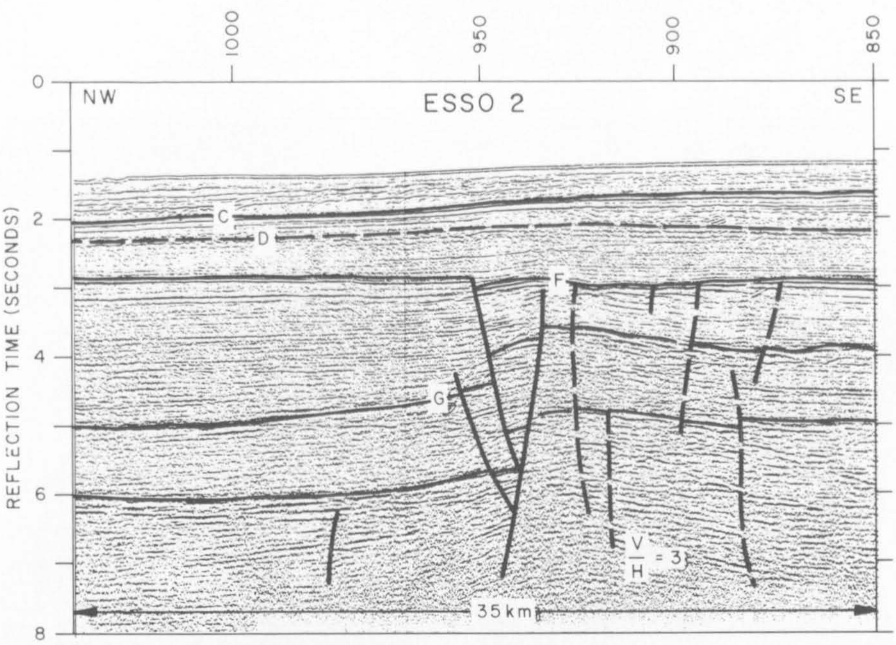


Fig. 19. Seismic profile showing faulted monocline within the Palaeozoic section beneath the Exmouth Plateau Arch: Esso 2.

panied by gentle folding in the Dampier Sub-basin and was possibly followed by erosion. Some faults show opposite throws at the F and G horizons and are probably Permian faults which were rejuvenated in the Triassic under different stress conditions.

Exmouth Plateau Arch

The Exmouth Plateau Arch becomes broader and simpler upward at successive stratigraphic levels (Pls. 23-26). The crestal area, which is complex at the Late Triassic level, shows three distinct structural highs in the Early Cretaceous; these coalesce to form a single structural high in the Late Cretaceous to Recent section.

The structure of the Late Triassic unconformity (Horizon F) is dominated by the numerous north-northeast-trending fault-blocks, with faults largely downthrown to the west and antithetic to the bedding (Fig. 20). On the southern part of the arch, regional changes in elevation of the unconformity are relatively small except in the west, where the faults have bigger throws and the blocks have greater landward rotations. In the north, the faults have a more easterly trend, probably following older structural trends. In the southwest the faults seem to have a northwest trend. Stratigraphic and structural evidence suggests that these faults are of much the same age as those elsewhere on the plateau, although evidence from DSDP 263 suggests that the southwestern margin started to form only in the Early Cretaceous, much later than the other margins. On the flanks of the arch, horst-blocks of Triassic sediments are directly overlain by sediments ranging in age from Early Jurassic to mid-Cretaceous.

The only area where erosion of the fault-blocks has obviously taken place is on the arch crest (Pl. 30, Esso 2) where the unconformity has little relief. However, there may be other areas on the arch, as on the Northwest Shelf, where extensive erosion has occurred but is not evident owing to the concordance of beds above and below the erosional surface. The steeply dipping blocks around the margins must have submerged rapidly, or have always been below wave-base, as the only sign of erosion is a slight rounding of the corners which probably led to locally derived sands being deposited between them.

On the southern part of the arch the Late Triassic unconformity culminates at about 2200 m below sea level, beneath 1200 m of younger sediment, and the structural high has a vertical closure of 900 m. Within the anticline on the northern prolongation of the arch the unconformity is about 2600 m deep.

A 2000 m thick prograded section, correlated with the deltaic Upper Jurassic-Neocomian Barrow Formation, was built up in a delta which advanced northward across the southern part of the Exmouth Plateau (Fig. 21). Its upper surface is marked by the Horizon D unconformity (Pls. 16 & 24) which culminates southwest of the plateau crest. North of the delta front the horizon dips abruptly northward and degenerates into a weak reflector, which is within an acoustically semi-transparent layer in many places. Although it cannot be followed with certainty, the horizon generally appears to overlie wedges of ponded sediments lying on the downthrown sides of faults, and a lens of poorly bedded sediments on the southern part of the arch (Pl. 28, BMR 17/068). Beyond the delta and near the margins of the plateau the underlying interval is thin and the horizon is draped over the more prominent fault-blocks; minor compaction faults and rejuvenated Late Triassic faults are apparent within the interval.

On the topset beds of the delta (shown on Plate 24), Horizon D is at its shallowest depth, 1700 m below sea-level, beneath an overburden of about 800 m. Between the delta front and the northern margin of the Plateau it forms two terraces (Pl. 28, BMR 18/069), one 2200 m below sea-level extending from the delta front to 19°S, and the other 2700 m below sea-level extending from 19°S to 18°S. Farther north, the horizon is apparent in the half-graben south of the Wombat Plateau. The entire delta now has a marked southerly tilt which is probably partly the result of the formation of the southwest plateau margin and partly of Miocene warping (Pl. 28, BMR 18/069).

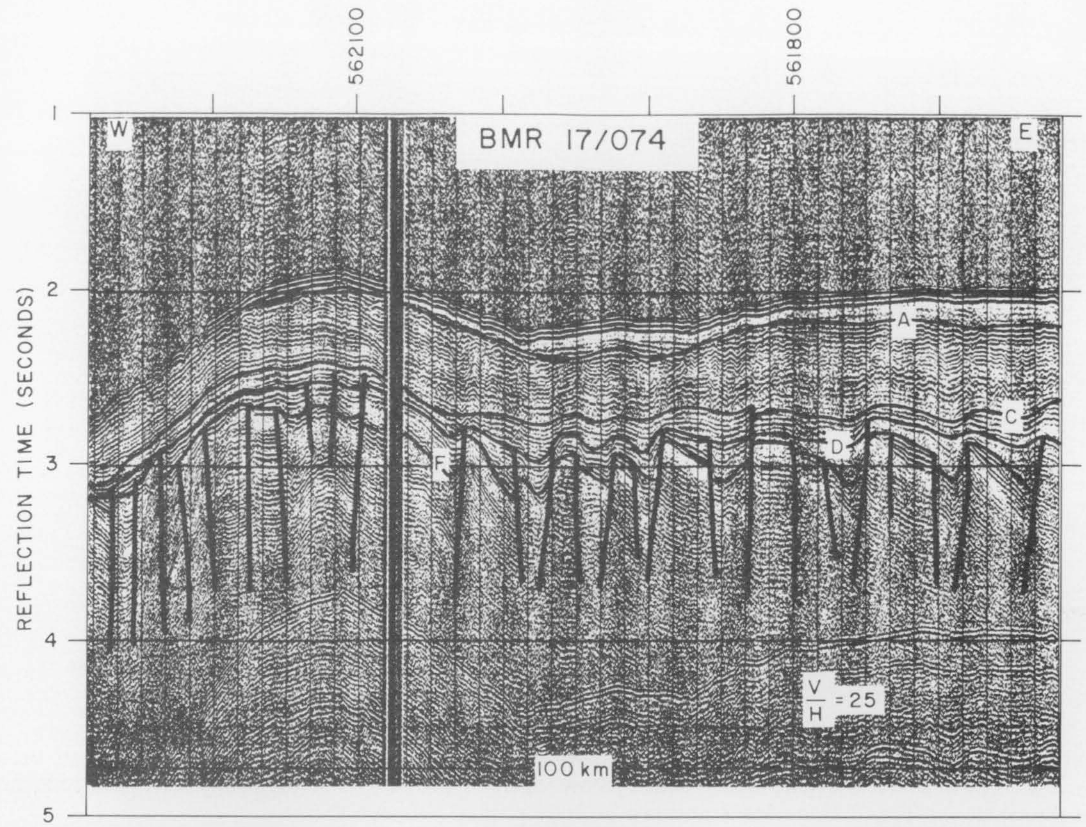


Fig. 20. Seismic profile showing block-faults on the northern part of the Exmouth Plateau Arch: BMR 17/074.

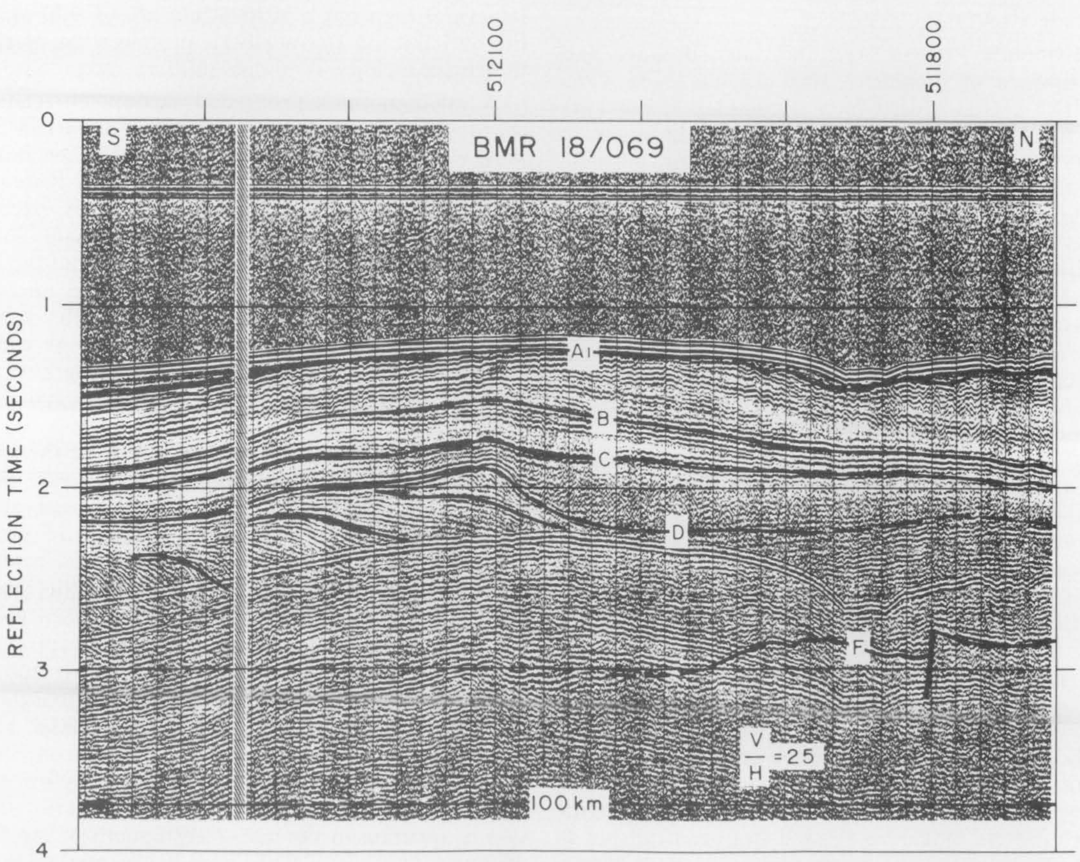


Fig. 21. Seismic profile showing prograding within the Early Cretaceous deltaic section beneath the southern part of the Exmouth Plateau: BMR 18/069.

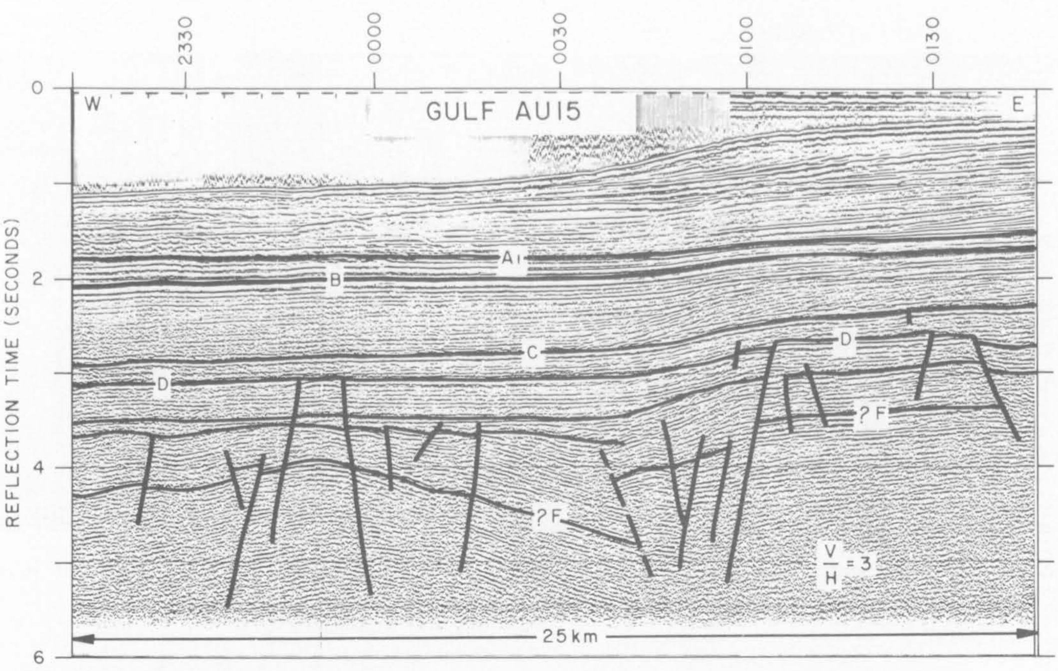


Fig. 22. Seismic profile showing block-faults in the southern part of the Kangaroo Syncline: Gulf AU-15.

The Late Cretaceous Horizon C (Pls. 17 & 25) is considered to overlie a blanket of shallow marine muds of mid-Cretaceous age. In general it is not significantly affected by the relief of the Early Cretaceous delta front or the Late Triassic fault-blocks, although on the northwest flank of the arch (at about 112-113°E, 19-20°S) a few fault-blocks extend to this level and slightly affect it. Draping and differential compaction have resulted in flexures over some underlying structures. The Exmouth Plateau Arch is a broad, simple structure at this level. Several culminations occur at 1600-1700 m depth near the plateau crest, and the overall closure is about 800 m.

The Paleocene unconformity (Pl. 26) culminates at about 1300 m beneath the plateau crest, with secondary culminations in the north of the arch and on its eastern flank. Some draping of the surface over older features is apparent on the western limb of the arch.

The Exmouth Plateau Arch is broadest at the Miocene level (Pl. 27), probably a result of redeposition of Eocene sediments down its flanks. The Miocene horizon has a closure of at least 600 m and culminates at 950 m below sea level beneath the plateau crest.

Kangaroo Syncline

The Late Triassic unconformity is the lowermost horizon which can be reliably identified in the Kangaroo Syncline. The syncline appears to have developed at about this time as a series of grabens (Pl. 30, Esso 2), although our interpretation of profiles across the northeastern part of the feature (Figs. 22 & 23) indicates the continuation of faulting through into the Late Cretaceous. The syncline appears to have been infilled with Jurassic to Recent sediments and its depocentre has migrated northeastward with time (Pls. 23-27). In places the eastern limb of the syncline lies partly under the Miocene prograded sediments forming the continental shelf.

Structure contours of the Late Triassic unconformity (Pl. 15) show a series of faulted depressions, with minima up to 6000 m below sea level, lying along the axis of the syncline. The depressions are separated by more elevated areas, some of which remained structural highs into the Late Cretaceous (Pl. 17). Amongst these is the Brigadier Trend, a major northeast-trending structural high separated from the Rankin Platform by the Victoria Syncline. In general, the throws of the faults are less than on the arch and the blocks appear to be larger; however, this impression may be caused by the poorer resolution of structural features on seismic profiles across the area.

The Early Cretaceous structure map (Pl. 16) shows the syncline as a much more continuous feature which resulted from infilling of the Middle Jurassic troughs. Several fault-bounded structural highs in the northeast remain prominent. The axis is at an average depth of about 3100 m, with a depression at 3800 m in the south.

At the Late Cretaceous level (Pl. 17) the syncline is a simple elongate structure with a more northerly trend in the north than at lower levels; it underlies the Montebello Trough. Its axial depth ranges from about 2800 to 3000 m. In the northeast the numerous structural highs occurring at lower levels are amalgamated to form a major high, 2400 m below sea-level, which incorporates the Brigadier Trend.

The Paleocene and basal Miocene structure maps indicate a broadening of the Exmouth Plateau Arch (Pls. 26 & 27) and a corresponding contraction of the syncline to the northeast. The seabed almost follows the Cainozoic horizons except for the shelf-break, which moved oceanward as carbonate sediments prograded northeastward, causing extension of the continental shelf. A southerly saddle between the Exmouth Plateau Arch and the upper continental slope separates the Montebello Trough from a system of canyons which discharge southwestward.

Southwest margin

The southwest margin is almost straight and is formed by numerous northwest-trending faults which have average individual throws of about 100 m, result-

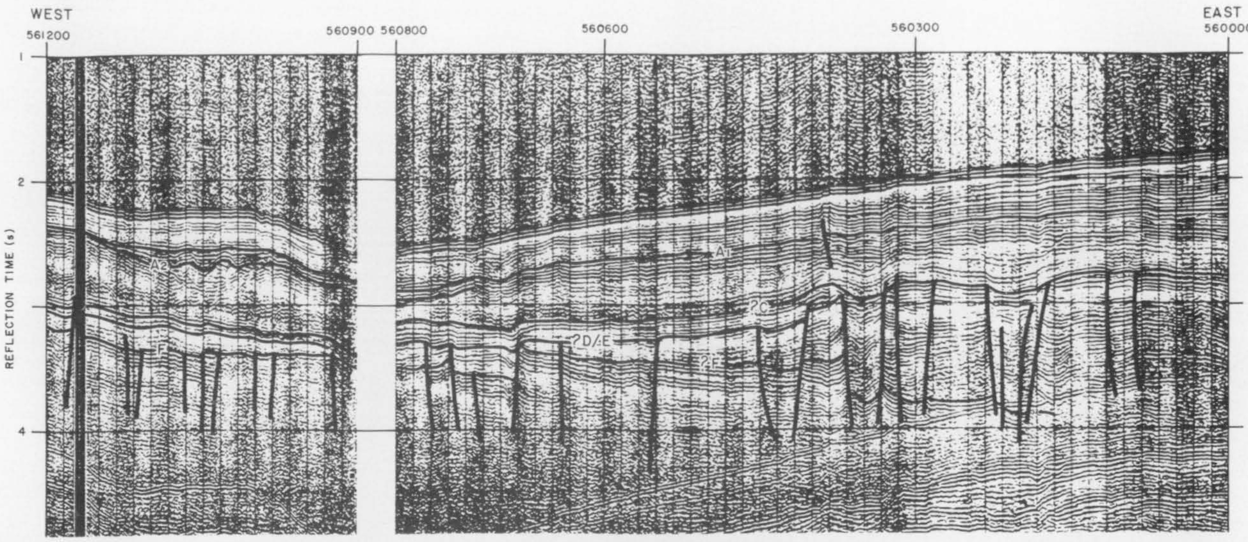


Fig. 23. Seismic profile showing block-faults extending up to the Oligocene horizon in the northeast part of the Kangaroo Syncline: BMR 17/074.

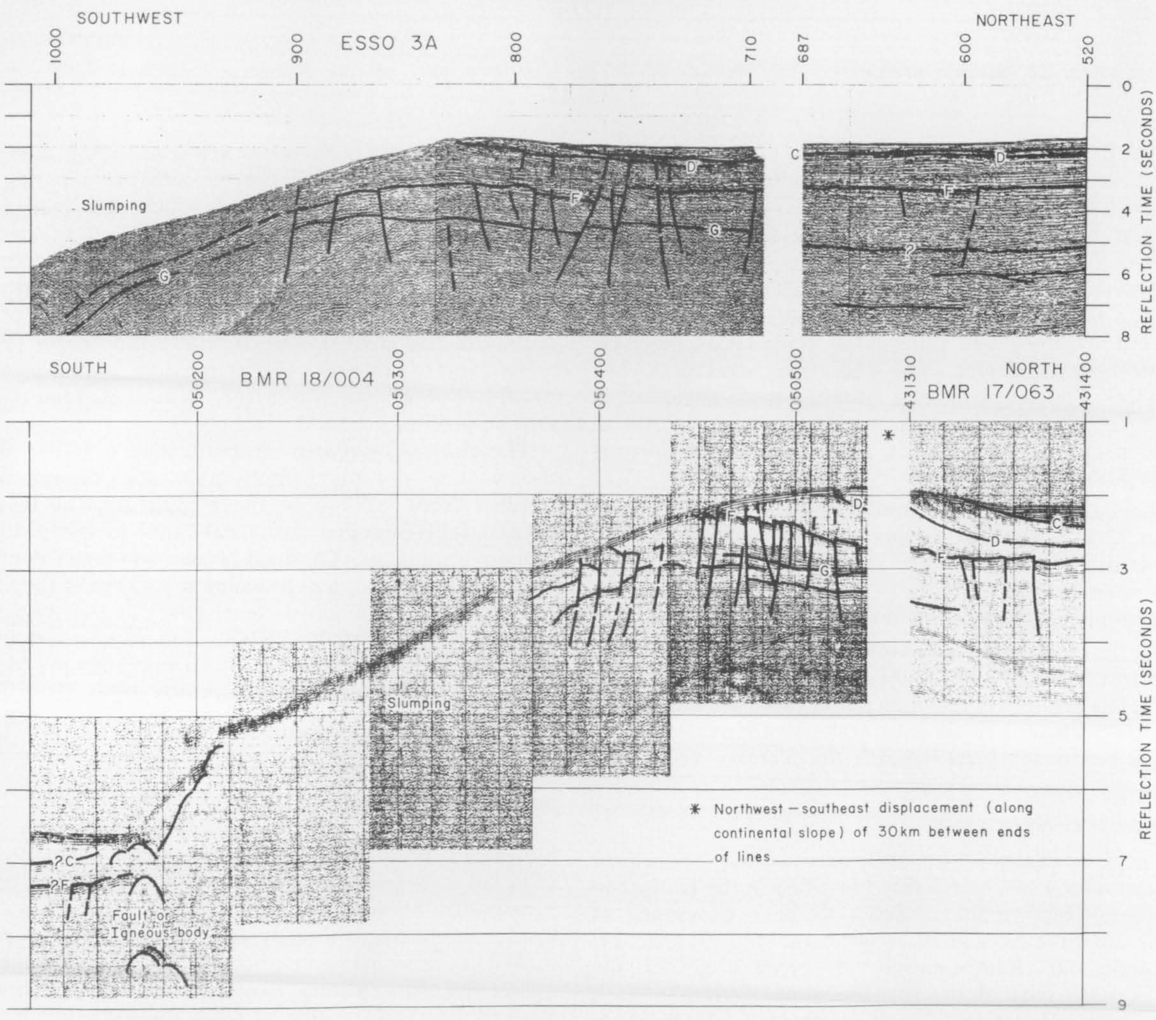


Fig. 24. Seismic profiles across the southwest margin: Esso 3A, BMR 17/063 and 18/004.

ing in a total downthrow of 2000 to 3000 m to the southwest. A large northwest-trending anticline (Fig. 24, Pl. 31) lies just beyond the edge of the plateau proper, beneath the lower continental slope. The anticline is dissected by numerous faults parallel to its axis, and horizons F and G are downthrown to the northeast and southwest along its northeast and southwest limbs respectively. The anticline has two major culminations on Horizon F, at depths below sea level of 1400 and 1600 m, with respective closures of 700 and 600 m (Exon & Willcox 1976). In the southeast there is a syncline eastward of and parallel to the anticline, with its axis about 4400 m below sea level. The lower continental slope truncates the southwest part of the anticline, so that the older rocks apparently crop out on the seabed (Pl. 14). A veneer of Tertiary to Recent sediments may overlie the older rocks but is not visible on the seismic profiles. In places such sediments may have been stripped by gravity sliding and current action on the slope. The thickness of any sedimentary veneer cannot be determined from the existing profiles as the pulse generated by the seismic source is too long to allow the structure of the uppermost 50 m of the sedimentary section to be resolved.

An interpreted zone of sedimentary slumping on the lower continental slope, in water depths of about 3000 to 4800 m, obscures the underlying deep structure. On the seismic profiles the slumped sequence is characterised by numerous diffractions and generally by absence of bedding (Fig. 24; Pl. 14), and might have been interpreted as igneous rocks if it were not for the relatively low amplitude and long wavelength of the magnetic anomalies with which it is associated. The magnetic anomalies suggest that the total sedimentary thickness is between 500 and 1500 m. The age of the slumped sequence is unknown, but Jurassic, Cretaceous, and Cainozoic sediments may well be involved.

Igneous bodies, which penetrate the younger sedimentary section, are observed near the foot of the lower continental rise on line BMR 17/060. The deepest body is associated with a major magnetic high which extends northwestwards along the edge of the Cuvier Abyssal Plain, and its presence justifies the assumption of a high-density body in the gravity model for BMR 18/004 and 17/063 (Fig. 7).

Seismic profiles extending onto the edge of the Cuvier Abyssal Plain show that structures in the sedimentary section are similar to those on the plateau, with undisturbed sediments overlying normally faulted sediments. More than 1700 m of pre-Upper Jurassic sediments may be present, below 1000 m of younger material (Fig. 24).

On the Exmouth Plateau as a whole, the main episode of faulting, which gave rise to the north-northeast-trending faults, postdates Horizon F, but generally antedates most of the sediment within the interval F-D, indicating that it is Late Triassic (or possibly earliest Jurassic). On the southwest margin, the northwest-trending faults appear to truncate the north-northeast-trending faults and may therefore be younger, although no obvious age difference can be inferred directly from the seismic data available to us. The seismic evidence, that the two sets of faults are of about the same age, apparently conflicts with the results from DSDP Sites 260, 261, and 263 which Veevers, Heirtzler et al. (1974) interpreted as indicating that the northern and possibly northwest margins of the Exmouth Plateau formed in the Late Jurassic (Callovian), and that the southwest margin formed in the Early Cretaceous. If this is correct it is probable that at least some of the faults which affect outcrops of pre-Cretaceous strata on the lower continental slope along the southwest margin are of Cretaceous age, and are directly related to formation of that margin. It is also possible that major Cretaceous faults are obscured by the zone of slumped sediment and that the igneous bodies under the continental rise are associated with faults of this age. A further alternative is that the interpretation of the data from Site 260 is incorrect, and that the western margin started to form in the Early Cretaceous. In this case the latest movements on the normal faults aligned to the northeast would coincide with the movements parallel to the southwest margin, and the seismic picture would give no clear evidence of the relative age of the two fault systems.

