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Marine Geophysical Survey of the North-west Continental Shelf, 1968

Survey 4

by

R. Whitworth

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R. Whitworth

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SUMMARY

From September to December 1968, a marine geophysical survey of the North-west Continental Shelf was carried out by Ray Geophysical Division of Mandrel Industries Inc. under contract to the Bureau of Mineral Resources. About 15,000 miles of combined gravity, magnetic, and seismic reflection traverse were covered over a period of 75 days. Ties were made into previous seismic and gravity work done in the area.

Thirteen gravity and magnetic provinces were delineated by the survey, and six refraction velocity regimes were outlined. The veolcity regimes were shown to coincide approximately with larger groupings of the gravity-magnetic provinces. However, the correlation between the provinces and the underlying geology does not conform with simple consistent theories in all instances.

The preliminary results indicate that on a regional scale the offshore area forms a sedimentary wedge dipping monoclinally towards the north-west. It is unlikely that a basement ridge underlies the edge of the continental shelf. There are indications of a basinal feature in the Browse Island region, but its major development appears to be sub-Tertiary.

Nine major structural trends covering about 40 features were defined upon the continental shelf, of which perhaps four trends were known previously. One major and two minor structures were found in an anomalous area in deep water to the west of Barrow Island. This area appears to have a continental-type crust with a thick development of sediments.

1. INTRODUCTION

The emphasis on oil exploration in Australia has gradually shifted from land to offshore areas over the last few years (Williams, 1968). This trend has been accentuated by the proving of considerable oil and gas reserves in the offshore Gippsland Basin. The results to date indicate that the volume of prospective Palaeozoic sediments offshore is about equal to the volume on land, while the volume of post-Palaeozoic sediments is nearly three times as large offshore (Vale & Jones, 1967), so the trend is expected to continue and possibly accelerate during the next decade.

The Bureau of Mineral Resources (B.M.R.) has now made three large-scale marine geophysical surveys, the first two in the Joseph Bonaparte Gulf/Timor Sea area, and the last over the North-west Continental Shelf. They have been carried out by BMR. to assist in the exploration of the continental shelf, and to introduce and test the feasibility of geophysical methods not previously used on surveys in Australia. The areas covered by these surveys are shown in Plate 1.

The 1965 survey was mainly confined to the Joseph Bonaparte Gulf (Smith, 1966; Geophysical Associates, 1966). Navigation was by the Toran hyperbolic radio-location system which, while accurate, is expensive to install and operate; at distances over 100 miles it operated satisfactorily only during the daylight hours. The seismic reflection system used a spark-array energy source of 14,000 joules. A La Coste and Romberg gimbal-mounted surface gravity meter was installed on the ship and gave a standard deviation of the gravity difference at line intersections of 3 milligals.

The Toran navigation system was replaced in 1967 by a v.l.f. system which, though of lower accuracy, was still adequate and enabled 24-hours-a-day operation to be maintained. As the seismic system had proved successful in 1965, the source energy was increased to 21,000 joules to give greater depth of penetration. Multi-channel magnetic tape recording and a six-channel seismic cable were added. Unfortunately the six-channel cable was lost at sea shortly after the start of the survey, so only single-channel seismic information was obtained for most of the survey. An Askania marine gravity meter on a gyro-stabilised platform gave a slightly improved performance despite the less accurate position and consequent velocity determination. A mean difference of 2.5 milligals was achieved at traverse intersections, equivalent to a standard deviation of 2.8 milligals. Continuous magnetic profiling was carried out using a Varian proton-precession magnetometer with the sensor towed behind the ship and a magnetic diurnal monitor installed at Darwin.

The 1968 marine geophysical survey, discussed in the present Record, covered roughly 140,000 square miles of the continental shelf from Ashmore Reef to Barrow Island. A schematic plan of the location of traverse lines is shown in Plate 2. The area predominantly covered on inferred Mesozoic-Tertiary basin subparallel to the coast and believed to stretch from north of Melville Island to the Rowley Shoals area. The northern part of the 'basin' has been covered by several subsidised seismic surveys and the BMR 1967 marine survey (e.g. Arco, 1966