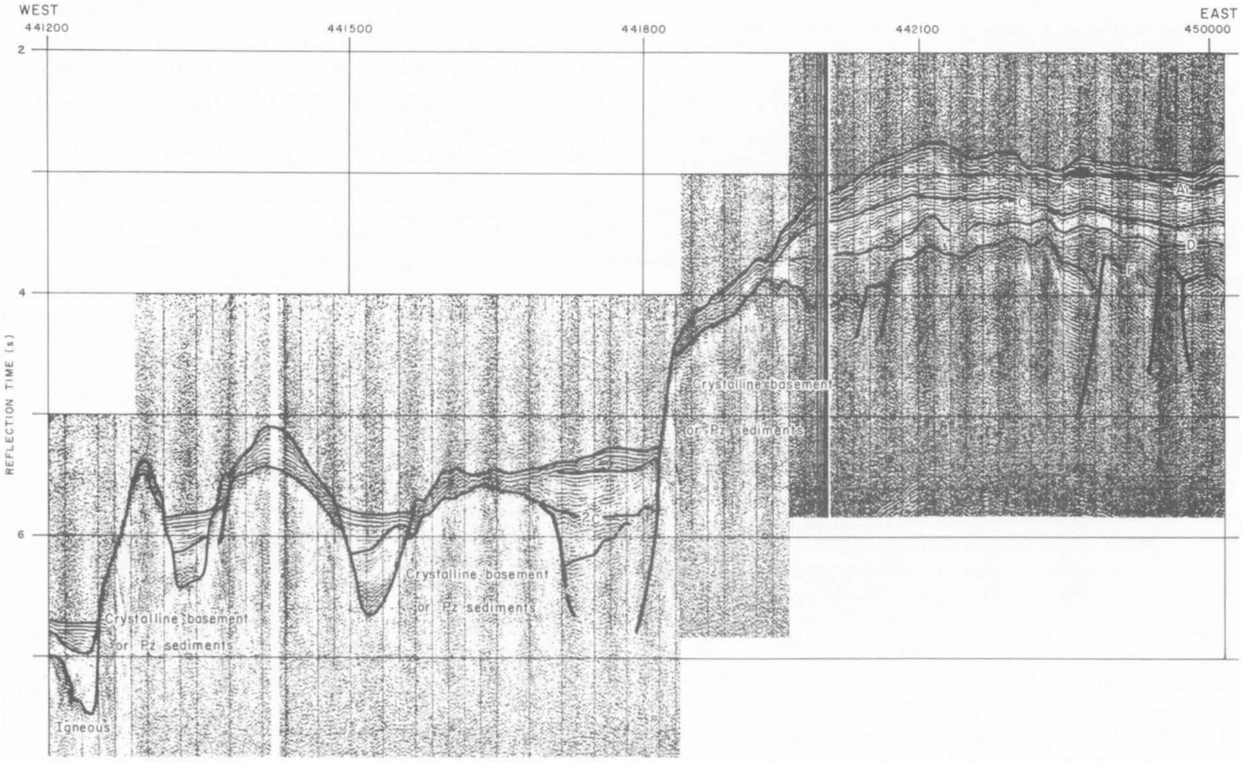


Fig. 25. Seismic profile across the northwest margin: BMR 17/068.

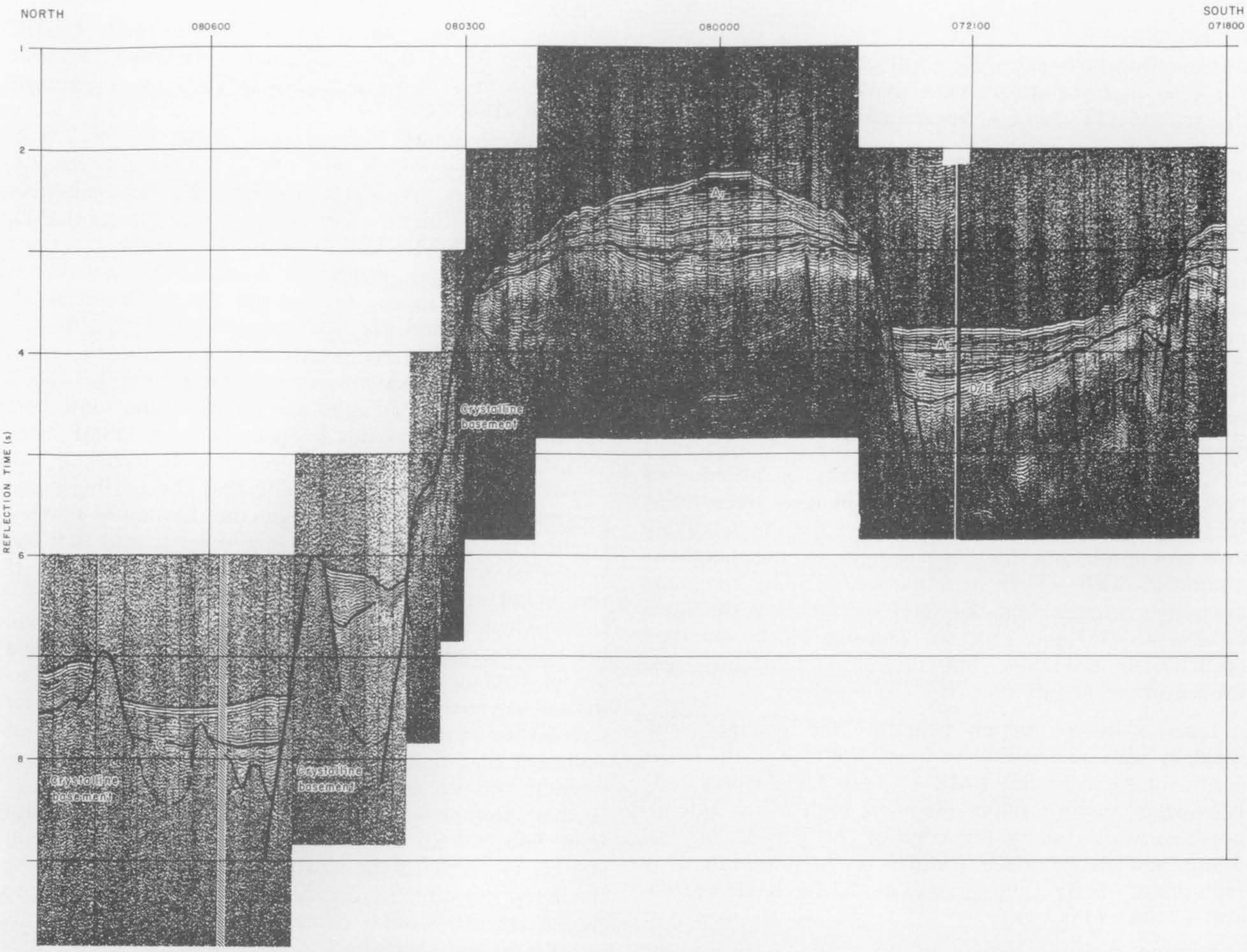


Fig. 26. Seismic profile across the northern margin: BMR 18/008.

NORTHWEST MARGIN

The northwest margin of the Exmouth Plateau generally consists of one or more terraces, which were probably formed by the oceanward collapse of major blocks of pre-Jurassic sediments (Fig. 25). The collapse relative to the plateau crest has taken place since the time of formation of the block-faults (rift-valley stage of continental break-up). It was probably fairly rapid shortly after continental separation and the generation of oceanic crust during the Callovian, and is believed to have preceded the overall subsidence of the plateau region.

Gradual shallowing of crystalline basement towards the margin is observed on most seismic profiles, and is the cause of the general decrease in the wavelengths of magnetic anomalies. The pre-breakup sedimentary sequence wedges out against basement along the margin, where water depths are 2000 to 2500 m. Between faults the basement surface and bedding planes generally dip southeastward, although in some places the beds appear to dip oceanwards forming the western limb of a marginal anticline. A large anticline near the margin on BMR 17/074 (Fig. 20) is considered to be a pre-breakup structure which has formed the foundation of Platypus Spur. Faults are generally normal and down to the west, antithetic to the predominant dip of the beds.

The marginal terraces are probably underlain by Cretaceous and Cainozoic pelagic sediments, and basement blocks consisting of Proterozoic metamorphic rocks and pre-breakup sediments, which are intruded and extensively altered by oceanic basalts in places. Gravity modelling suggests that blocks of relatively dense material, probably largely basalt, are separated by blocks of lower density, probably composed of pre-breakup sediments (Fig. 6). The thickness of crust beneath the terraces ranges from about 15 to 17 km, suggesting that marginal upwarping and erosion may have preceded break-up.

NORTHERN MARGIN

Adjacent to the northern margin of the Exmouth Plateau (northward of latitude 18°S) is a complex of horsts and grabens produced by vertical movements along northeast and east-striking faults. Displacements on individual faults of either trend exceed 1000 m in places. Closely-spaced faults have caused a total displacement of the order of 2500 m down the lower continental slope. Gravity modelling indicates that the crust thins abruptly under the lower continental slope (Fig. 8), which is consistent with the interpretation of Veevers & Heirtzler (1974) that it developed as a transform fault.

Several small subplateaux in water depths of 1600 to 2300 m (Pl. 28, BMR 17/079) coincide with the horst blocks and were once part of the Exmouth Plateau. The largest, the Wombat Plateau (Fig. 26), covers an area of about 3500 km^2. Identification of seismic horizons in the northern area is impeded by lack

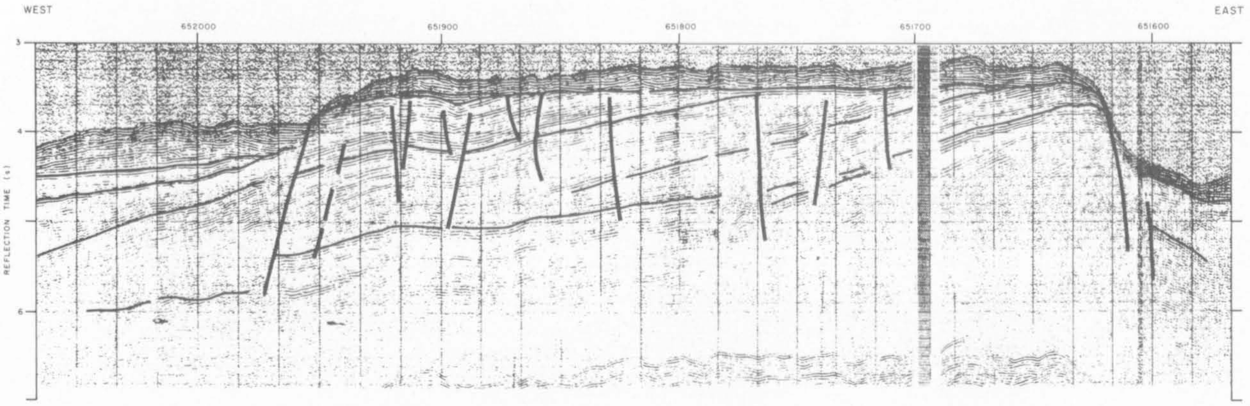


Fig. 27. Seismic profile across the Emu Spur showing probable Oligocene unconformity, presumed to be of shallow-water origin: BMR 17/079.

of continuity between the subplateaux across the grabens which separate them, and between the subplateaux and the Exmouth Plateau proper. However, Horizons F and D can be traced with moderate confidence onto the Echidna and Emu Spurs; horizons in other parts of the northern area have all been identified by character correlation with horizons on the plateau. The pattern of faults shown on the structural map of the Late Triassic unconformity and the Jurassic-Early Cretaceous thickness map (Pls. 15 & 16) is interpretative and somewhat schematic, as there are too few lines in the area for the orientation of faults to be accurately determined.

In general, the northern margin of the plateau is downwarped along an extensively faulted hinge zone, which is made up of numerous blocks down-faulted northward or northwestward into a series of half-grabens (Pls. 28, 29, & 31). The subplateaux which separate the half-grabens from the Argo Abyssal Plain are probably largely composed of west-dipping Triassic and Palaeozoic strata (pre-Horizon F), beneath nearly horizontal Mesozoic and Cainozoic strata, and have been buttressed against collapse by igneous intrusions along their northern edges.

The deepest reflector identified on the seismic profiles, Horizon G, is correlated with the Late Permian. It is an extensively faulted horizon which on Echidna Spur lies 4000 m below sea level beneath an overburden of about 1800 m, and in the adjacent graben lies 6600 m below sea level beneath an overburden of about 3600 m. On the eastern side of Wombat Plateau, pre-Horizon G beds are folded into a north-trending anticline and crop out on the intensely faulted eastern escarpment (Pl. 28, BMR 17/079). Other pre-Horizon G beds may crop out on the lower continental slope along the northern edge of Wombat Plateau, although these is no indication of this on profile BMR 18/008 which crosses the area.

As on the plateau, the Late Triassic unconformity (Horizon F) on the northern margin and in the half-grabens is a surface broken by normal faults. However, few faults are observable within the subplateaux. In the half-graben south of the Wombat Plateau the Jurassic-Early Cretaceous interval (F-D) is 1200 m thicker than on Wombat Plateau and must have been deposited in a structural low. The mid-Cretaceous interval (D-C) is about equally thick under the subplateau and half-graben, but is absent and was presumably eroded from the northern edge of the Exmouth Plateau.

On Emu and Echidna Spurs pre-Jurassic strata appear to lie beneath a wavecut platform upon which post-Miocene carbonates have been deposited (Fig. 27). This area may have been structurally high throughout the Cretaceous and Early Cainozoic, or may have been uplifted and stripped of sediment during final formation of the Exmouth Plateau Arch in the early Miocene. At about this time Oligocene sediments were eroded from the Rowley Shoals area to the east (Challinor, 1970). A well-defined magnetic anomaly trough corresponds with the half-graben south of the Wombat Plateau and extends eastwards along the northern margin of the Exmouth Plateau. The trough is due in part to the negative anomalies of large dipolar fields associated with elevated basement blocks to the north, but its linearity suggests that there may also be a contribution from a deepseated structural trough. This trough could be a westerly extension of the Fitzroy Trough in the northern Canning Basin. North-south offsets of the magnetic anomaly trough on meridans 115°30′, 116°30′, and 117°00′E are reminiscent of transcurrent faults.

GEOLOGICAL HISTORY

Much of the geological history presented here is inferred from information gained from outcrop geology and petroleum exploration drilling in the adjacent parts of the Carnarvon and Canning Basins (Thomas & Smith, 1974; Powell, 1976). The geological evolution of the Exmouth Plateau is summarised by schematic cross-sections in Figure 28, which are based on BMR seismic profiles 17/068, 18/069 and 18/008 (see Pl. 1), and by palaeogeographic sketches in Figure 29. Gravity and magnetic data suggest that under much of the plateau, basement lies at about 10 km, and the base of the crust at about 20 km, below sea level.

Precambrian and Palaeozoic

By analogy with the Pilbara Block to the southeast, it is inferred that basement below the plateau is probably composed of Proterozoic granite, gneiss, schist, and sedimentary rocks. Throughout the Palaeozoic the plateau area was an embayment marginal to the Tethyan Ocean on the northern shores of Gondwanaland,

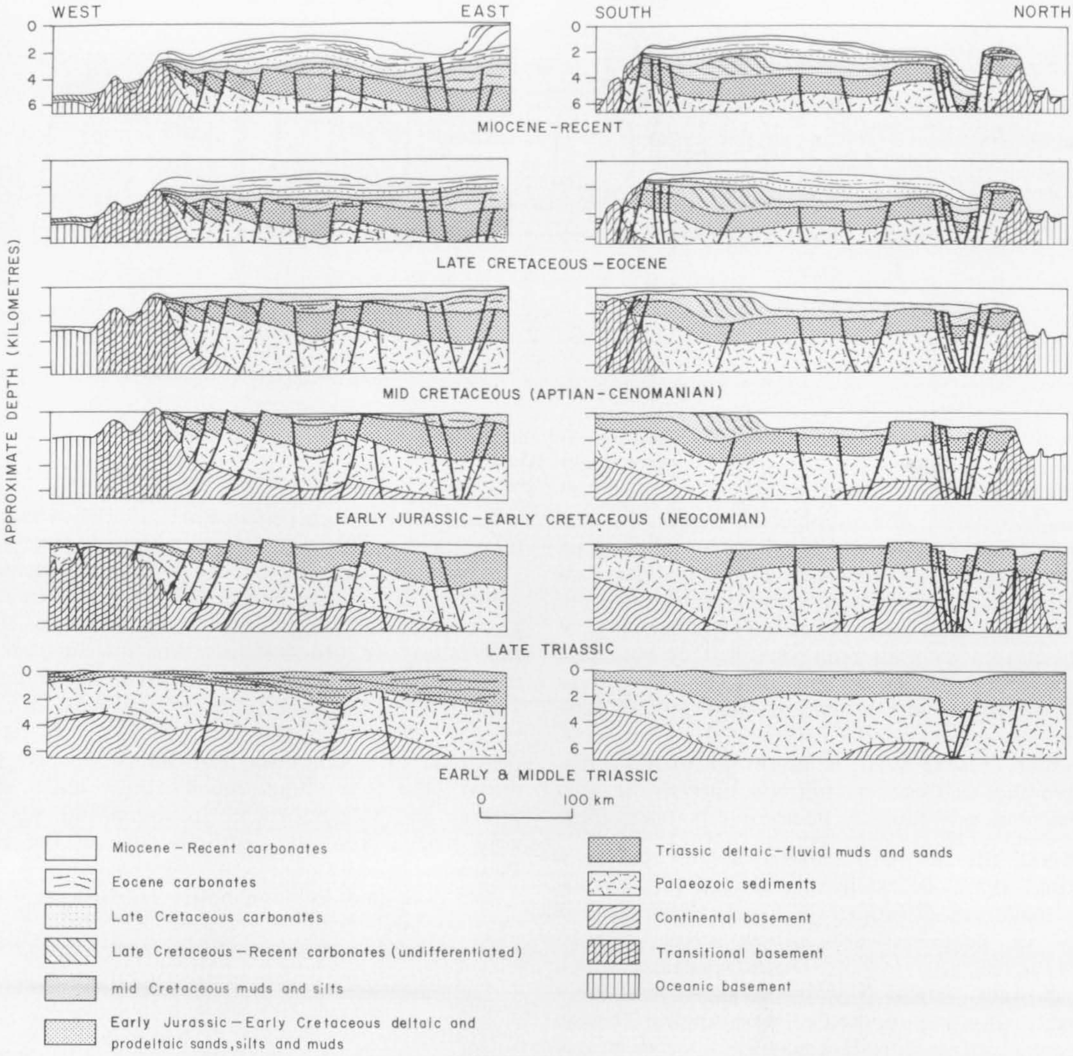


Fig. 28. Schematic cross-sections showing the structural evolution of the Exmouth Plateau (assuming that continental crust lay north and northwest of the plateau until the Early Jurassic, and southwest of the plateau until the Early Cretaceous; see for example Veevers & Cotterill, 1976).

and up to 5000 m of Palaeozoic rocks appears to be preserved. During the Cambrian and Ordovician, shelf sediments were probably deposited in the northern Exmouth Plateau area, while non-marine sediments were laid down farther south (Veevers, 1971). Silurian uplift, weathering, and erosion of the Precambrian hinterland provided abundant sand, which was deposited as redbeds, associated with marginal marine evaporites, in the Carnarvon Basin. Non-deposition and erosion in the Early Devonian preceded a marine transgression which persisted into the Early Carboniferous and gave rise to a widespread sequence of shallow marine sandstones and carbonates (Thomas & Smith, 1974). The transgression appears to reflect the formation of a broad elongate trough off the present west Australian coast, whose existence was first recognised by Teichert (1939). The offshore part of the Exmouth Plateau area was probably covered by sediments in the Devonian and Early Carboniferous. These sediments were probably largely shales and carbonates, finer-grained sediments than those laid down elsewhere in the Carnarvon Basin at that time.

The eastern margin of the Carnarvon Basin was uplifted in the Late Carboniferous, and glaciers capped the higher areas in the Early Permian. During this period fluvioglacial and shallow marine sands probably blanketed the Exmouth Plateau area. A phase of gentle folding, possible faulting, and erosion on the plateau appears to have coincided with the Late Permian block-faulting in the inner Browse Basin, mentioned by Powell (1976).

Triassic

The Triassic was a period of gentle subsidence and steady deposition, during an initial transgression and later regression, of shallow marine and paralic sediments over the eroded, gently undulating surface of the Palaeozoic sequence. The thickness of these sediments over the Exmouth Plateau averages 3000 m and exceeds 4000 m in places (Willcox & Exon, 1976).

The Early Triassic was probably characterised by the deposition of muds and silts in a broad shallow sea. As the basin filled, conditions changed to predominantly paralic, and fluviodeltaic sands and muds were laid from Middle to Late Triassic times. Upper Triassic fluviodeltaic sandstones constitute the main reservoirs for gas/condensate discoveries on the Rankin Platform.

Tension related to the later break-up of Gondwanaland caused extensive normal faulting in the offshore

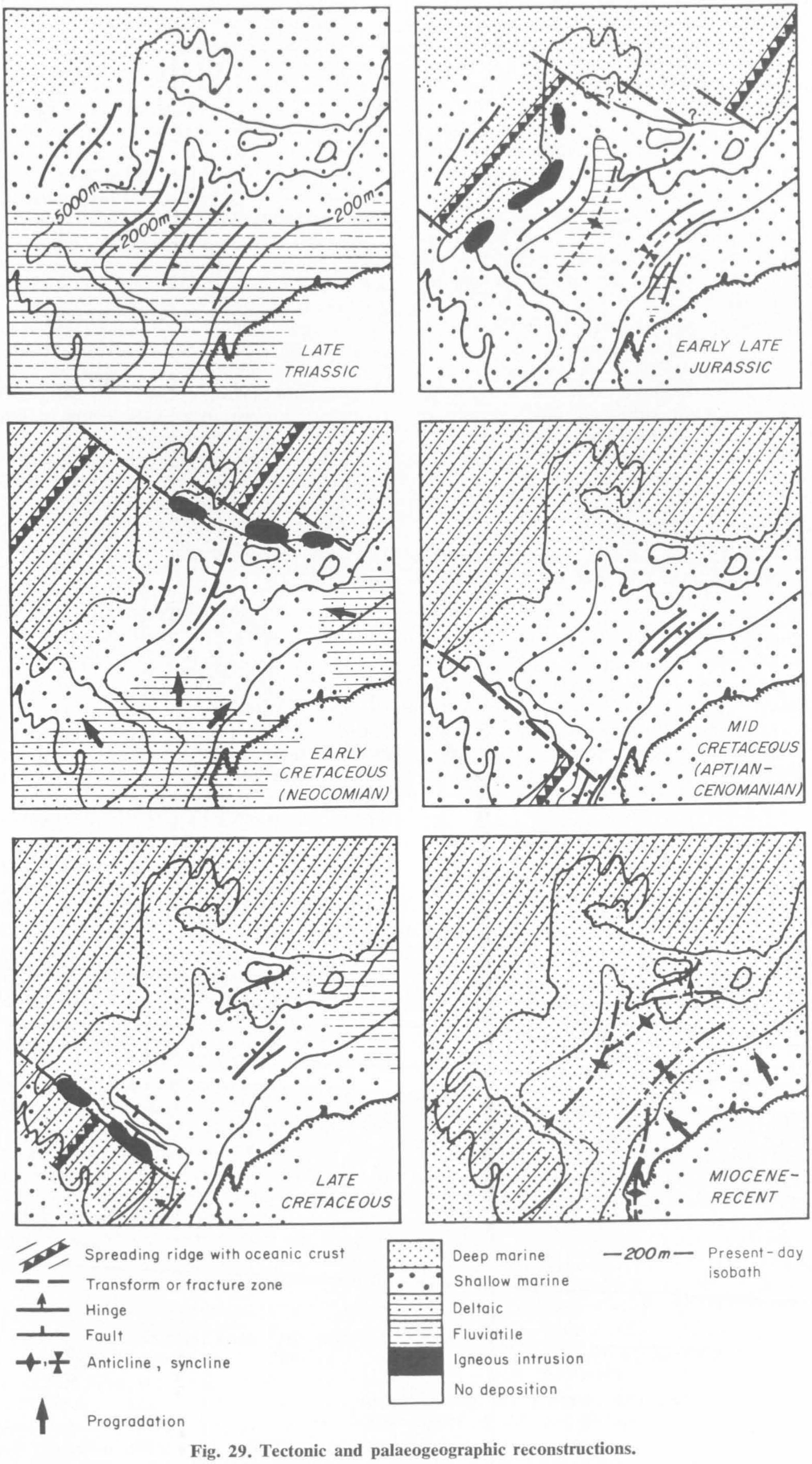


Fig. 29. Tectonic and palaeogeographic reconstructions.

Canning Basin, the Browse Basin, and the Exmouth Plateau, in the Late Triassic, although evidence from parts of the Northwest Shelf (Powell, 1973, 1976) indicates that sedimentation was continuous from the Triassic to Early Jurassic there. Elsewhere in the Carnarvon Basin faulting was relatively unimportant in the Triassic but very important in the late Middle and early Late Jurassic. The faulted downwarps of the Barrow-Dampier Sub-basin and the Kangaroo Syncline are interpreted as rift troughs which formed as a result of tensional stresses associated with the onset of seafloor spreading in the region. The Kangaroo Syncline was probably initiated in the Late Triassic as was the Exmouth Plateau Arch.

A great number of northeast-trending antithetic normal faults, many with displacements of hundreds of metres, developed during the Late Triassic tensional phase; some of them were probably rejuvenated older faults. East-west faulting within the northern part of the plateau was probably related to Palaeozoic trends, which are evident in the Canning Basin farther east. The fault-blocks are possible petroleum traps.

Early and Middle Jurassic

During the Early and Middle Jurassic extensive erosion of the fault-blocks in the central Exmouth Plateau provided detritus which was probably deposited in a non-marine to marginal marine environment in the Kangaroo Syncline (Fig. 22, Gulf AU-15). Less than 200 m of locally derived sediment was deposited on the Exmouth Plateau Arch. The thickest deposits were ponded between tilted fault-blocks on its western flank and across its northern prolongation (Fig. 20, BMR 17/074). Draping, differential compaction, and minor rejuvenation of the Late Triassic faults occurred throughout this period.

Late Jurassic to Early Cretaceous

Evidence from the Deep Sea Drilling Program suggests that during the early Late Jurassic seafloor spreading commenced along the north and possibly northwest margins of the Exmouth Plateau. The northwest margin was probably one side of the main rift along which the Indian and Australian plates separated, and the northern margin appears to have formed as a transform fault or series of transform faults.

The separation of the northwest margin of the plateau from the adjacent part of Gondwanaland extended and thinned the crust. This led to slight subsidence of the plateau area, especially along the northwest and northern margins. Draping, differential compaction of sediment, and some minor readjustment of fault-blocks continued into the Late Jurassic. During this period deltas advanced across the highly irregular surface of the Triassic blocks, fed from the south and east.

In the deeper water of the northwest plateau area generally less than 500 m of offshore mud was laid down (Pl. 11). Nearer the shoreline in the south and northeast, large deltaic complexes formed on either side of the central high area (Pl. 15), and shallow water sands and silts advanced over pro-deltaic muds.

Detritus in the southern deltaic complex was derived largely from source areas in the Pilbara Block, from the continental block in the region of the present-day Cuvier Abyssal Plain, and from the southern Carnarvon Basin, which Quilty (1974) stated was being eroded at the time. The complex consisted of a number of north-building lobes, averaging 1500 m thick (Pl. 11), and was probably continuous with the deltaic sequences of the Barrow Sub-basin. Little is known of the northeast complex, which has an average thickness of 1000 m (Pl. 11), but it appears to have been deposited in the faulted downwarp of the Kangaroo Syncline. The marine and deltaic shales and siltstones laid down during this time are possible petroleum source rocks, and the deltaic sandstones are possible reservoirs.

At the end of this depositional cycle paralic conditions prevailed near shore, and deeper-water conditions offshore. The strong relief of the block-faulted horizon (Pl. 15) is only weakly reflected at the late Neocomian unconformity (Pl. 16), although some horst blocks protrude through the Jurassic-Early Cretaceous sediments in the offshore areas. The depression of the block-faulted horizon (Pl. 15) beneath the thick deltaic complexes suggests that considerable sinking occurred during and after deposition.

The igneous bodies along the northwest margin (Fig. 6, Pl. 28) are believed to have been emplaced in the initial stages of seafloor spreading along and near the spreading axis (Figs. 28 & 29). Those along the northern margin (Fig. 8, Pl. 28) were probably emplaced along transform faults at about the same time (Figs. 28 & 29). Gravity and magnetic data suggest that the bodies are of high density and high magnetic susceptibility; they probably consist of mafic or ultramafic rocks.

Mid-Cretaceous

During the Late Neocomian to Cenomanian the area probably sank slowly and evenly. Coarse sediment no longer reached the plateau, and a thin sequence of marine silt and mud was deposited (Pl. 12). Deep-sea drilling results (Veevers, Heirtzler, et al., 1974) suggest that the southwest margin of the plateau started to form in the Aptian or Albian by normal or transform faulting. Thereafter deep water (the predecessor of the Cuvier Abyssal Plain) lay to the southwest, and southerly source areas no longer provided detritus.

A major marine transgression occurred in the Barrow-Dampier Sub-basin during the late Neocomian and Aptian (Powell, 1976), and this transgression submerged the Early Cretaceous inshore deltaic complexes in the plateau area. Farther offshore, depositional conditions continued unchanged. Only in fault-bounded depressions in the north, and in a depocentre on the northeast flank of the Early Cretaceous delta, was more than 500 m of sediment laid down (Pl. 12).

By Late Cretaceous times the area was structurally very simple, with a gentle tilt northwestward. Almost all the horst blocks had been covered (Fig. 28) by the mid-Cretaceous shales, which would make excellent seals for any hydrocarbons contained in the underlying sequences.

Late Cretaceous

During the Late Cretaceous slow sinking continued, and a generally thin sequence of carbonates was laid down. Everywhere along the west Australian margin, terrigenous clastic sedimentation changed to carbonate sedimentation in the Late Cretaceous (Veevers & Johnstone, 1974), and in wells in the northern Carnarvon Basin the change occurred in the Turonian or Coniacian (Powell, 1976). At the time of the change terrigenous influx into the basin must have declined, and carbonate productivity must have increased, the latter perhaps because of changes in oceanic circulation.

As much as 800 m of Late Cretaceous carbonate was laid down near shore, but offshore the sequence is very thin, and probably absent in places (Willcox & Exon, 1976). The thicker sequences have the gross form of banks and may have been laid down in shallow water, but the thinner sequences were probably outer shelf and slope oozes which currents removed in some areas.

Cainozoic

Cainozoic sedimentation probably kept pace with the gradual subsidence of the area until the Miocene when sinking became more rapid. The plateau appears to have assumed its present form in the Miocene, when warping and renewed movements of the old fault-blocks gave the Exmouth Plateau Arch its present form, and further downwarped the Kangaroo Syncline. The grabens and sub-plateaux along the northern margin, including the Wombat Plateau and the half-graben on its southern side, probably took up their present form at about this time, although reactivation of old faults may have commenced during the Cretaceous. Carbonate sedimentation continued, in water depths ranging from shallow marine to bathyal. The aggregate thickness of Late Cretaceous to Recent carbonate sediments ranges from 500 m near the outer plateau margins to 2000 m at the shelf edge, suggesting that carbonate productivity was greatest at the present shelf edge where the water was presumably shallowest.

Cainozoic sedimentation commenced after a plateau-wide early Paleocene hiatus. Late Paleocene to Eocene sediments averaging 500 m thick were laid down on Late Cretaceous carbonates, or directly on mid-Cretaceous terrigenous sediments in many areas near the edge of the plateau. The earliest of these deposits were probably bathyal oozes, but the water may have shallowed with time, and a scoured early Eocene unconformity perhaps formed in subaerial or shallow marine conditions. An Oligocene hiatus was followed by deposition of Miocene to Recent carbonates — largely bathyal oozes averaging 200 m thick, but near the Northwest Shelf containing a considerable component of reworked shelf sediments. Along parts of the northern margin, particularly on Emu Spur, Miocene sediments appear to have been deposited directly over Triassic and/or Jurassic terrigenous sediments, indicating that areas of the northern margin may have been exposed during Jurassic to Oligocene times, and have subsided as much as 2000 m thereafter. Substantial post-Oligocene subsidence also occurred on the eastern side of the Kangaroo Syncline, where Miocene to Pleistocene dunes are covered by up to 800 m of water. During the early Miocene some slumping of unconsolidated Eocene sediments appears to have taken place as a result of relative uplift of the Exmouth Plateau Arch.

PETROLEUM GEOLOGY

As no drilling has been carried out on the Exmouth Plateau, this preliminary assessment of the petroleum potential of the plateau largely depends on our seismic interpretation and understanding of the palaeogeography of the area. Although structures on the plateau are in many respects similar to those of the Rankin Platform, the apparent thinness of Early and Middle Jurassic sediments (possible source rocks on the Northwest Shelf) tends to downgrade the area. Another problem is that the age identifications of Horizons D, E, and F are uncertain. If, for example, the break-up unconformity were higher in the section, say at Horizon D, the potential would be reduced by lack of 'Rankin-type' Late Jurassic source rocks.

Despite the lack of drill information the present study has indicated that the plateau is geologically similar to the northern Carnarvon Basin, at least as regards the Palaeozoic and Mesozoic sequences. The plateau is adjacent to the Rankin Platform with its major gas and minor oil reserves (Kaye, et al., 1972; Meath & Bird, 1976), and Barrow Island with its oil field (Crank, 1973). By analogy the plateau, which has a thick Phanerozoic sequence and an abundance of fault-blocks, must be considered prospective for petroleum. The probable Late Jurassic-Early Cretaceous delta and the broad fold of the Exmouth Plateau Arch further upgrade the area. As the Cainozoic and Late Mesozoic sequences are thinner on the plateau than on the shelf, older sequences could be more readily penetrated by drilling on the plateau.

The broad Exmouth Plateau Arch contains some of the most likely targets, and will probably be drilled first. The arch is apparent throughout the sequence; the seabed above its Triassic culmination lies in nearly 1000 m of water about 270 km north-northwest of Exmouth, the nearest point on the Australian mainland; the seabed above the culmination of the Late Cretaceous sequence lies in about 880 m of water about 220 km from Exmouth.The shallowest water on the plateau is 815 m deep. Because of the large water depths involved it is quite apparent that only major hydrocarbon fields, and possibly only oil fields, would be economically viable for many years to come. At present the technology to produce hydrocarbons in such water depths has not been developed, but it should be available when needed. Until 1976 the deepest water in which a petroleum exploration well had been drilled was 800 m (Koonce, 1976).

Source rocks

The main source rock for major gas and minor oil accumulations in the Triassic sequence of the Rankin Platform is believed to be shale of the Late Jurassic Dingo Claystone (Powell, 1976; Meath & Bird, 1976). Subsidiary sources for gas and oil may be Triassic and Cretaceous shales respectively (Thomas & Smith, 1974). At Barrow Island gas has been produced from sandstone interbedded with overpressured shales of the Dingo Claystone, which are believed to be the source rocks (Meath & Scott, 1973). Crank (1973) suggests that oil within sandstones in the relatively impermeable Cretaceous sequence of Barrow Island developed virtually in place from shales and siltstones within the mid-Cretaceous Winning Group, and Powell & McKirdy (1973a) support this view.

Thus almost all the shaly sequences of the Northwest Shelf are believed capable of producing hydrocarbons, given sufficient depth of burial. On the basis of the variable wax content, the moderate pristane/phytane ratio (1.7-4.3) and the correlation index (30-65 at 250-300°C) Powell & McKirdy (1973a, b) suggested that the organic matter from which hydrocarbons in Carnarvon Basin wells were derived was a mixture of land plant debris and marine micro-organisms, deposited in a near-shore marine environment where reducing conditions made preservation possible. Powell (1975) rejected the possibility that this oil had formed by the biodegradation of Jurassic oil.

On the Exmouth Plateau a variety of shaly source rocks are probably present. Among likely sources are equivalents of the Cretaceous Winning Group and Barrow Formation, the Jurassic Dingo Claystone, and the Triassic Mungaroo Formation and Locker Shale. Possible sources within the older sediments include equivalents of the onshore Permian sequences and possible equivalents of the largely marine onshore sandstones and carbonates of Silurian, Devonian, and Carboniferous age (see Thomas & Smith, 1974, for generalised descriptions of Carnarvon Basin sequences).

TABLE 8. MATURATION OF HYDROCARBONS (PRESENT-DAY SITUATION)

Condition (after e.g. Reel & Griffin, 1971)	*Sub-bottom depth (m)*		*Stratigraphic level on culmination* ×
	North West Shelf *	*Exmouth Plateau* +	
Onset of hydrocarbon production (65°C)	1450	1950	Low in Jurassic
Onset of mature oil production (100°C)	2750	3050	High in Triassic
Maximum oil production (130°C)	3850	4000	Within Triassic
Onset of destruction of oil to form condensate and gas (150°C)	4700	4700	Within Triassic
Production of dry gas alone (180°C)	5700	5300	Lowest Triassic

*Average gradient estimated to be 2.7°C/100 m (estimate based on well temperature logs). Immediate sub-bottom temperature assumed to be 25°C.

+Average crustal thickness (with respect to sea level) assumed to be 20 km compared with 23 km on Northwest Shelf, to given an average gradient of 3.1°C/100 m. Sub-bottom temperature assumed to be 5°C.

×Sub-bottom depths of horizons on Exmouth Plateau Arch's Santonian culmination (where the water depth is 1050 m): Santonian 700 m, Neocomian 1200 m, base Jurassic 2050 m, top Horizon G (?Permian) 5700 m.

Table 8 indicates the average sub-bottom depths at which various stages in the production of hydrocarbons might be expected today, and relates them to the stratigraphic section below the crest of the Exmouth Plateau Arch. These depths were calculated from an average value of temperature gradient for adjacent areas of the Northwest Shelf, from assumed temperatures immediately below the sea-floor on the Northwest Shelf and the Exmouth Plateau, and from the estimated difference in crustal thickness beneath the shelf and the plateau. Temperature gradients vary considerably on the shelf, and presumably on the plateau, so the results are no more than a general guide. However, the results do suggest that oil and gas could have been produced in parts of the plateau from suitable Early Cretaceous and older source beds.

The criteria shown in Table 8 do not apply in some situations. For instance, within Triassic and Jurassic sequences around the plateau margins igneous intrusions may have increased local temperatures sufficiently for the production of hydrocarbons, even though the sequences have too little overburden to be source rocks according to Table 8. Seismic profiles across the plateau margins give evidence of large igneous bodies which were probably emplaced during the Jurassic and Cretaceous phases of seafloor spreading. Furthermore, it is believed that theoretically immature source rocks have generated hydrocarbons at shallow depth under Barrow Island (Crank, 1973). These source rocks (containing abundant marine source material) which are adjacent to oil-bearing Cretaceous sequences, have only about 500 m of overburden, and may never have had much more. Similar source rocks could produce oil at shallow depth on the Exmouth Plateau.

Migration and entrapment

Considering the depths of burial discussed above it seems unlikely that hydrocarbons would have been generated in any abundance from organic matter in the Jurassic and younger sequences before mid-Tertiary times. Hydrocarbons may still be forming in Mesozoic and younger rocks, as appears to be the case in the overpressured Dingo Claystone at Barrow Island. The migration of hydrocarbons has probably been a continuous process since the Early Mesozoic, when Permian and older hydrocarbons began to migrate. Petroleum migrating during the Late Triassic may have escaped during the phase of tensional faulting. If the Jurassic is the major source sequence, much of the migration probably occurred in the Late Tertiary when structures had evolved to their present-day form.

Little is known of the lithologies of the various sequences on the plateau, other than by comparison with sequences on the Northwest Shelf and in the onshore Carnarvon Basin, and by extrapolations making use of palaeogeographic information. Because the Cainozoic sequence is much thinner on the plateau than on the shelf it will be possible to penetrate older strata on the plateau (older Triassic and possibly Permian) by drilling there, than it has been by drilling on nearby parts of the shelf.

Possible reservoirs include Silurian, Devonian, and Carboniferous sandstones and limestones, such as those occurring elsewhere in the Carnarvon Basin (see Thomas & Smith, 1974), Triassic fluvial to marginal marine sandstones (Mungaroo Formation equivalent) and sandstones within the deltaic Jurassic/Neocomian sequence (especially the Barrow Formation equivalent), and Late Cretaceous and Early Cainozoic marine limestones.

The Mungaroo Formation contains excellent reservoirs on and near the Rankin Platform where it consists of interbedded sandstone and shale. The thickest petroleum-bearing sandstone section (310 m) was encountered at North Rankin No. 1, where porosities up to 28 percent and permeabilities up to 2200 millidarcies were measured (Kaye et al., 1972).

The bulk of the Jurassic sequence is probably shaly although prospective sandstones may also be present. The largely Neocomian Barrow Formation is about 1100 m thick at Barrow Island where it is dominantly coarse sandstone interbedded with some shale and siltstone (Crank, 1973). At Barrow Island, six thin discontinuous sandstone reservoirs within the group have yielded hydrocarbons; porosities exceed 20 percent but permeabilities are low. The Barrow Island wells have sampled only a very small part of the sequence geographically, and good reservoir sands probably exist within the formation in other areas. The equivalent of the Barrow Formation appears to make up most of the thick deltaic sequence on the southern Exmouth Plateau.

Late Cretaceous and Early Cainozoic limestones have yielded hydrocarbons in a number of wells on the Northwest Shelf, but they have very low permeabilities and hence the equivalent sequences do not appear to be attractive targets on the plateau. Much of the Cainozoic sequence on the plateau may consist of bathyal oozes, which would typically have high porosities but low permeabilities, and therefore be non-prospective. However, there are, almost certainly, shallow water limestones in places, and possibly aeolian dunes on the eastern flank of the Kangaroo Syncline (Pl. 14), and these could contain hydrocarbon reservoirs.

There are a number of impermeable sequences which would make excellent cap-rocks. Among the best of these could be shales in the Triassic, Jurassic, and Cretaceous sequences, and impermeable limestones in the Late Cretaceous and Cainozoic sequences. On the Rankin Platform the Triassic petroleum reservoirs are capped mostly by Cretaceous shales.

Major exploration targets

Obvious targets for initial exploration are culminations of the Triassic sequence beneath the Exmouth Plateau Arch. The arch itself is a very broad structure with a vertical closure of about 600 m defined by the 3000 m structure contour on the map of the Triassic unconformity (Pl. 15). The area of closure is about 20 000 km^2, suggesting that petroleum fields, if present, may be very large despite the structural complexity of the arch.

The arch is dissected into a number of large, tilted, north-northeast-elongated fault-blocks (Fig. 25 and Pls. 28 and 33) which are as much as 20 km wide, and have vertical closures of up to 300 m. Some of them are larger than individual blocks of the Rankin Platform, and could conceivably contain giant petroleum accumulations. Hydrocarbons could have accumulated within Triassic sandstones in the fault-blocks, Jurassic and Cretaceous shales draped over the fault-blocks being one trapping element, and shales laterally juxtaposed across normal faults being the other, as on the Rankin Platform.

Source rocks supplying hydrocarbons to the Triassic sequence in the central plateau area could be older sediments, shales within the Triassic sequence itself, or shales in laterally adjacent Jurassic and Neocomian sequences. The individual blocks formed in the Early Mesozoic, and the Exmouth Plateau appears to have been a relatively high area then, but the Exmouth Plateau Arch probably did not take up its final form until the Miocene. Even the southerly slope south of 20°S probably did not develop until Cretaceous times when deltaic loading caused downwarping. Thus any pre-Tertiary migration paths would have been very different from those prevailing at present.

The thick Late Jurassic-Early Cretaceous deltaic sequence just south of the culmination of the Exmouth Plateau Arch (Pl. 11) is also prospective as it contains potential source and reservoir rocks. This area is much less faulted than are the central and northern parts of the arch, and perhaps the best initial drilling target would be the culmination of the sequence near 113°E, 20°20'S (Pl. 16). Sandstones within the deltaic sequence are likely to be lenticular, so stratigraphic traps should predominate, and exploration would be more difficult than over Triassic prospects.

Gentle folds in the Palaeozoic sequence are also possible targets. These folds are most apparent in the northeast, and below the Exmouth Plateau Arch (Pl. 30, Esso 2).

The delineation of other targets must await more seismic work, and the stratigraphic results of the drilling of exploration wells in the shallow-water part of the plateau. The area is enormous, and numerous targets are possible, both structural and stratigraphic.

Conclusions

Suitable petroleum source rocks, especially Triassic to Neocomian shales and siltstones, and suitable reservoir rocks, especially Triassic and Neocomian sandstones, appear to exist in the Exmouth Plateau region, where as much as 10 km of prospective sediment rests on basement. Whether the depth of burial has been adequate to generate hydrocarbons from Jurassic and Neocomian shaly sequences depends on present and past temperature gradients in the area. Major generation of hydrocarbons has probably been from Mesozoic and Palaeozoic source rocks.

The area is structurally complex, and the structures are large enough to be attractive targets even in the water depths of more than 815 m. Because of technological limitations it seems likely that the first exploration wells will be drilled in the central part of the plateau, in water shallower than 1200 m.

Prime targets are the numerous large fault-blocks, which probably contain Triassic sandstones and are sealed by Jurassic and Cretaceous shales. Possibly the best such targets lie on the broad Exmouth Plateau Arch. However, this arch may have developed only in the Late Tertiary, in which case it would have formed a focus only for hydrocarbons migrating later.

Another major exploration target is the extensive Jurassic to Neocomian delta on the southern Exmouth Plateau. Deltaic sands would probably have had to obtain their hydrocarbons from within the deltaic sequence, whose depths of burial may possibly have been inadequate for hydrocarbon generation.

Because of the water depths and the distance of the prime targets from shore (more than 200 km), exploration and development will be expensive and difficult.

The economic factors suggest that only major fields would be of interest, and possibly only oil fields.

Despite these problems petroleum exploration wells will certainly be drilled on the Exmouth Plateau. In the meantime further seismic exploration will enable drilling targets to be adequately defined, and a program of geological sampling (Exon & Willcox, 1976) and heat flow measurements would substantially increase our knowledge of the history and prospectivity of the area.

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APPENDIX I

COMPUTATION OF FREE-AIR, BOUGUER, AND MAGNETIC ANOMALIES

The free-air anomaly is computed by applying latitude and Eötvös corrections (Glicken, 1962) to the observed gravity data. Essentially, it shows the differences between the gravity observed at sea level on a stationary platform, and theoretical gravity on the reference spheroid. It depicts the gravity effect of structures below sea level.

$$G_{FAA} = G_{OBS} - 978.049\ (1 + 0.005\,288\,4 \sin^2 \phi - 0.000\,005 \sin^2 2\phi) + 7.5\ Ve$$

where G_{FAA} = free-air anomaly
G_{OBS} = observed gravity
ϕ = latitude
Ve = eastward component of velocity in knots.

In the Bouguer anomaly, corrections have been applied to eliminate the gravity effect caused by variations in water depth. The water layer of density 1.03 $t.m^{-3}$ has been replaced with a layer of density 2.20 $t.m^{-3}$, which is assumed to be the density of sediments on the seabed. The Bouguer anomaly ideally shows the gravity effect of structures beneath the seabed.

$$G_{BA} = G_{FAA} + 2\pi G \Delta\rho d$$

where G_{BA} = Bouguer anomaly
G = Universal Gravitational Constant
$\Delta\rho$ = difference in density between water and sediments, assumed to be 1.2$t.m^{-3}$
d = water depth in metres.

The magnetic anomalies presented by Hogan & Jacobson (1975) were computed as the difference between the measured total field, corrected for diurnal variation, and the (IGRF) International Geomagnetic Reference Field (Cain, Langel, & Hendricks, 1966). However, when we attempted to produce a composite magnetic anomaly map based on data from the Continental Margin Survey and the 1968 Sparker Survey (Whitworth, 1969) the two were found to be incompatible. In the Exmouth Plateau area it appears that the annual change in total intensity (time terms) used in calculating the IGRF differs considerably from the actual annual changes in the area. At several primary magnetic stations the IGRF and the observed field are diverging year by year, and had diverged by about 500 nT from 1968 to 1972. Consequently, the magnetic anomalies were computed with reference to a regional field which more closely fits the observations in the Australian region. This is termed the Australian Geomagnetic Reference Field (AGRF) and is computed and discussed in detail by Petkovic & Whitworth (1975):

(magnetic anomaly) = (observed total magnetic field) − (diurnal) − (AGRF)

REFERENCES

CAIN, J. C., LANGEL, R. A., & HENDRICKS, S. J., 1966—A proposed model for the International Geomagnetic Reference Field. *J. Geomagn. Geoelect.*, 19, 335.

GLICKEN, M., 1962—Eötvös corrections for a moving gravity meter. *Geophysics*, 27, 531-3.

HOGAN, A. P., & JACOBSON, E. P., 1975—Geophysical results from the northwest margin. *Bur. Miner. Resour. Aust. Rec.* 1975/101 (unpubl.).

PETKOVIC, J. J., & WHITWORTH, R., 1975—Problems in secular variations in the Australian region. *EOS*, 56(8).

WHITWORTH, R., 1969—Marine geophysical survey of the northwest continental shelf, 1968. *Bur. Miner. Resour. Aust. Rec.* 1969/99 (unpubl.).

APPENDIX II

LOGS FROM PETROLEUM EXPLORATION WELLS ADJACENT TO THE EXMOUTH PLATEAU

Figures A, B, & C show well logs for WAPET West Tryal Rocks No. 1, WAPET North Tryal Rocks No. 1, and BOCAL Malus No. 1, redrawn from well completion reports submitted to BMR under the terms of the Petroleum (Submerged Lands) Act, 1967-1974.

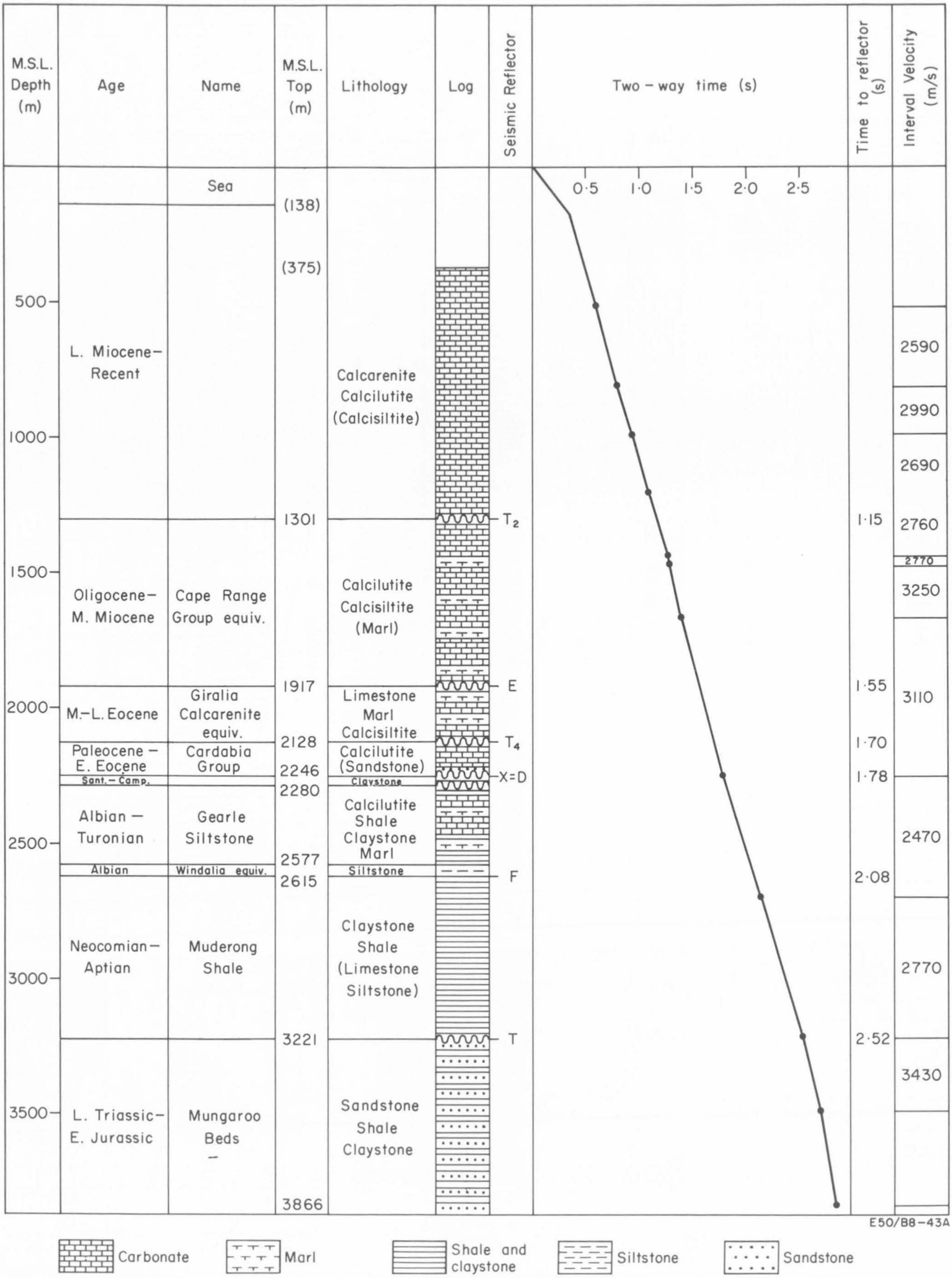


Fig. A. WAPET West Tryal Rocks No. 1 log.

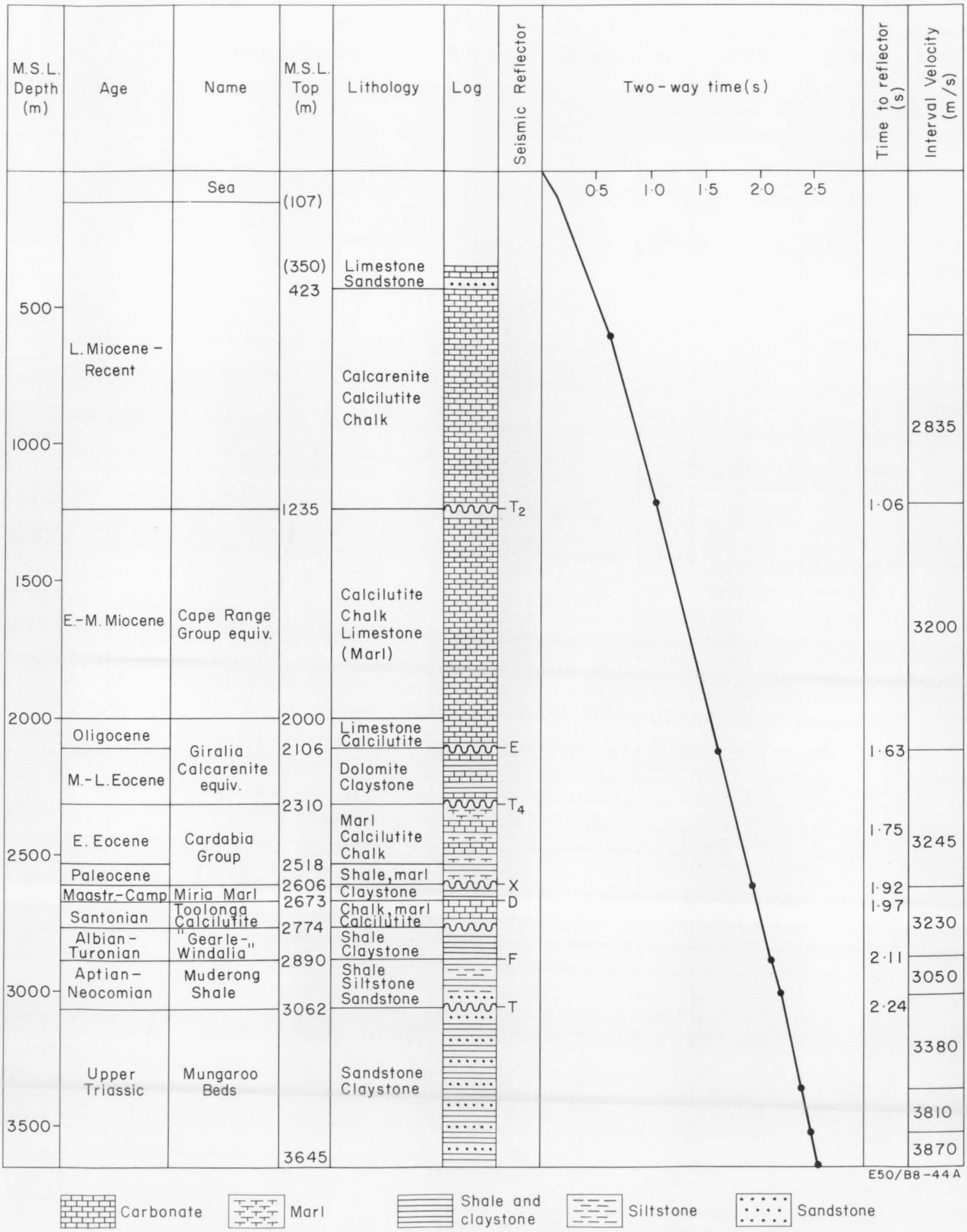


Fig. B. WAPET North Tryal Rocks No. 1 log.

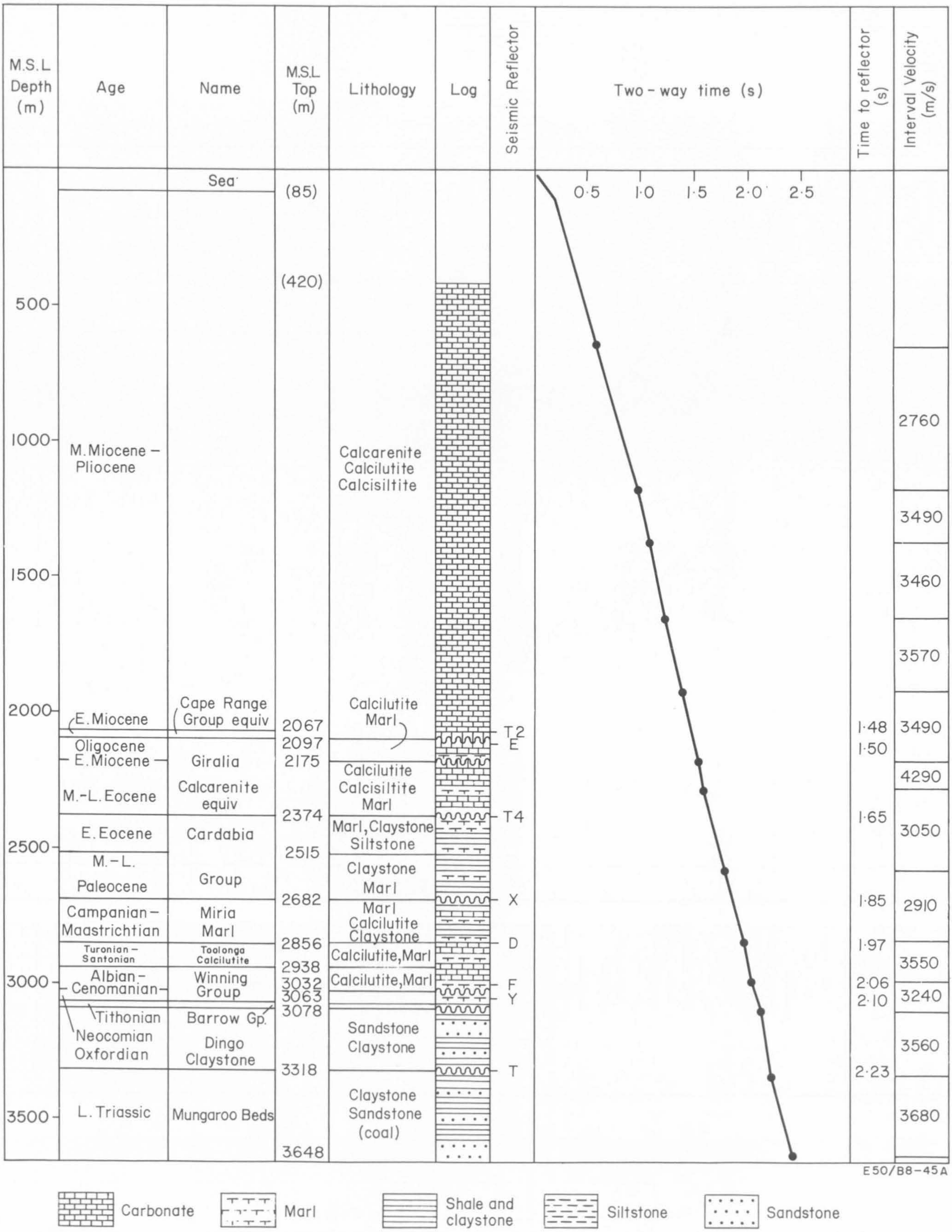


Fig. C. BOC Malus No. 1 log.

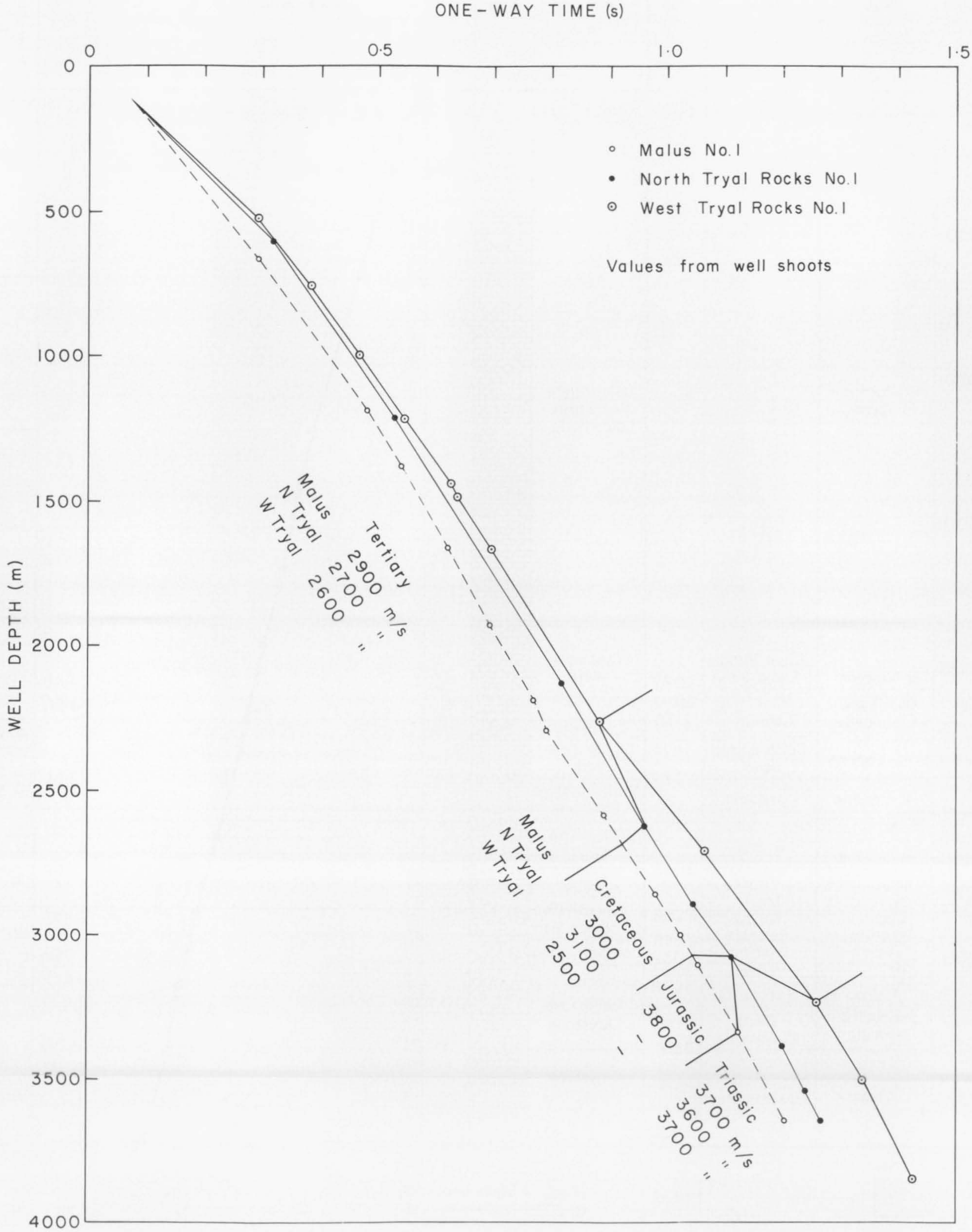
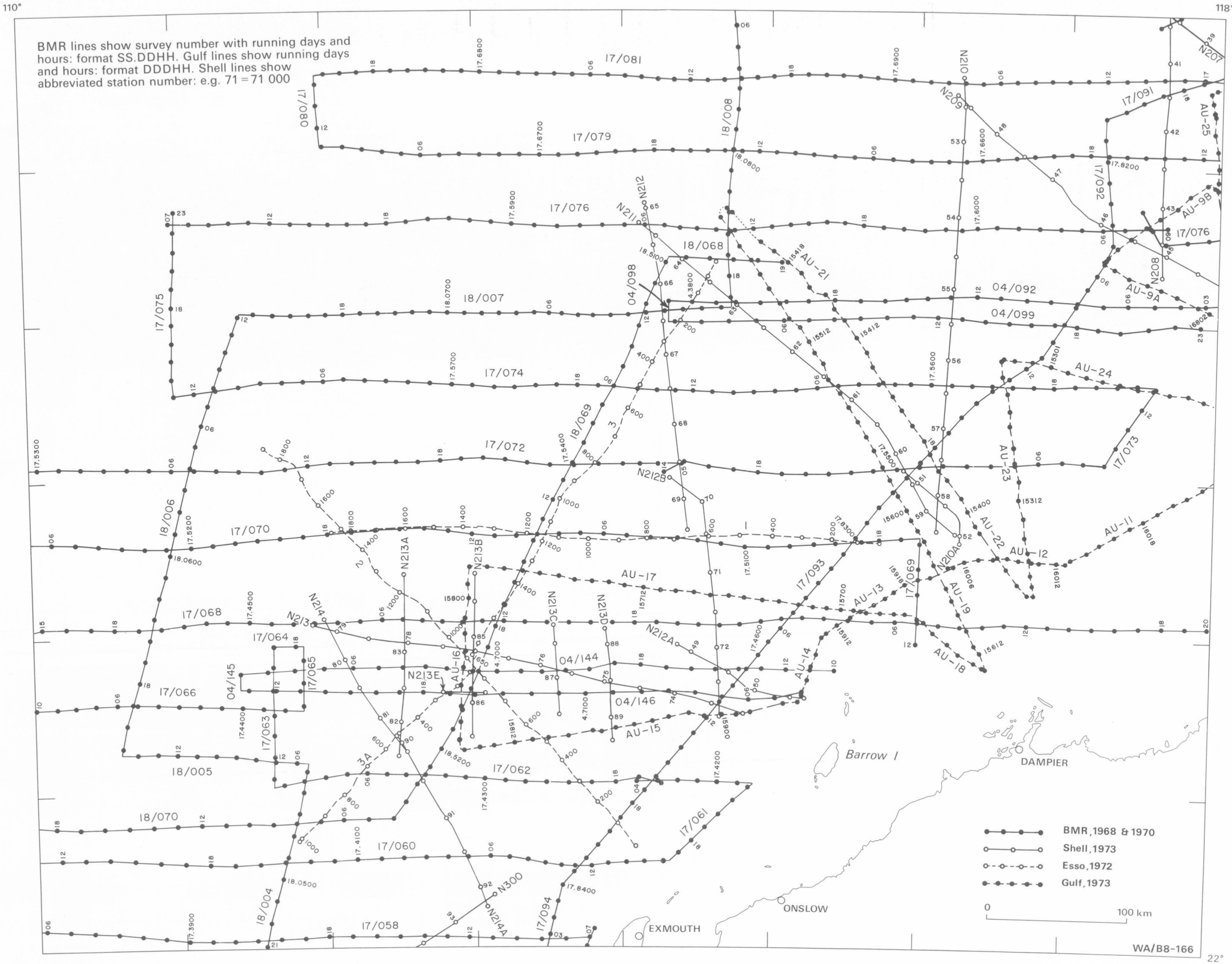
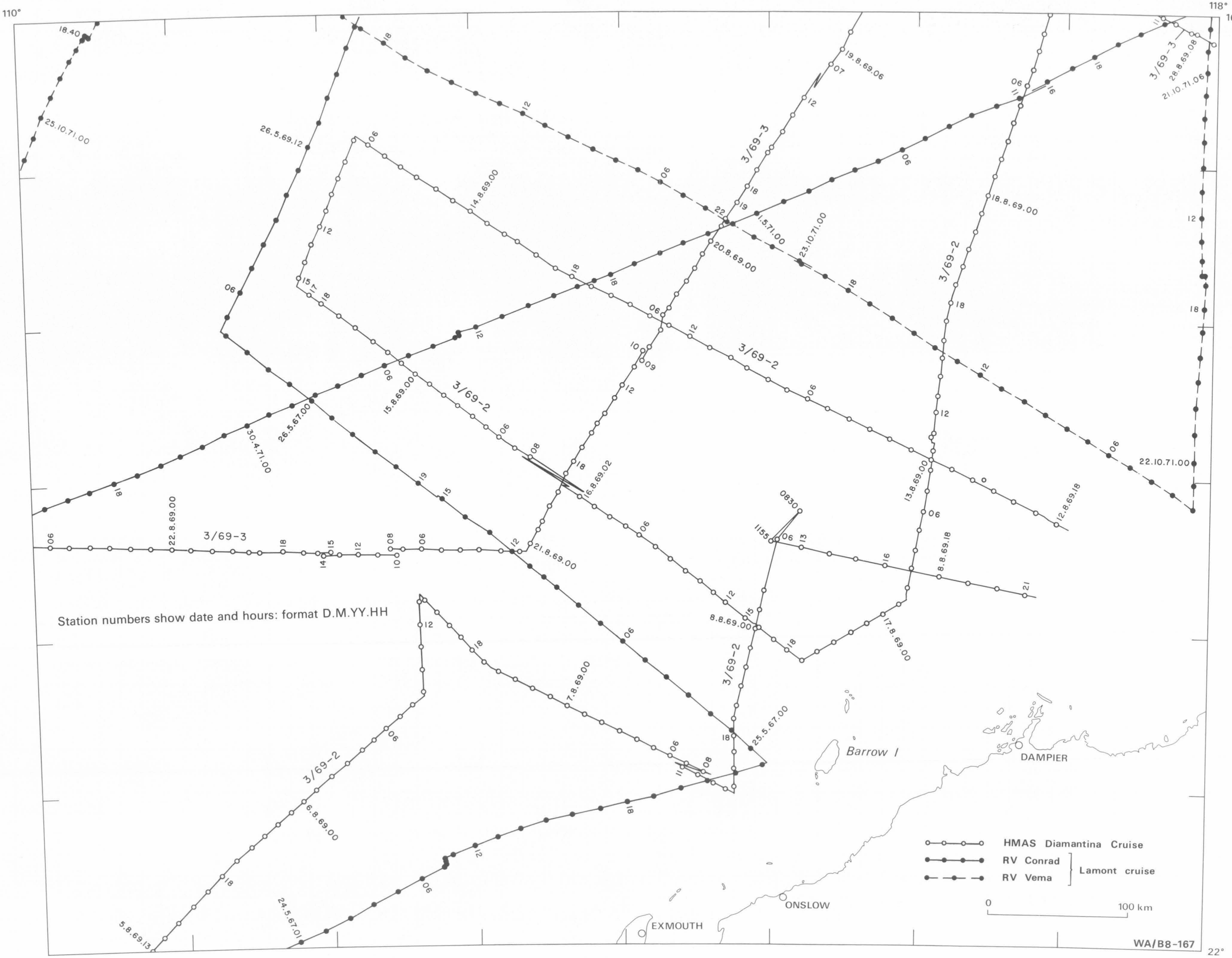


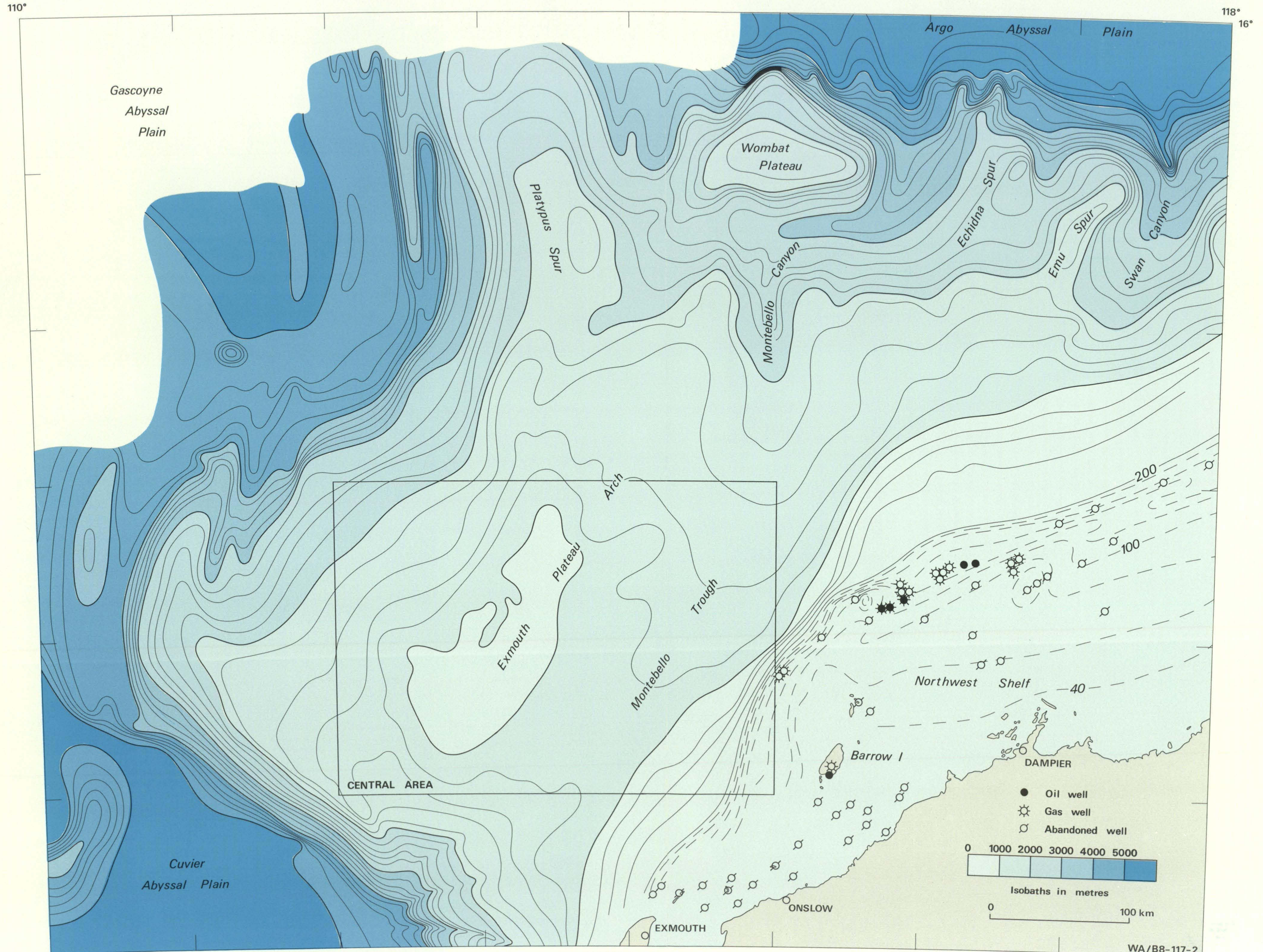
Fig. D. Time-depth curves for West Tryal Rocks No. 1, North Tryal Rocks No. 1, and Malus No. 1 wells.



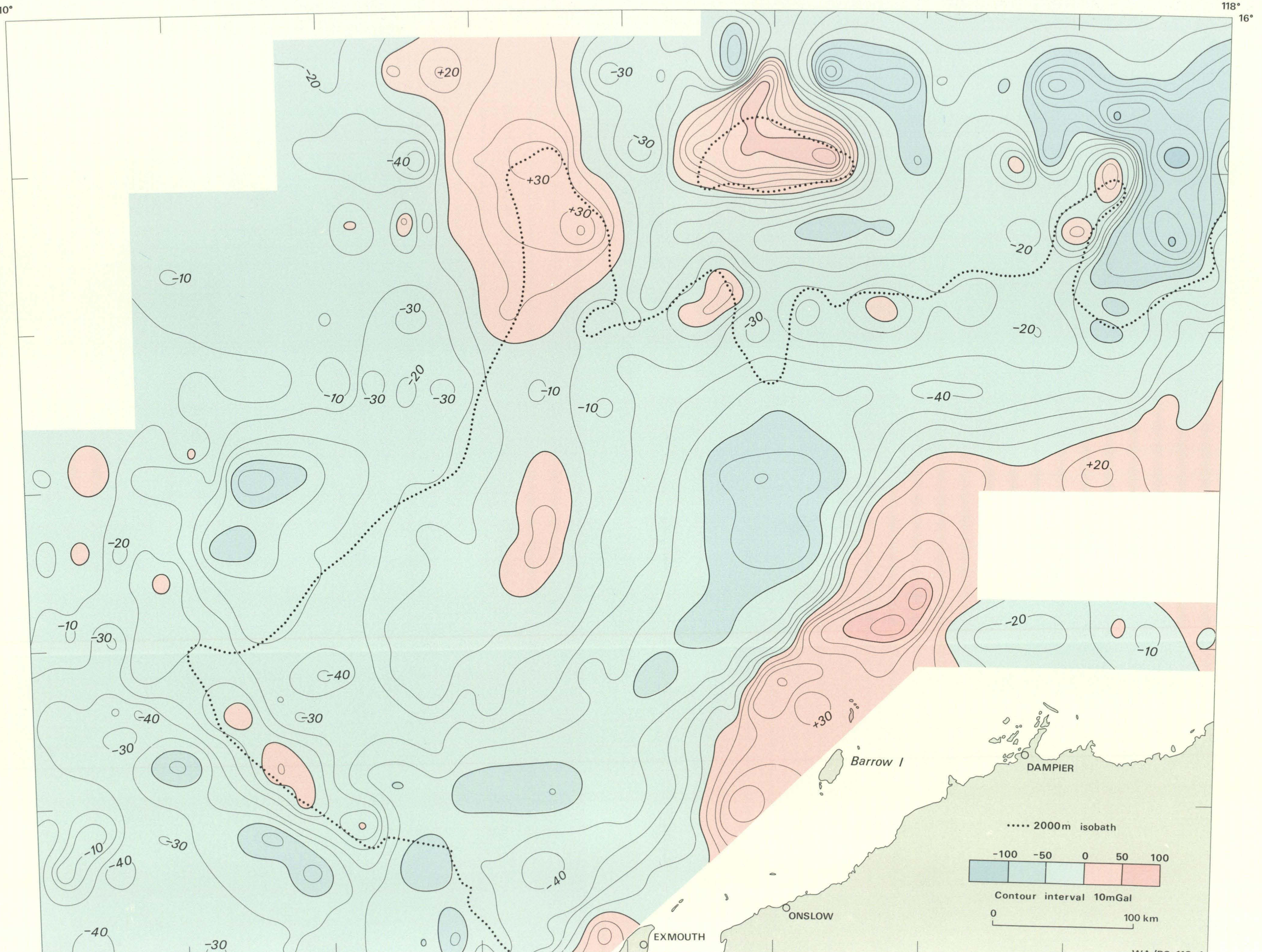
BMR AND EXPLORATION COMPANY TRAVERSES



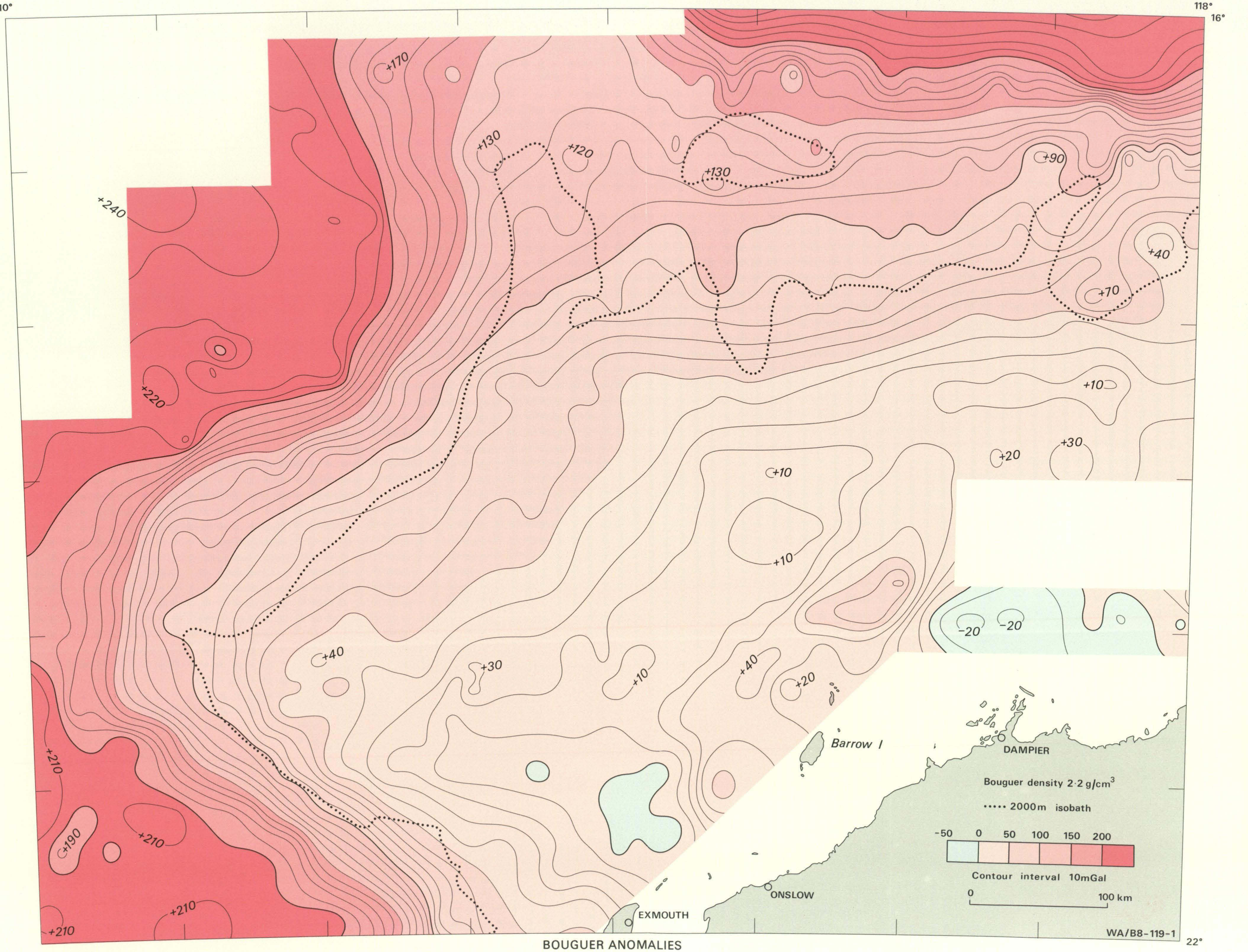
LAMONT–DOHERTY GEOLOGICAL OBSERVATORY AND HMAS DIAMANTINA TRAVERSES


110°
118°
16°
22°
Gascoyne Abyssal Plain
Argo Abyssal Plain
Wombat Plateau
Platypus Spur
Montebello Canyon
Echidna Spur
Emu Spur
Swan Canyon
Arch
Exmouth Plateau
Montebello Trough
Northwest Shelf
200
100
40
Barrow I
DAMPIER
ONSLOW
EXMOUTH
CENTRAL AREA
Cuvier Abyssal Plain
Oil well
Gas well
Abandoned well
0 1000 2000 3000 4000 5000
Isobaths in metres
0
100 km
WA/B8-117-2

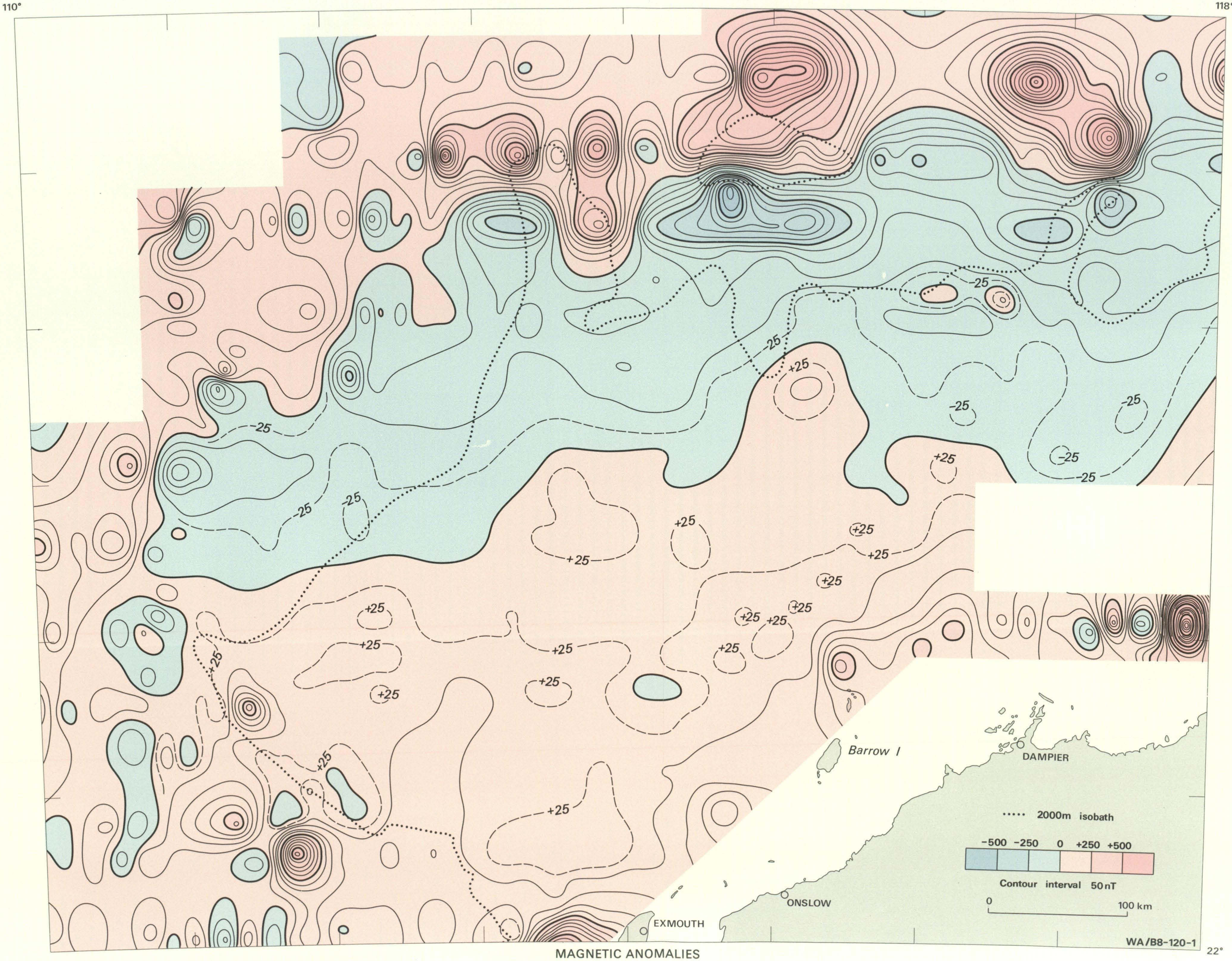
BATHYMETRY



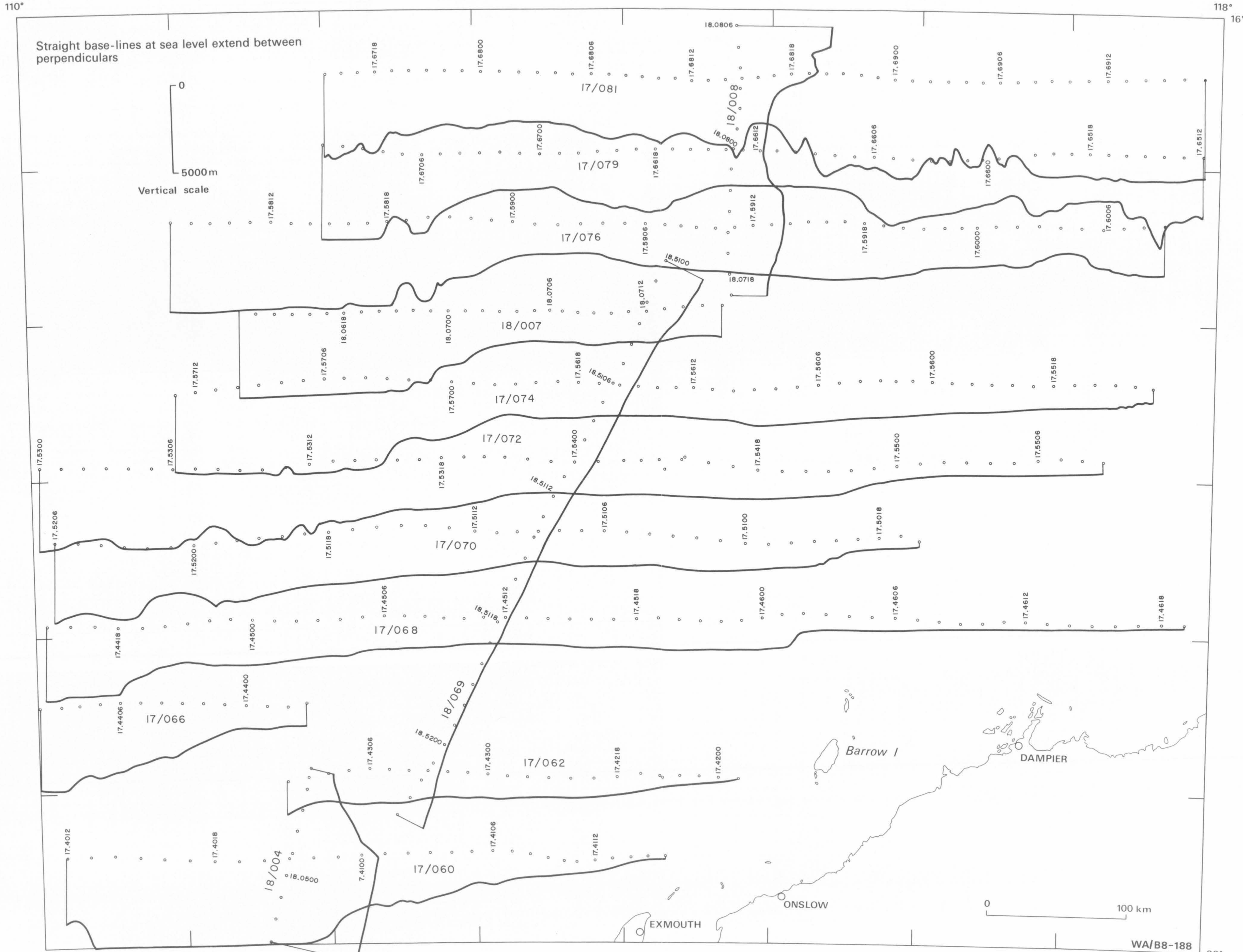
FREE AIR ANOMALIES



BOUGUER ANOMALIES

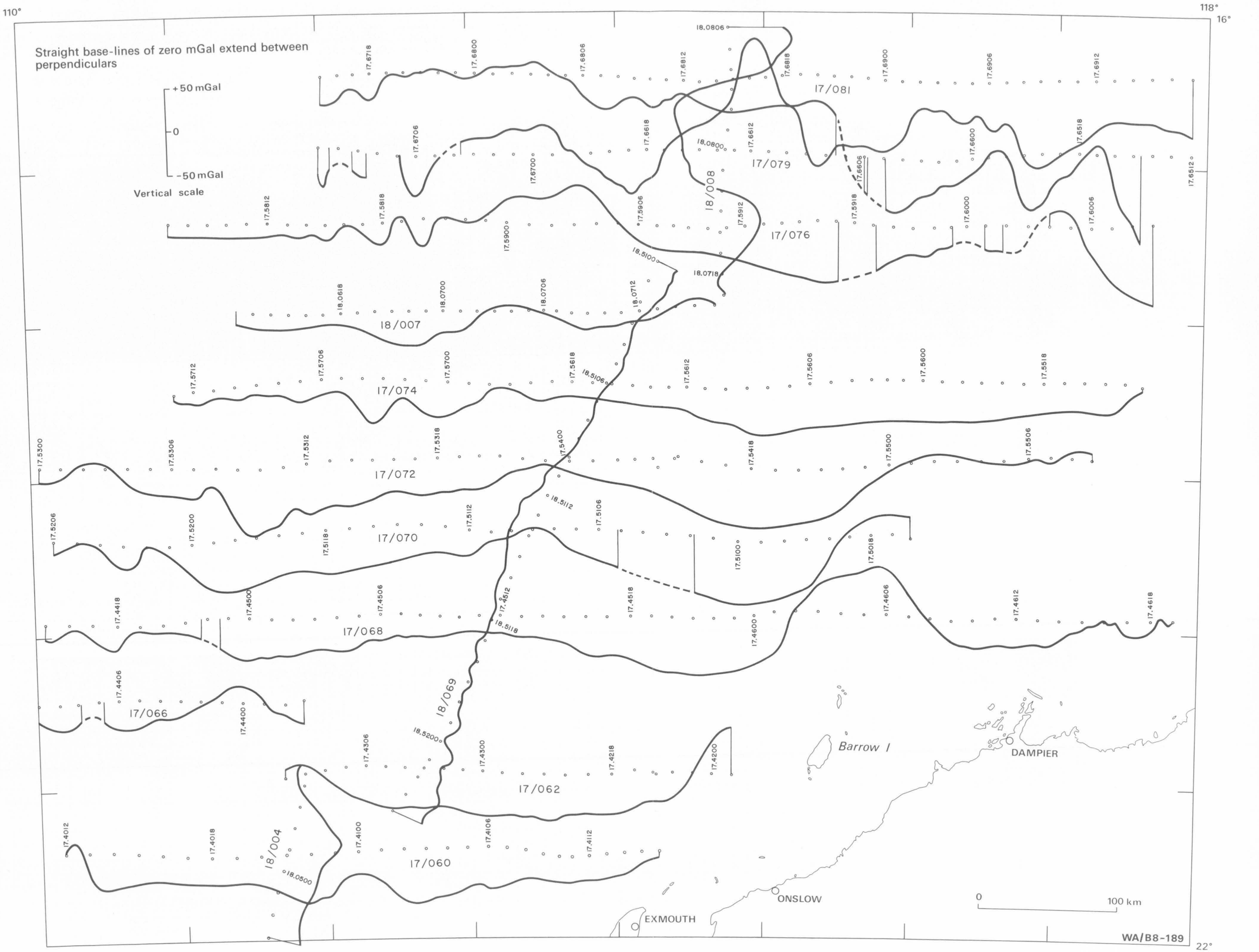


MAGNETIC ANOMALIES



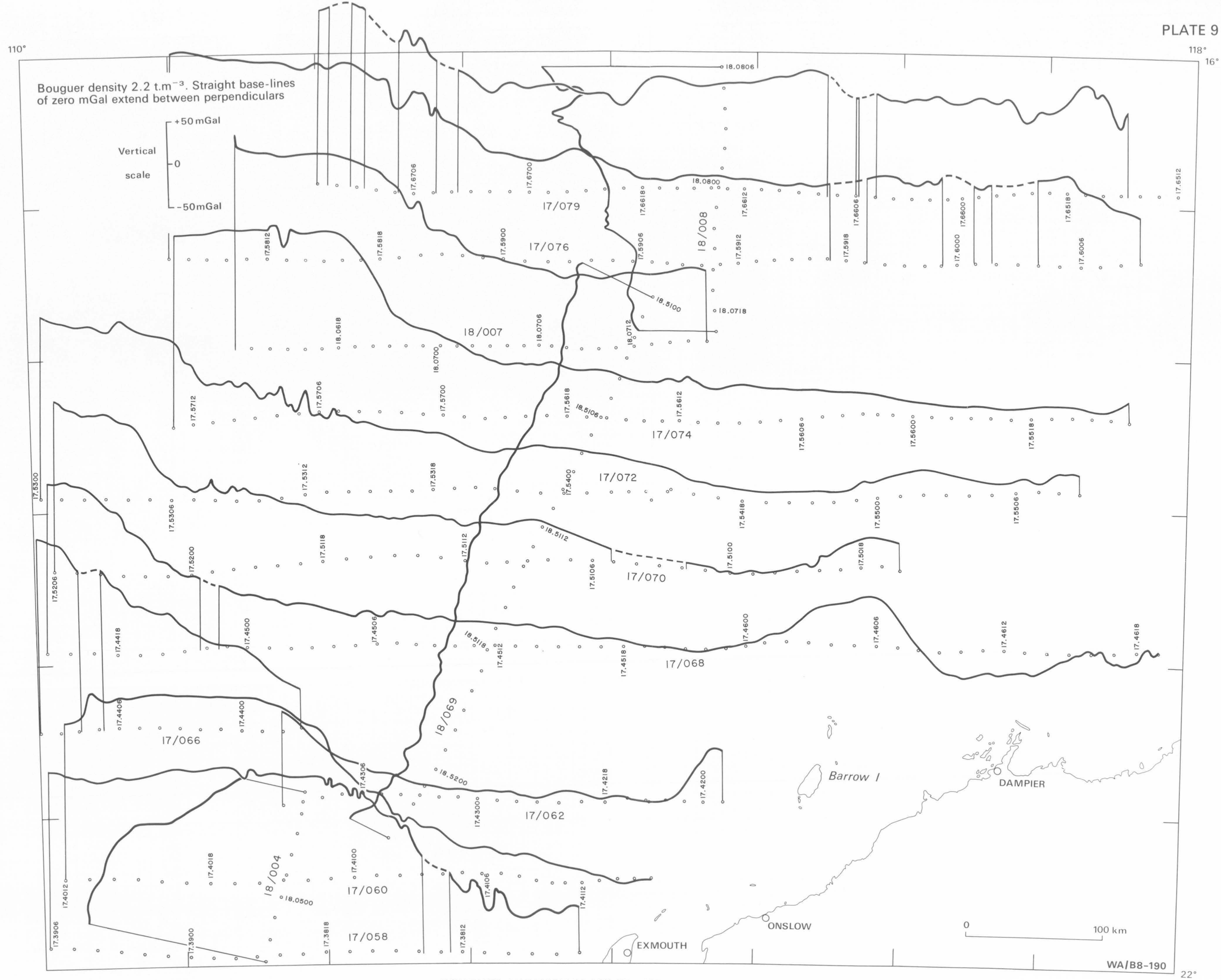
BATHYMETRIC PROFILES (SELECTED BMR LINES)

PLATE 8

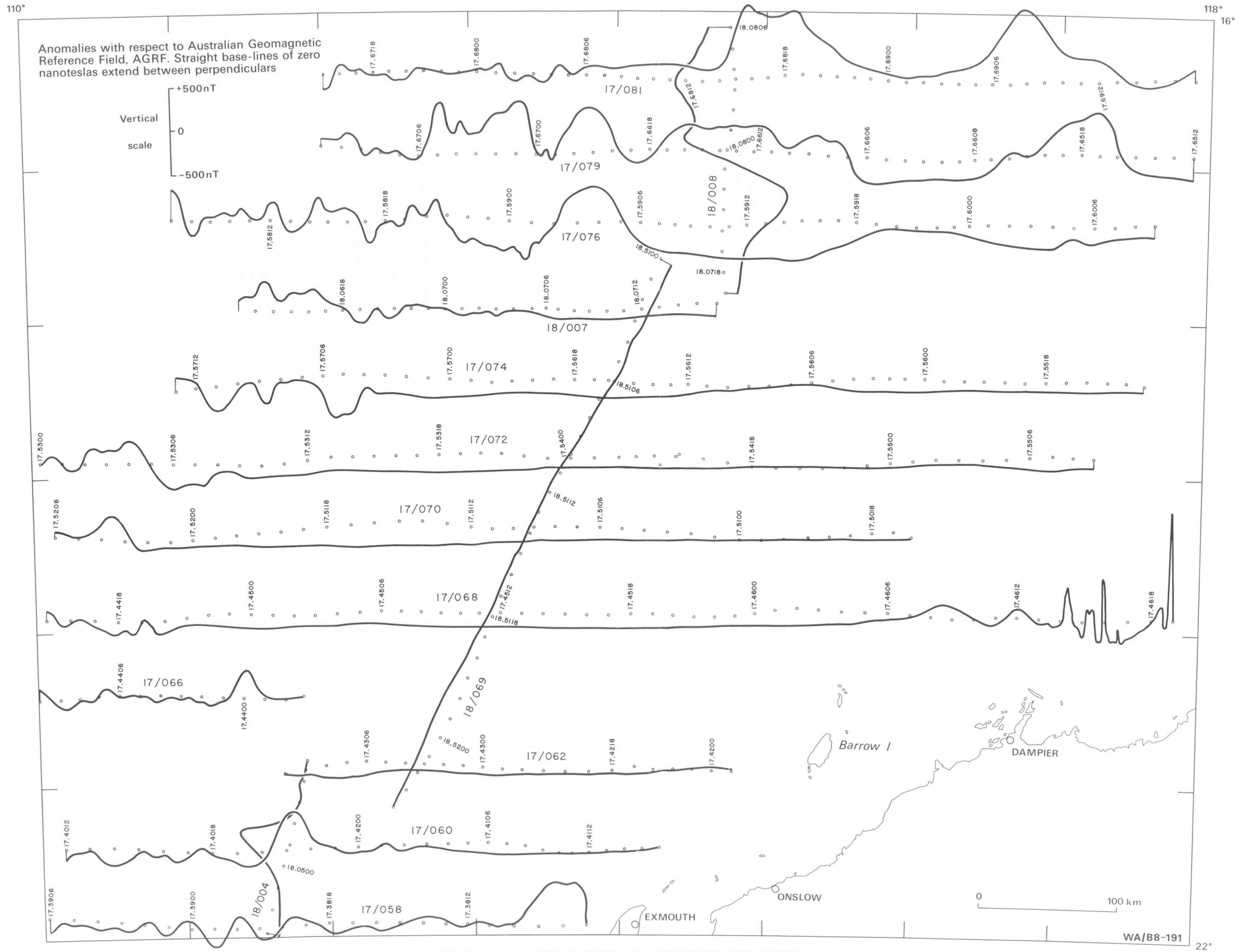


FREE-AIR ANOMALY PROFILES (SELECTED BMR LINES)

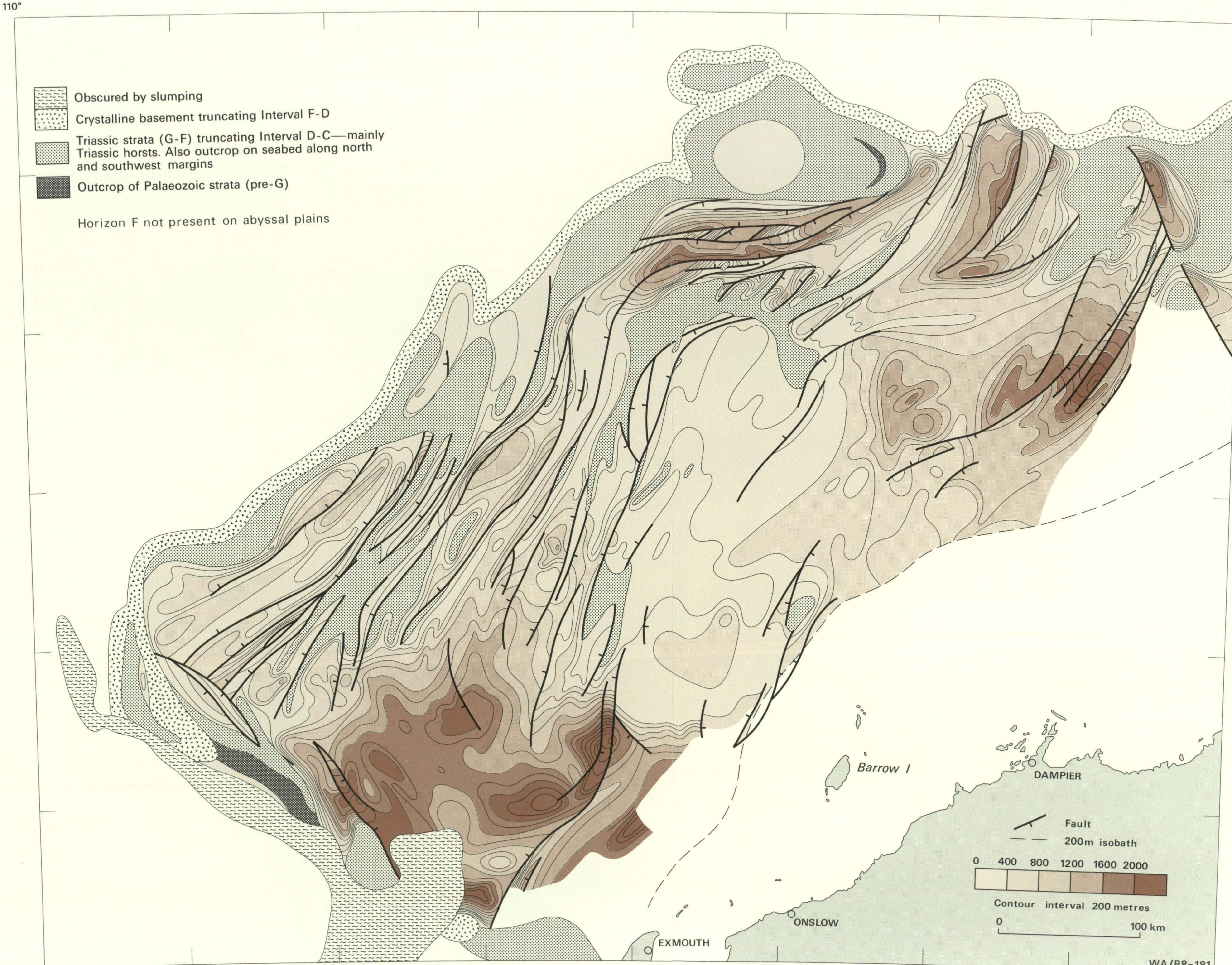
PLATE 9



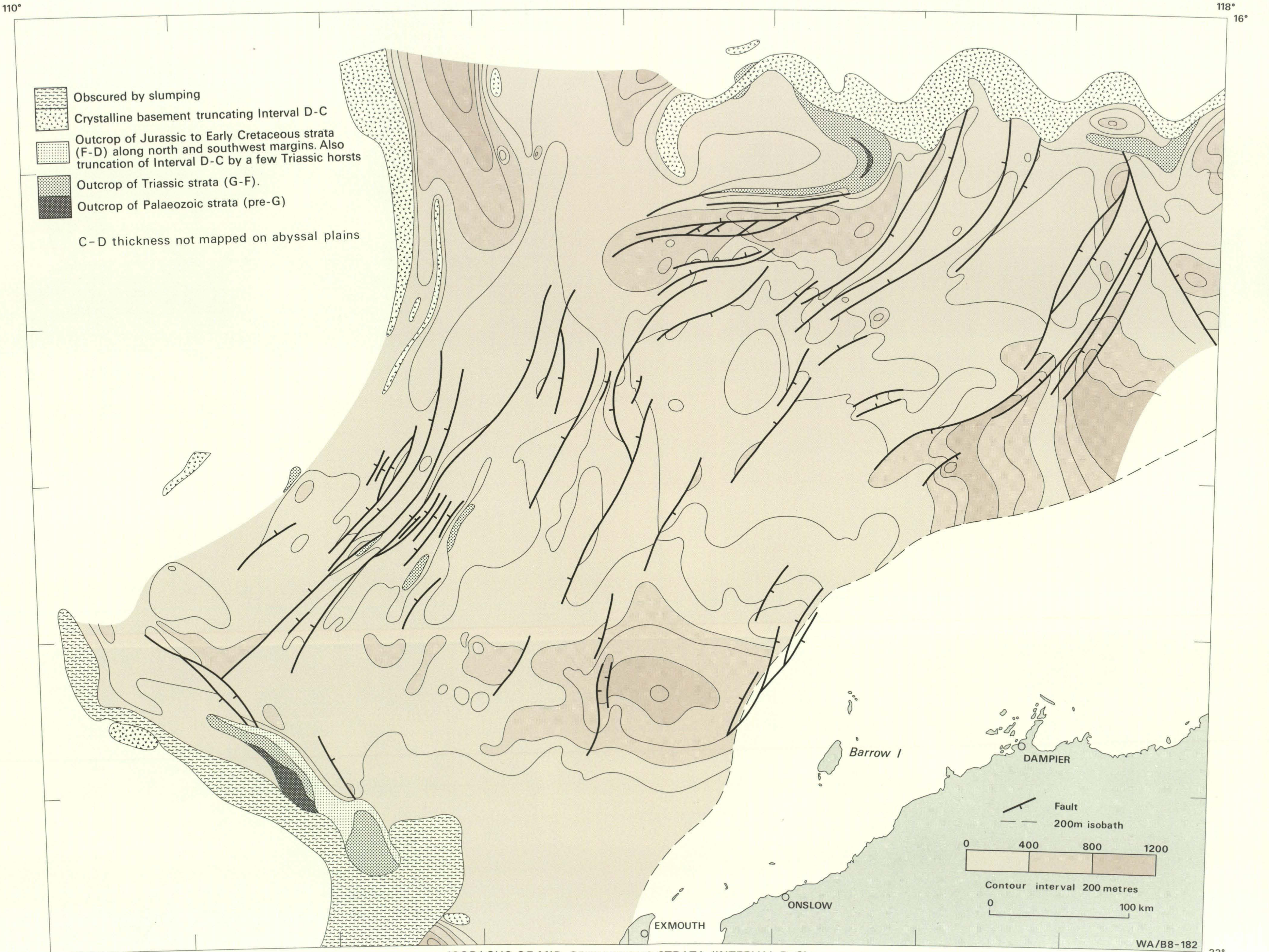
BOUGUER ANOMALY PROFILES (SELECTED BMR LINES)



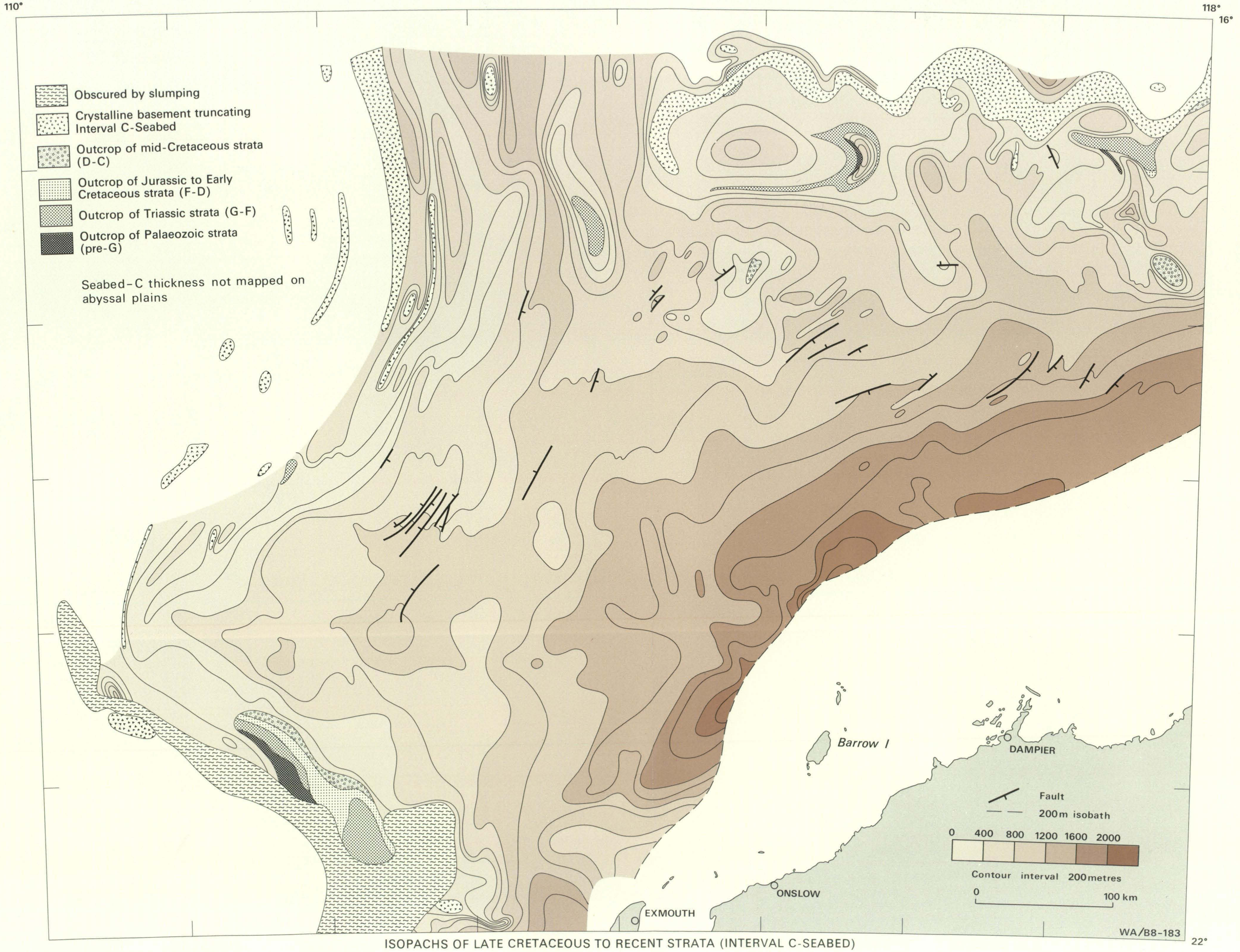
MAGNETIC ANOMALY PROFILES (SELECTED BMR LINES)



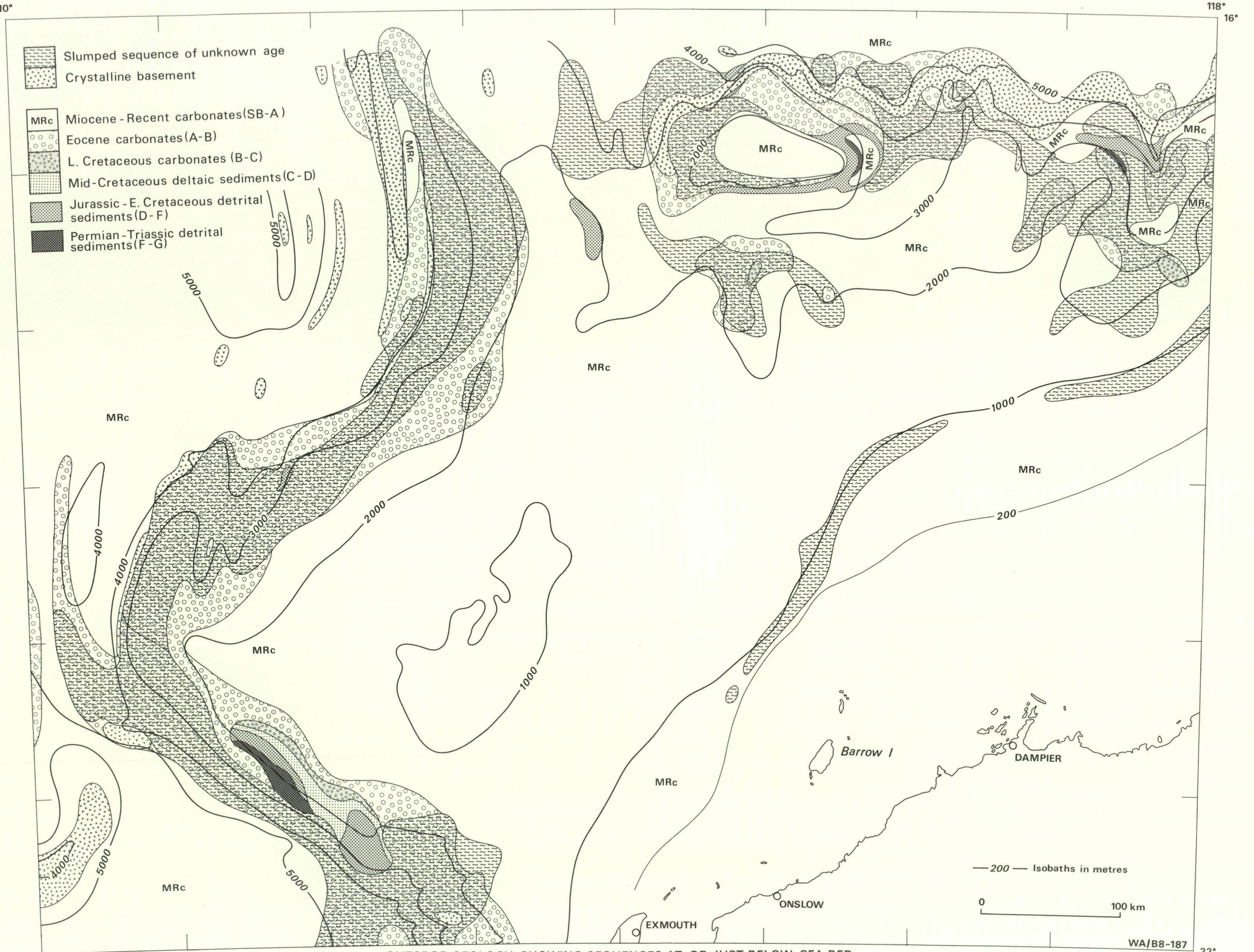
ISOPACHS OF JURASSIC AND EARLY CRETACEOUS STRATA (INTERVAL F-D)



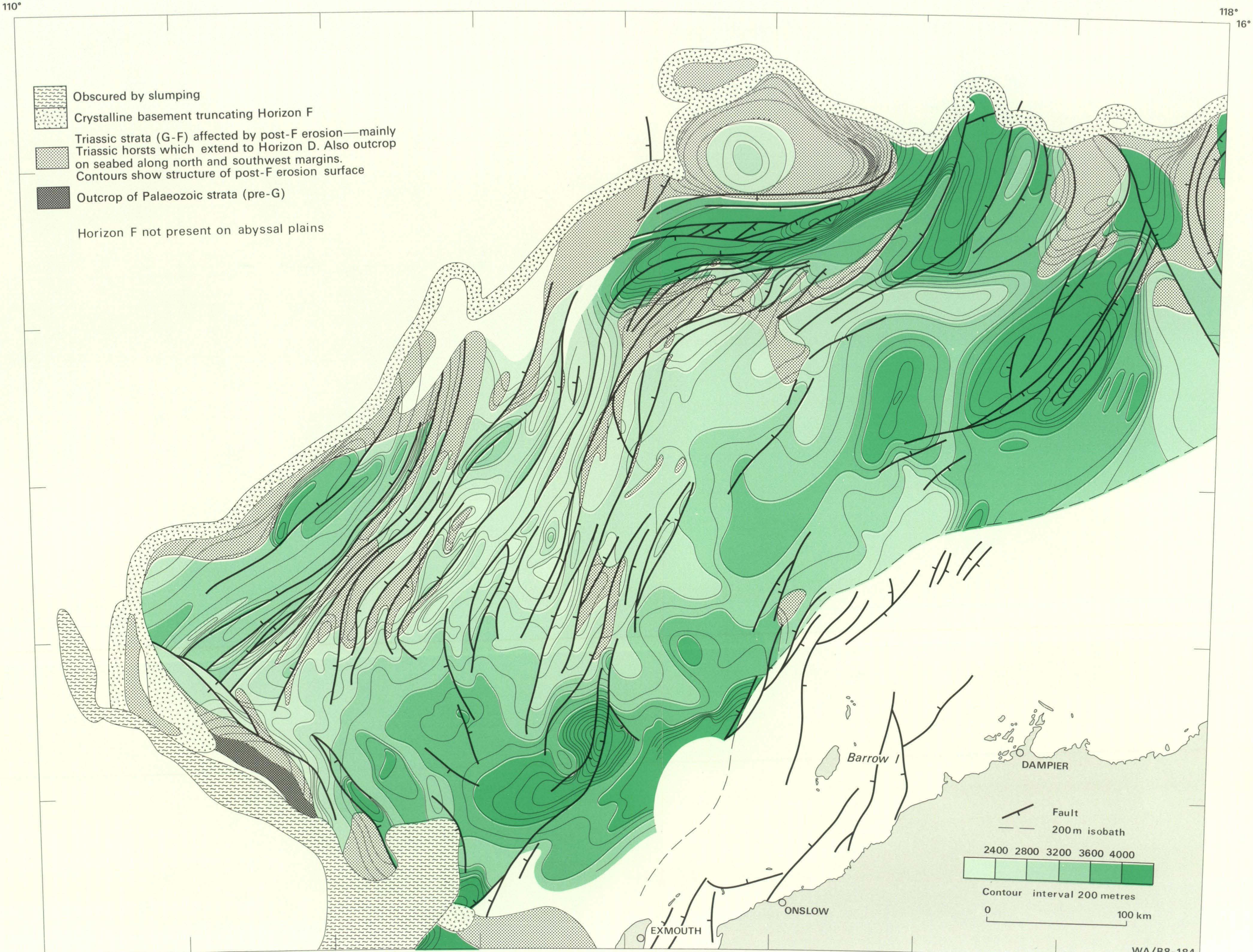
ISOPACHS OF MID-CRETACEOUS STRATA (INTERVAL D-C)



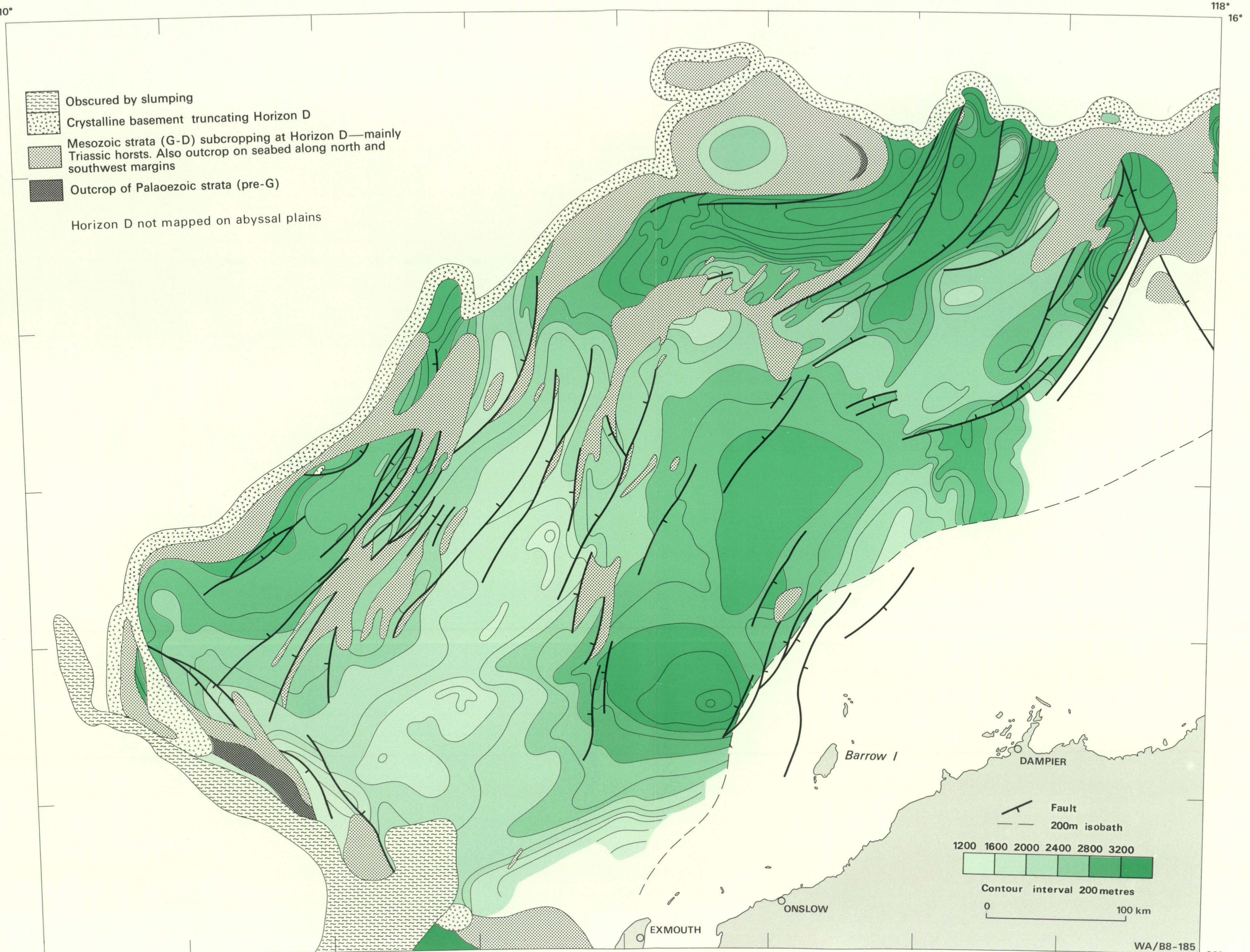
ISOPACHS OF LATE CRETACEOUS TO RECENT STRATA (INTERVAL C-SEABED)



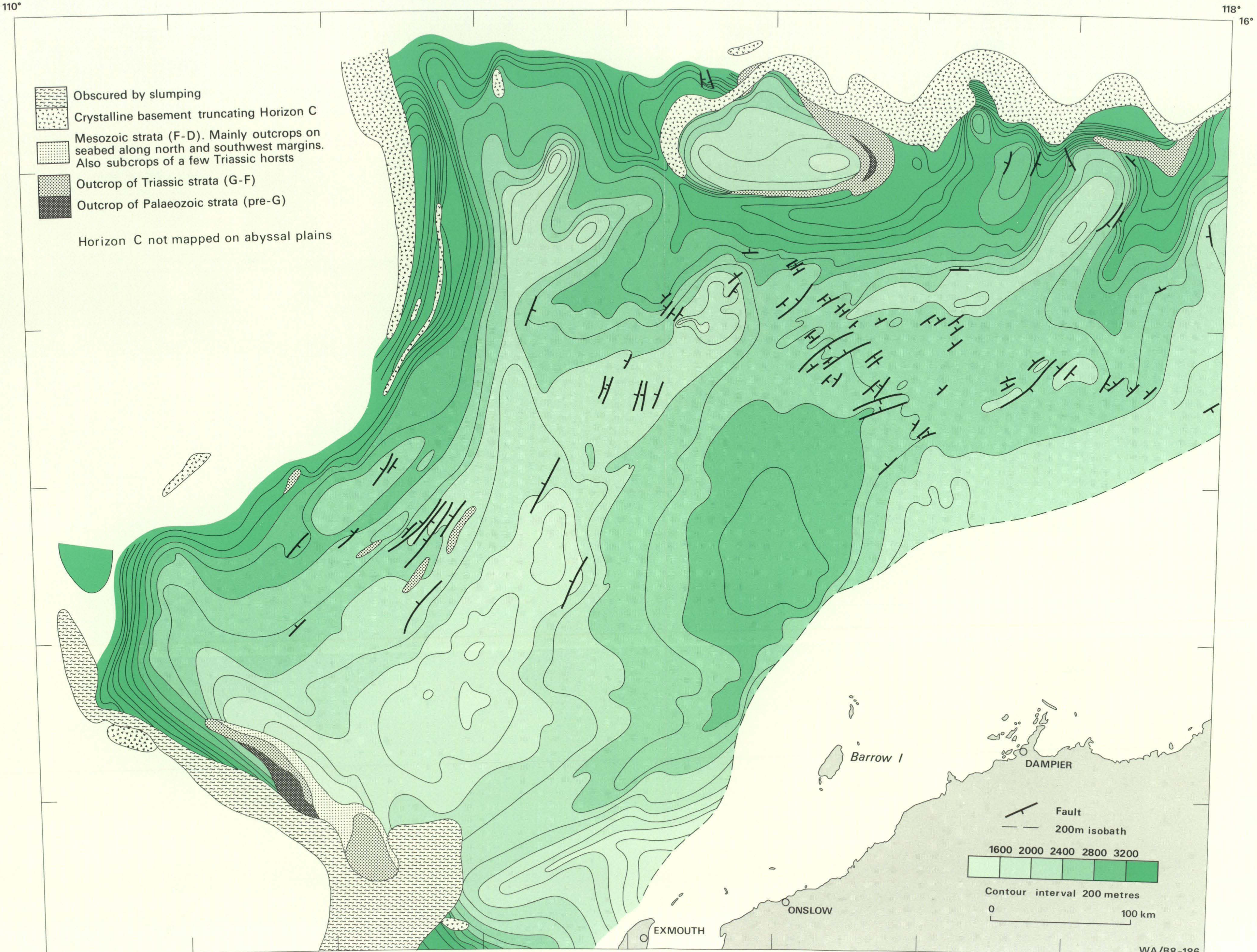
OUTCROP GEOLOGY, SHOWING SEQUENCES AT, OR JUST BELOW, SEA BED



STRUCTURE CONTOURS OF LATE TRIASSIC UNCONFORMITY (HORIZON F)

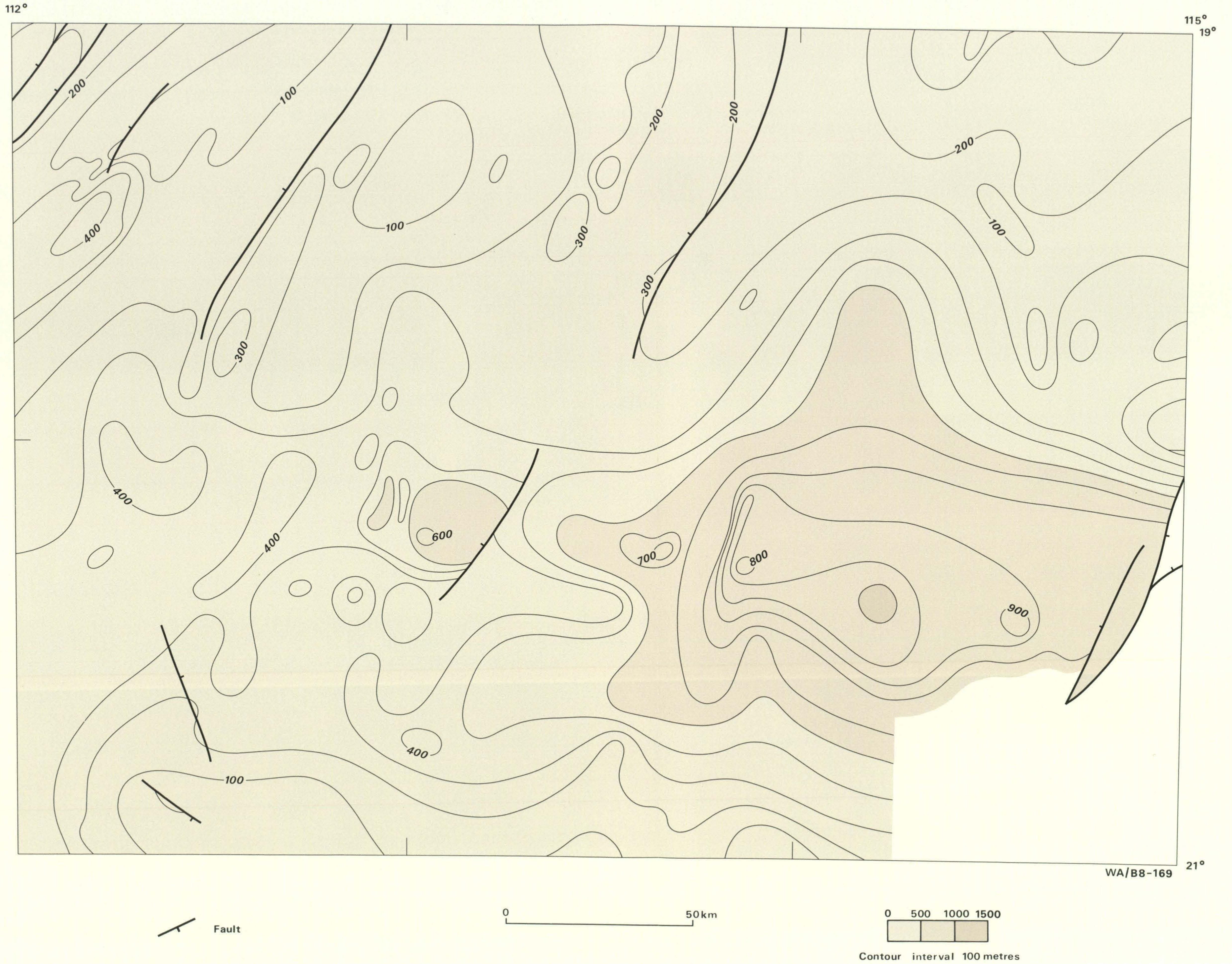


STRUCTURE CONTOURS OF EARLY CRETACEOUS HORIZON (D)



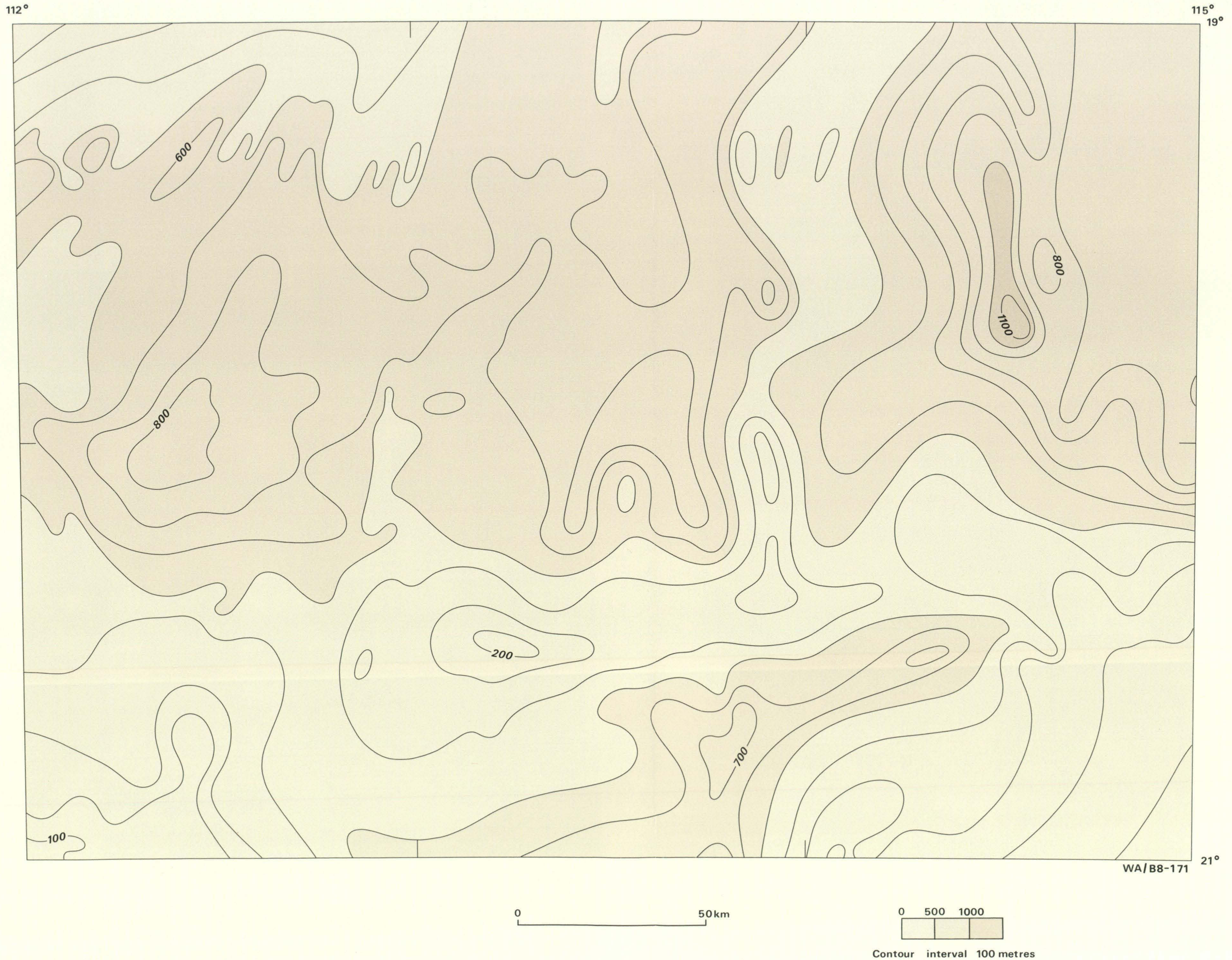
STRUCTURE CONTOURS OF LATE CRETACEOUS HORIZON (C)

ISOPACHS OF THE CENTRAL AREA, LATE TRIASSIC TO EARLY CRETACEOUS (INTERVAL F-D)

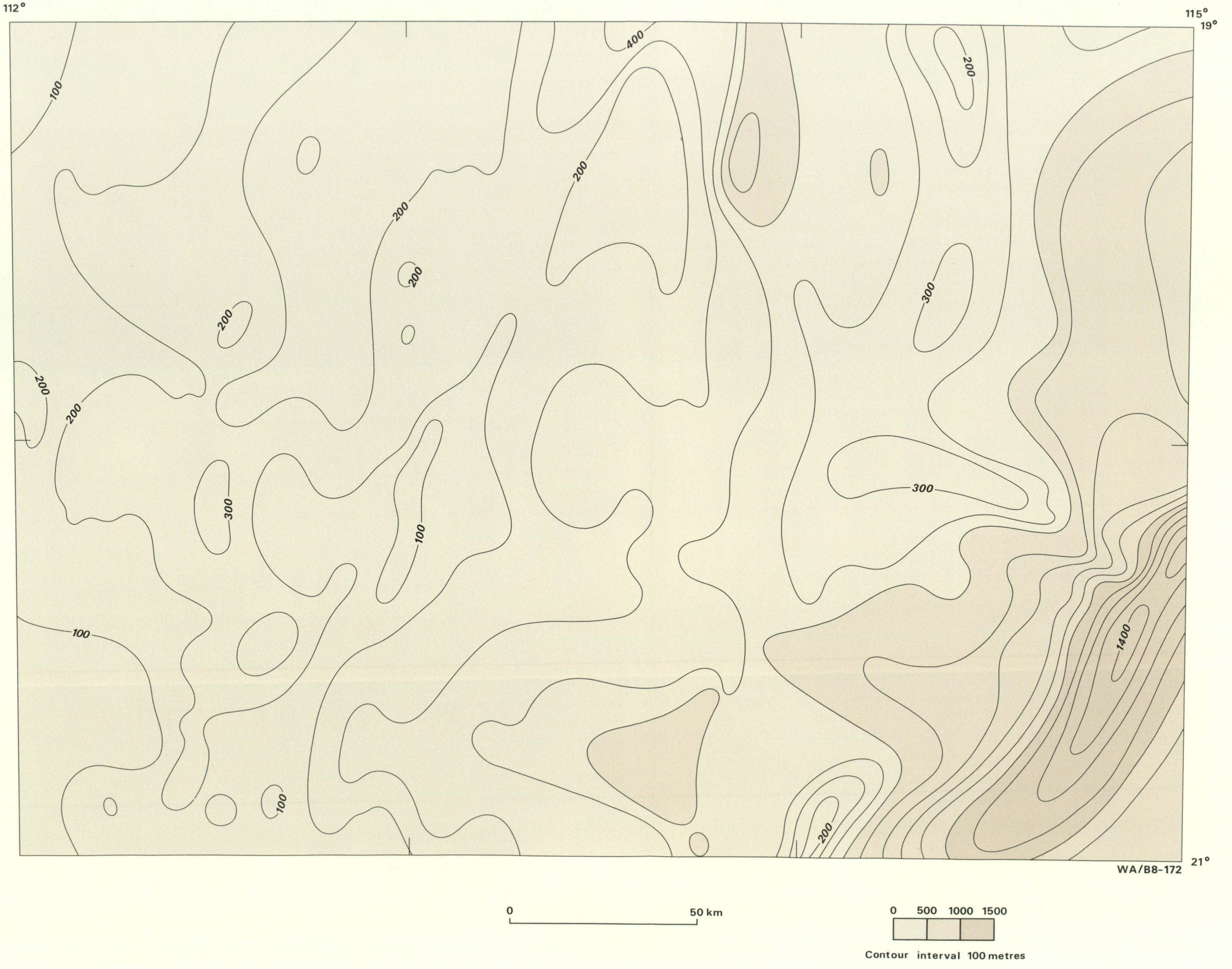


ISOPACHS OF THE CENTRAL AREA, MID-CRETACEOUS (INTERVAL D-C)

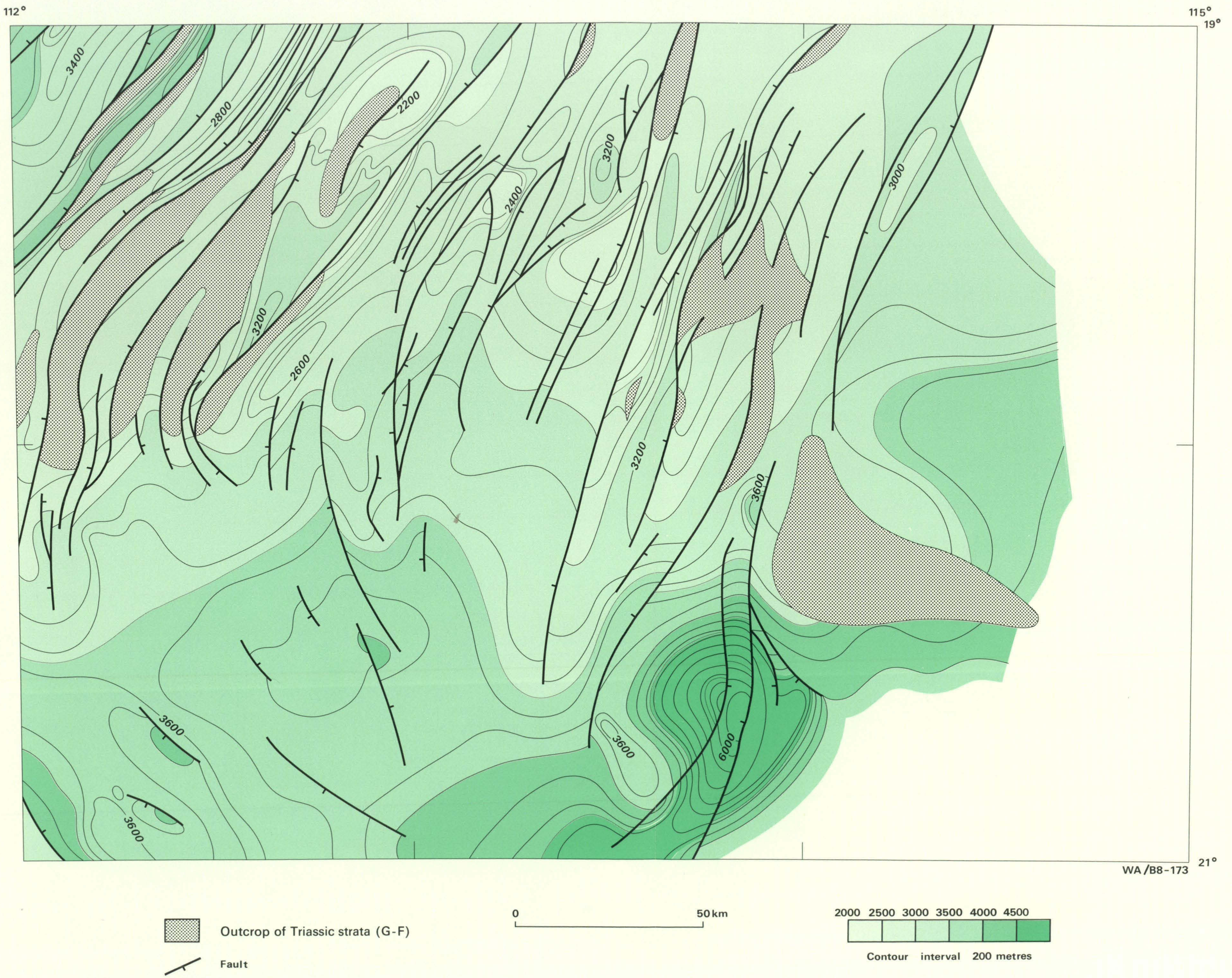
ISOPACHS OF THE CENTRAL AREA, LATE CRETACEOUS (INTERVAL C-B)



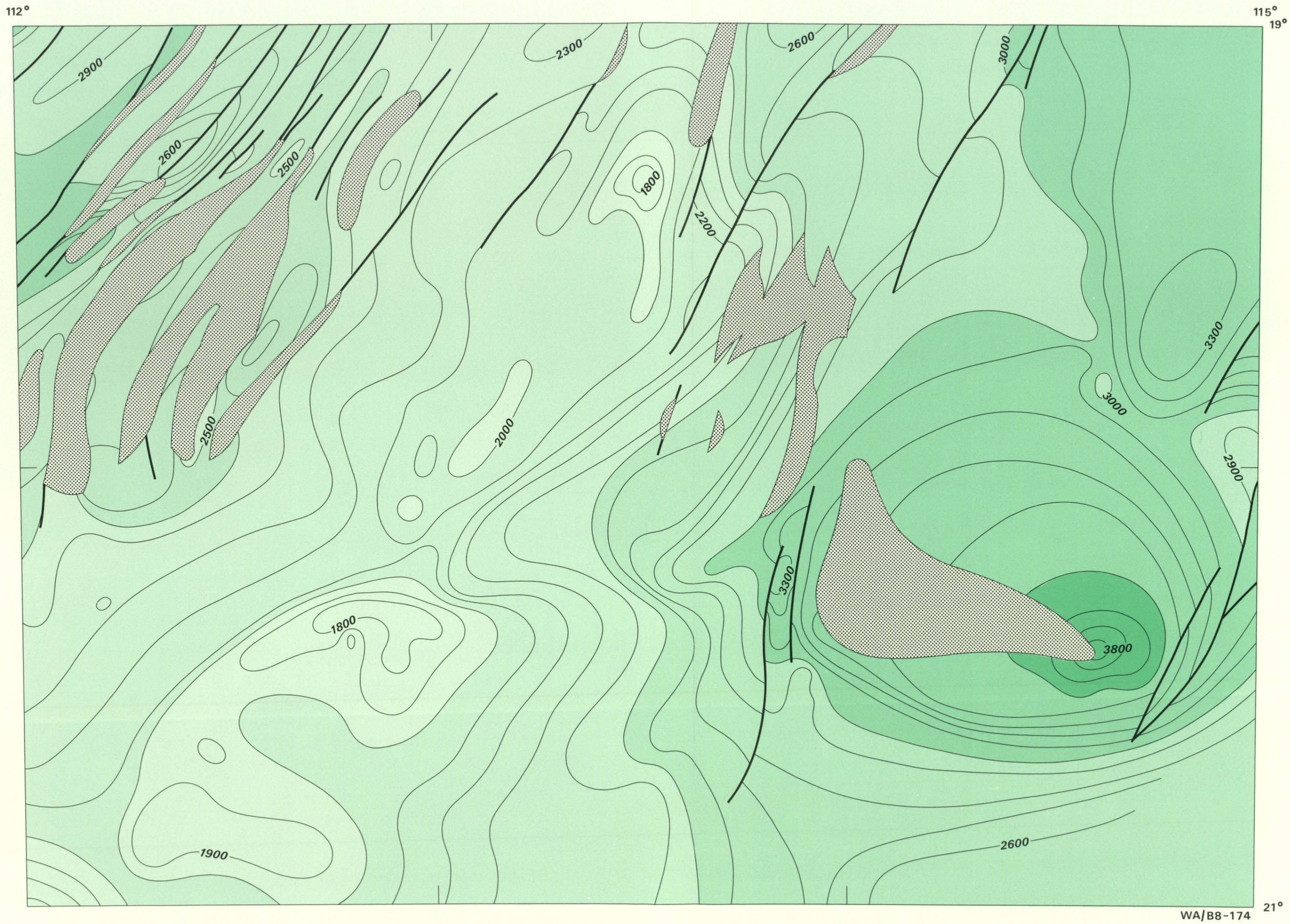
ISOPACHS OF THE CENTRAL AREA, EOCENE (INTERVAL B-A1)



ISOPACHS OF THE CENTRAL AREA, MIOCENE TO RECENT (INTERVAL A1-SEABED)



STRUCTURE CONTOURS OF THE CENTRAL AREA, LATE TRIASSIC UNCONFORMITY (HORIZON F)



Outcrop of Triassic strata (G-F)

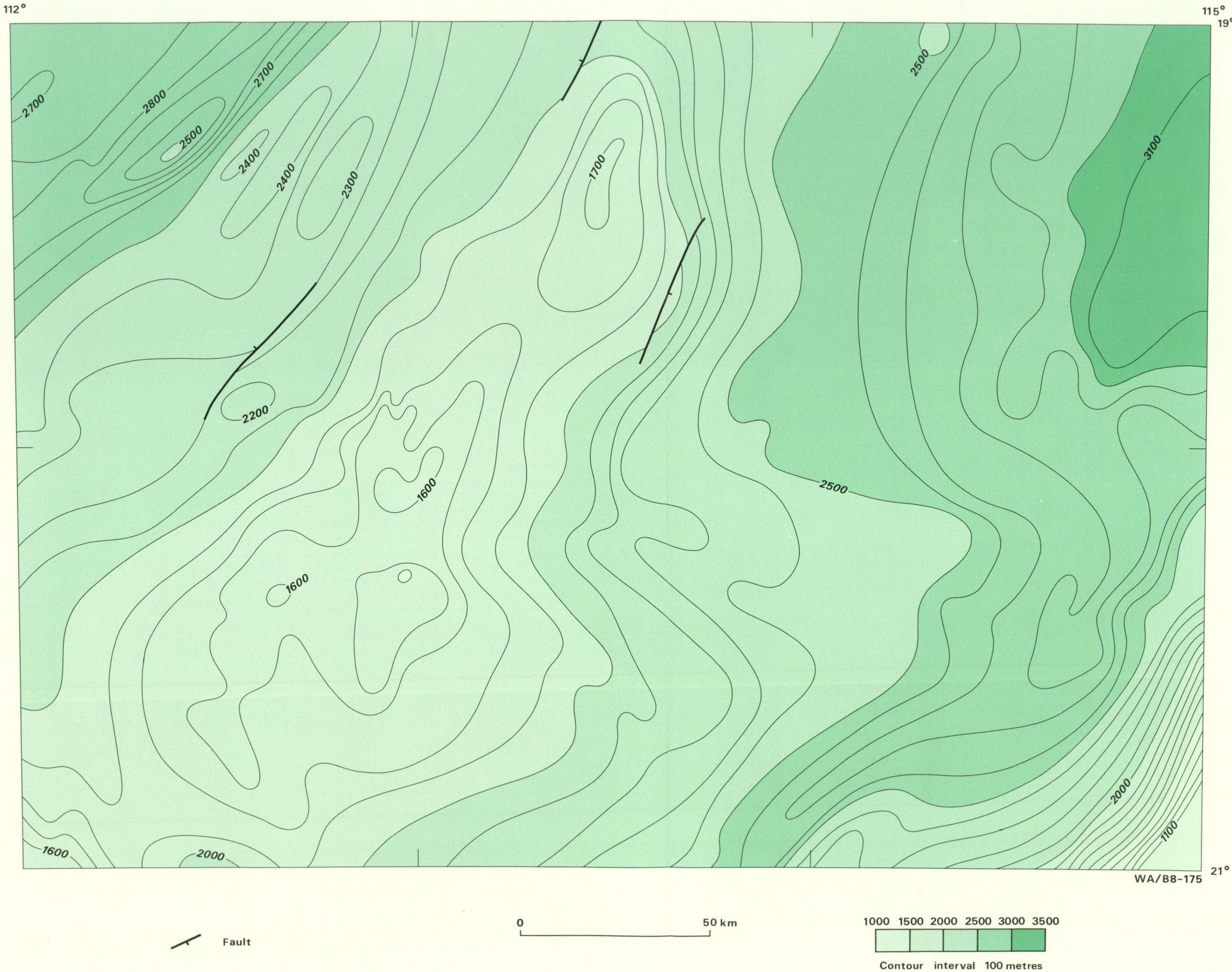
Fault

0 50 km

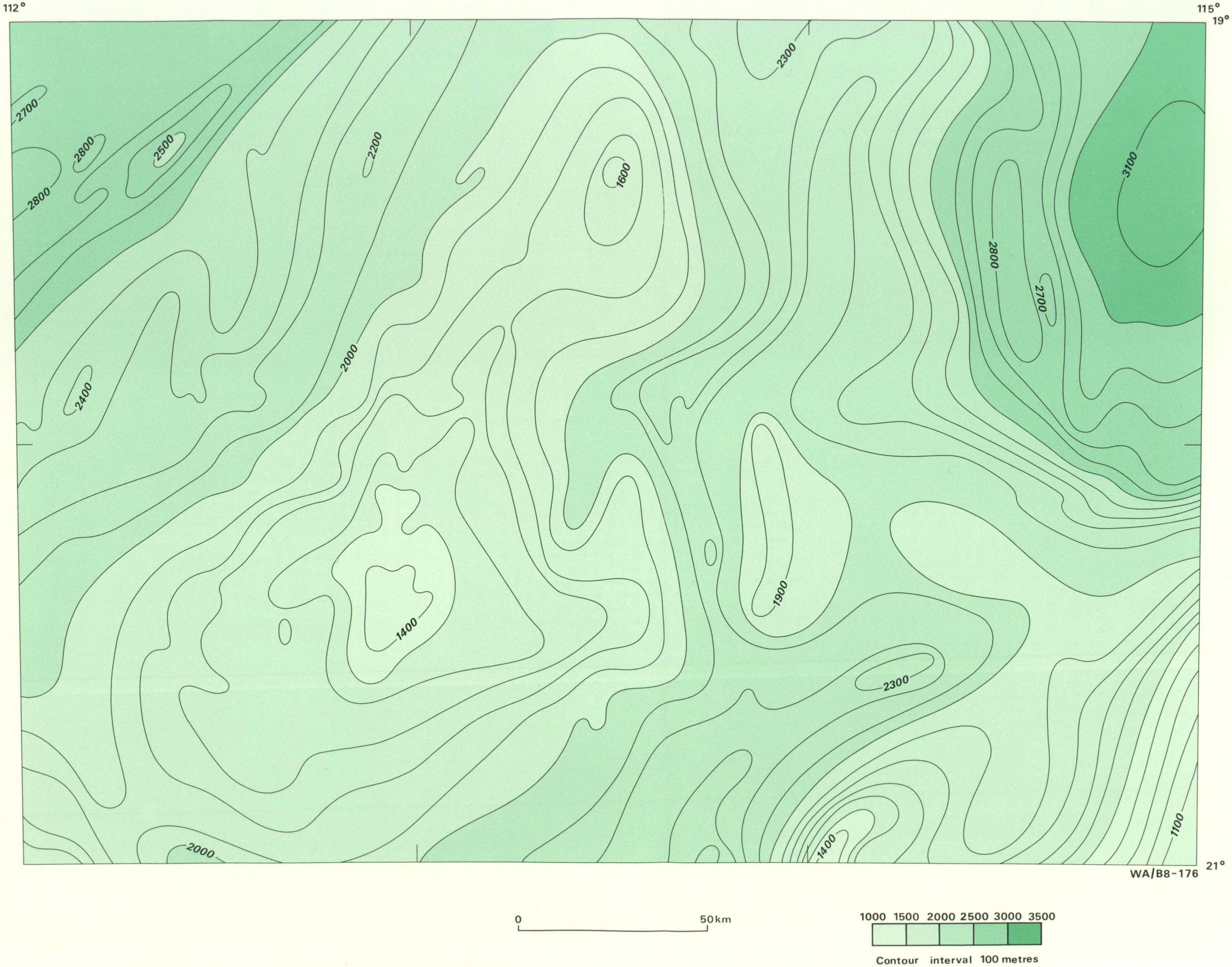
1500 2000 2500 3000 3500 4000

Contour interval 100 metres

STRUCTURE CONTOURS OF THE CENTRAL AREA, EARLY CRETACEOUS HORIZON (D)

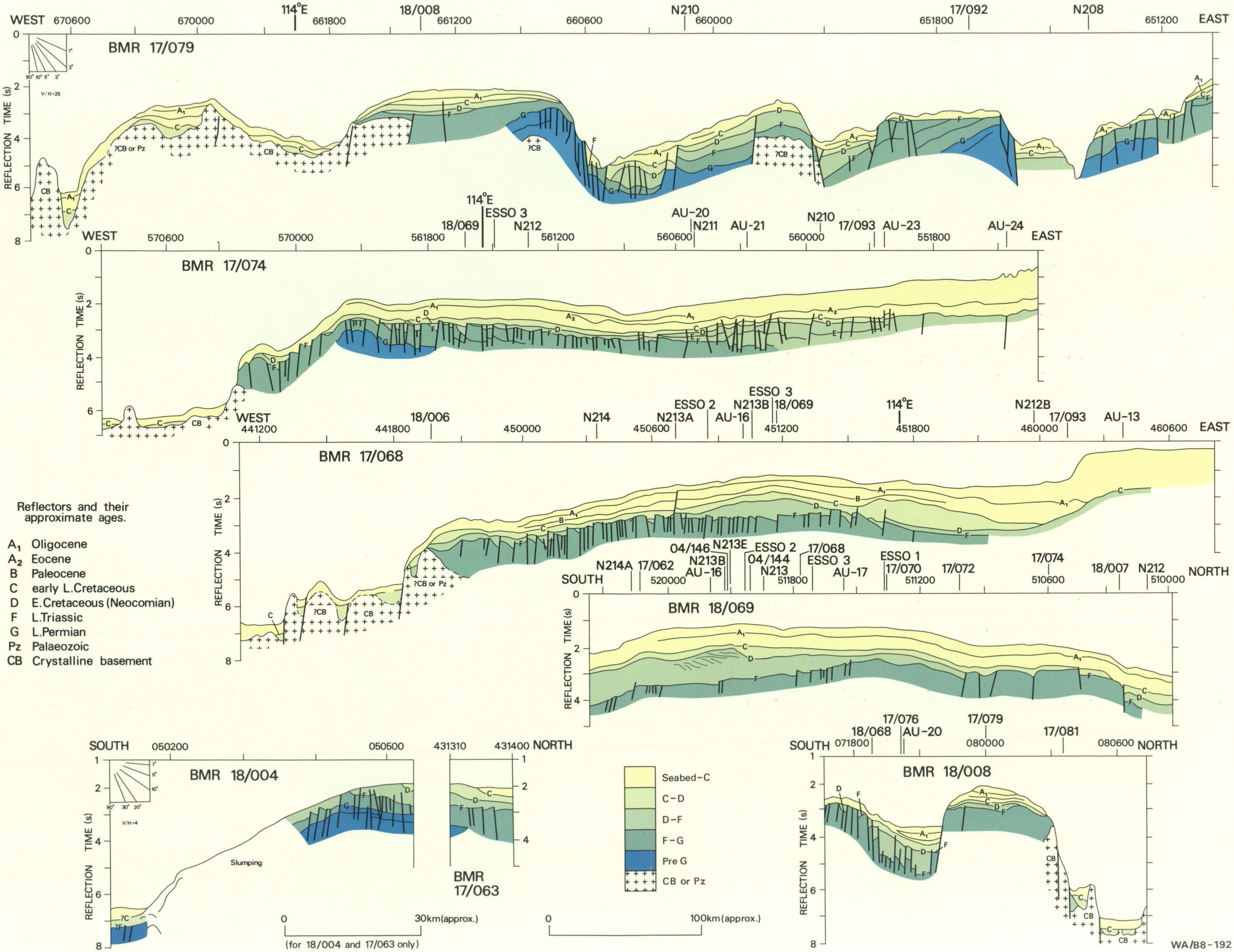


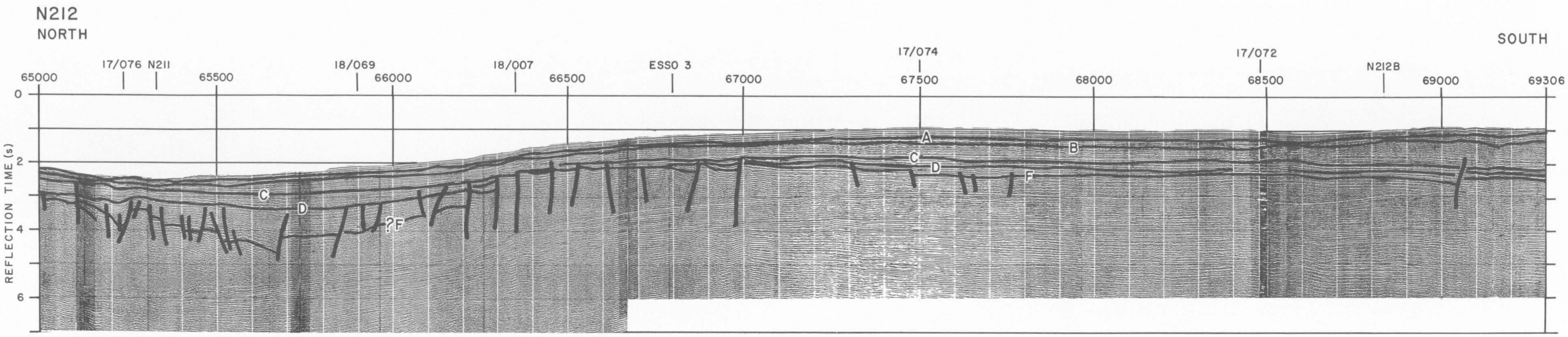
STRUCTURE CONTOURS OF THE CENTRAL AREA, LATE CRETACEOUS HORIZON (C)

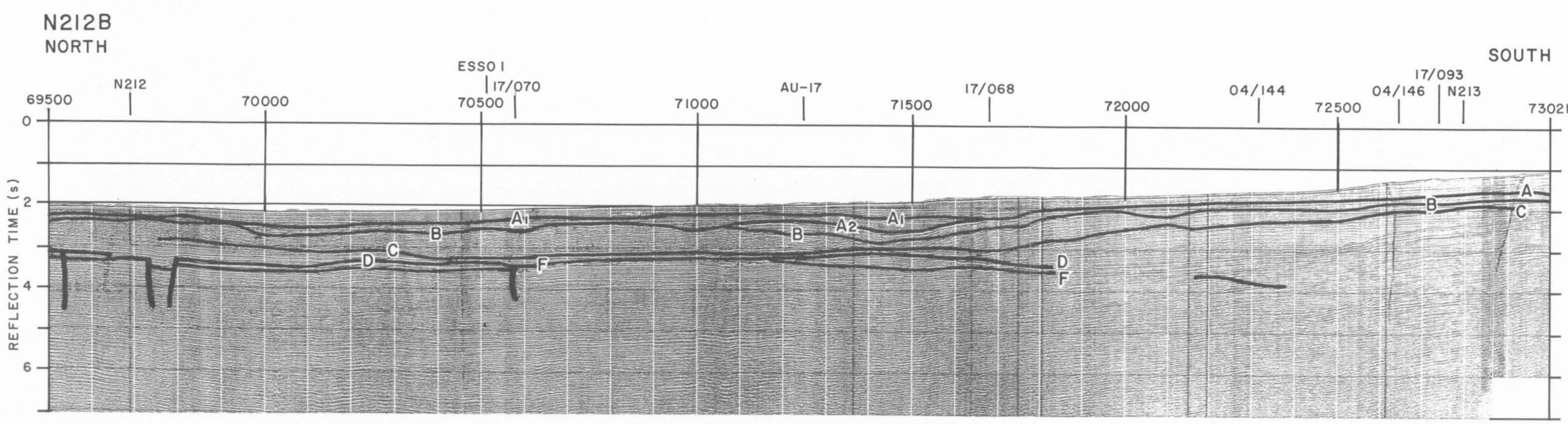


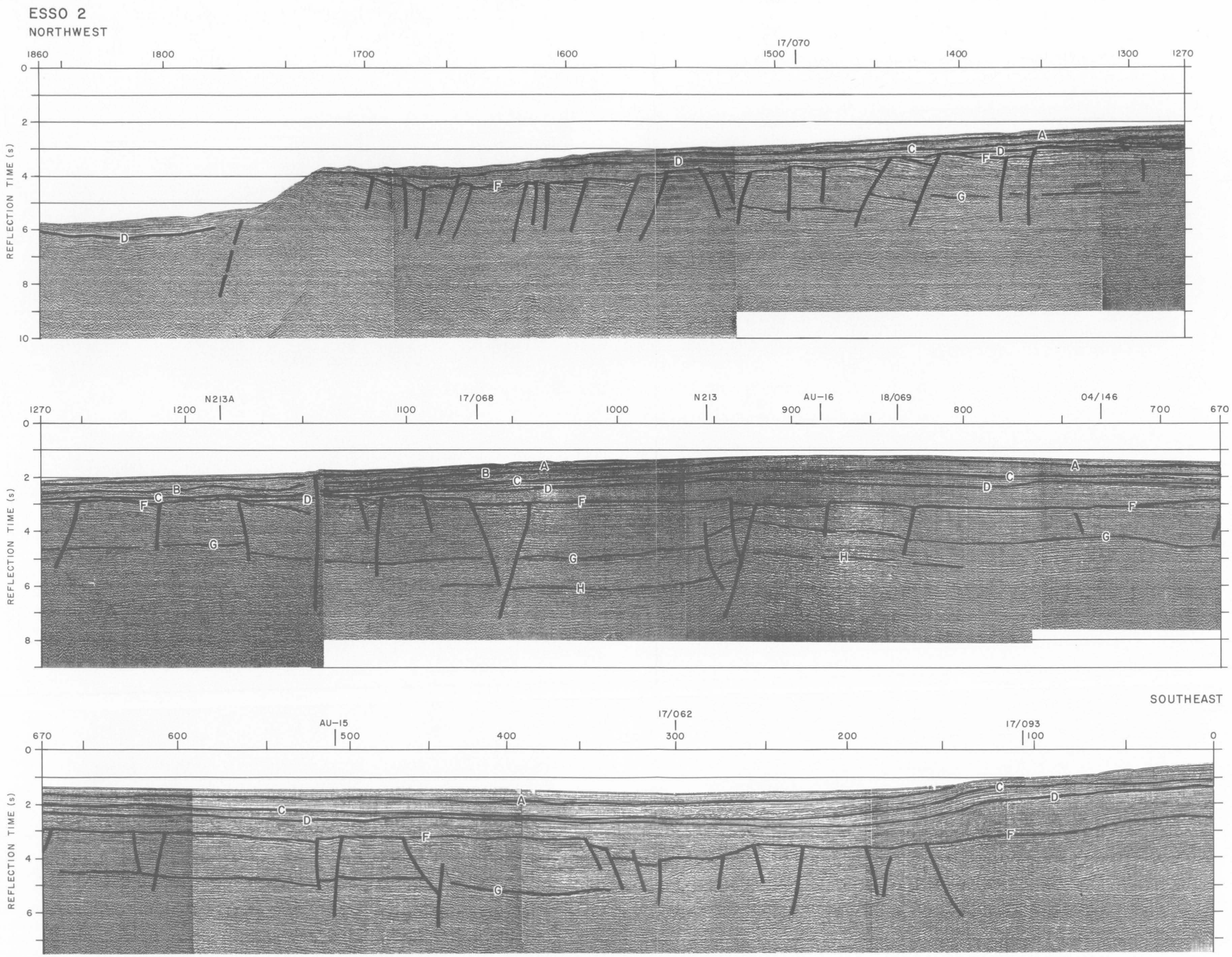
STRUCTURE CONTOURS OF THE CENTRAL AREA, PALEOCENE HORIZON (B)

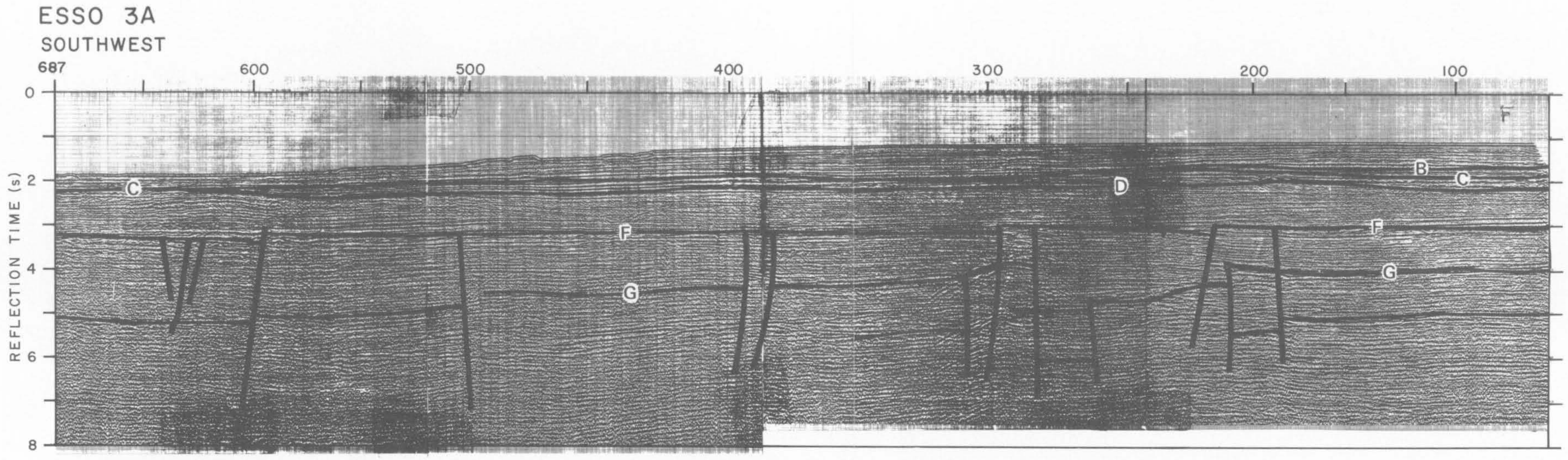
STRUCTURE CONTOURS OF THE CENTRAL AREA, OLIGOCENE HORIZON (A1)

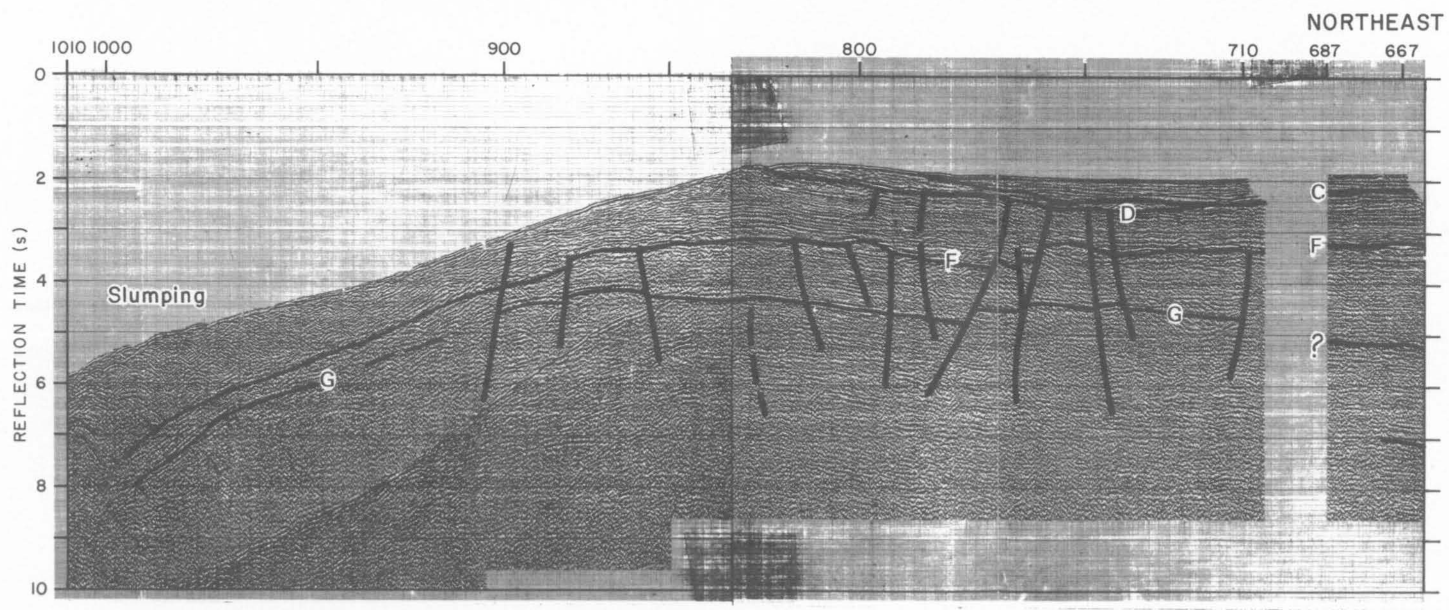

BMR 17/079
WEST
EAST
114°E
18/008
N210
17/092
N208
REFLECTION TIME (s)
V/H=25
?CB or Pz
CB
?CB
BMR 17/074
114°E
18/069
ESSO 3
N212
AU-20
N211
AU-21
N210
17/093
AU-23
AU-24
BMR 17/068
18/006
N214
ESSO 2
N213A
AU-16
N213B
ESSO 3
18/069
114°E
N212B
17/093
AU-13
BMR 18/069
SOUTH
NORTH
N214A
17/062
04/146
N213B
AU-16
N213E
04/144
N213
ESSO 2
17/068
ESSO 3
AU-17
ESSO 1
17/070
17/072
17/074
18/007
N212
Reflectors and their approximate ages.
A1 Oligocene
A2 Eocene
B Paleocene
C early L.Cretaceous
D E.Cretaceous (Neocomian)
F L.Triassic
G L.Permian
Pz Palaeozoic
CB Crystalline basement
BMR 18/004
V/H=4
Slumping
BMR 17/063
0 30km(approx.)
(for 18/004 and 17/063 only)
Seabed-C
C-D
D-F
F-G
Pre G
CB or Pz
0 100km(approx.)
BMR 18/008
18/068
17/076
AU-20
17/079
17/081
WA/B8-192

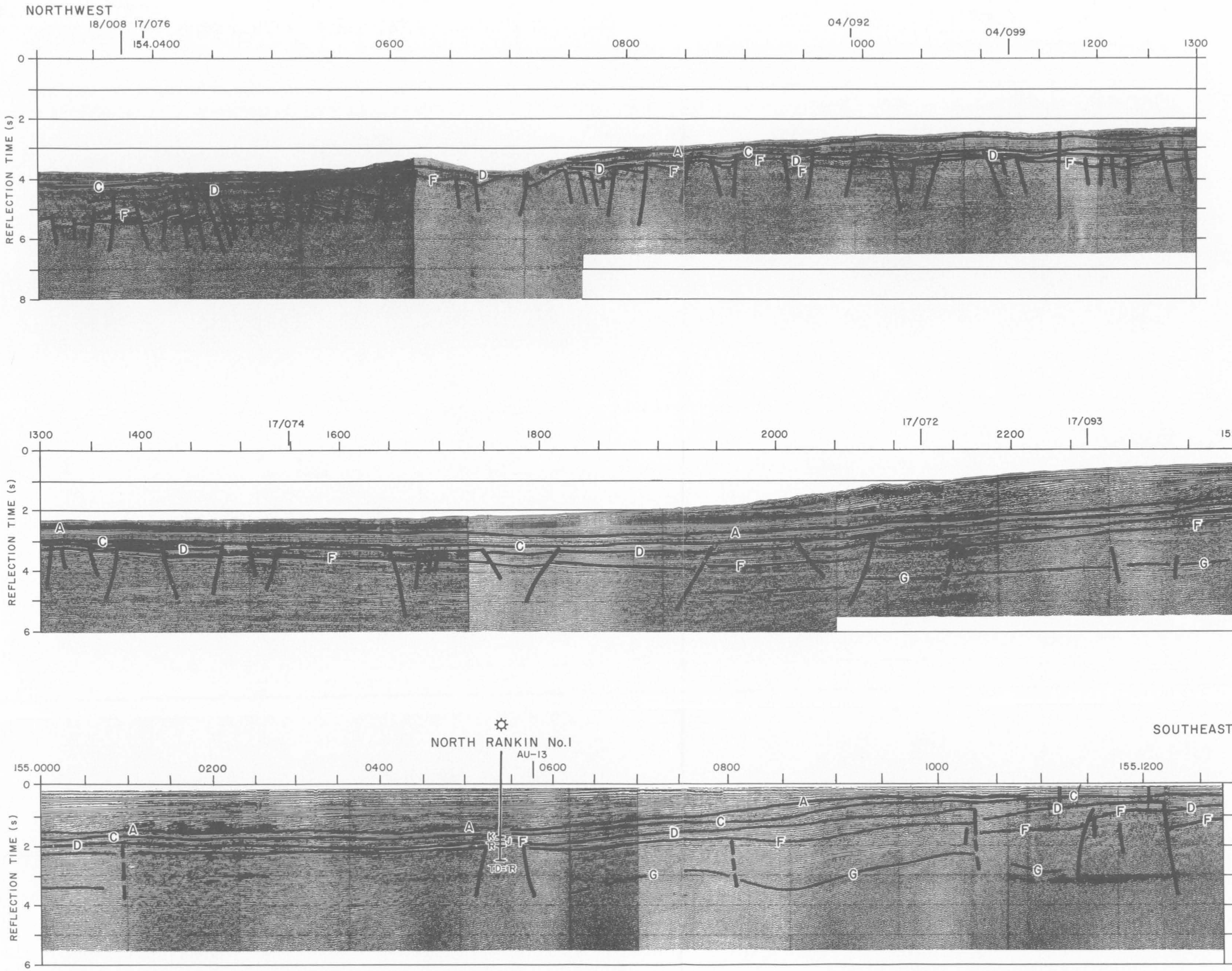

N212
NORTH
SOUTH
17/076 N211
18/069
18/007
ESSO 3
17/074
17/072
N212B
65000
65500
66000
66500
67000
67500
68000
68500
69000
69306
REFLECTION TIME (s)
0
2
4
6
A
B
C
D
F
?F

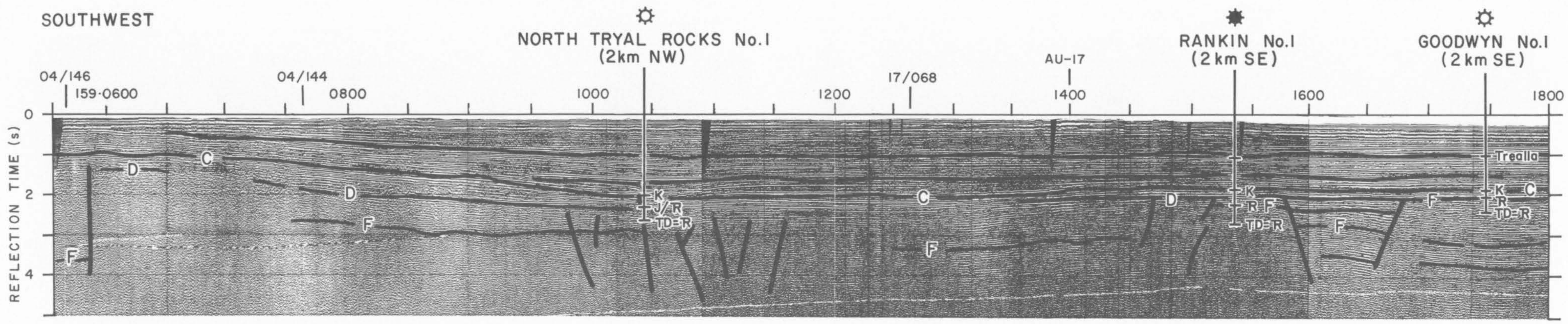

N212B
NORTH
SOUTH
N212
ESSO I
17/070
AU-17
17/068
04/144
04/146
17/093
N213
69500
70000
70500
71000
71500
72000
72500
73021
REFLECTION TIME (s)
0
2
4
6
A
A1
A2
B
C
D
F

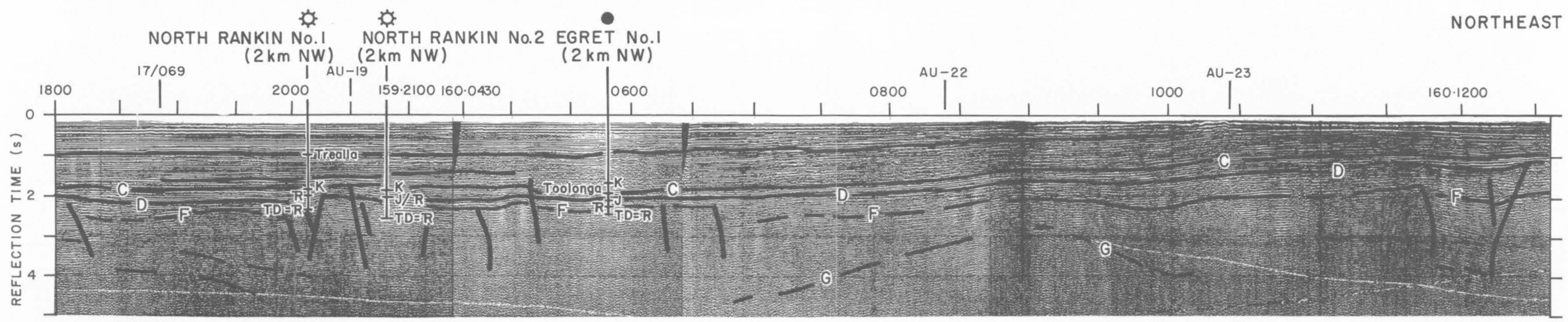

ESSO 2
NORTHWEST
1860
1800
1700
1600
17/070
1500
1400
1300
1270
REFLECTION TIME (s)
0
2
4
6
8
10
A
B
C
D
F
G
H
1270
N213A
1200
1100
17/068
1000
N213
900
AU-16
18/069
800
04/146
700
670
SOUTHEAST
670
600
AU-15
500
400
17/062
300
200
17/093
100
0


ESSO 3A
SOUTHWEST
687
600
500
400
300
200
100
0
2
4
6
8
REFLECTION TIME (s)
C
F
G
D
B
C
F
G


NORTHEAST
1010 1000
900
800
710
687
667
0
2
4
6
8
10
REFLECTION TIME (s)
Slumping
G
F
D
G
C
F
?


NORTHWEST
18/008
17/076
154.0400
0600
0800
04/092
1000
04/099
1200
1300
REFLECTION TIME (s)
0
2
4
6
8
A
C
D
F
1300
1400
17/074
1600
1800
2000
17/072
2200
17/093
155.0000
G
NORTH RANKIN No.1
AU-13
SOUTHEAST
155.0000
0200
0400
0600
0800
1000
155.1200
TD=R


SOUTHWEST
NORTH TRYAL ROCKS No.1
(2km NW)
RANKIN No.1
(2km SE)
GOODWYN No.1
(2km SE)
04/146
159·0600
04/144
0800
1000
1200
17/068
AU-17
1400
1600
1800
REFLECTION TIME (s)
0
2
4
C
D
F
K
J/R
TD=R
R
Trealla


NORTH RANKIN No.1
(2km NW)
NORTH RANKIN No.2
(2km NW)
EGRET No.1
(2km NW)
NORTHEAST
1800
17/069
2000
AU-19
159·2100
160·0430
0600
0800
AU-22
1000
AU-23
160·1200
REFLECTION TIME (s)
0
2
4
Trealla
Toolonga
C
D
F
G
K
J/R
J
R
TD=R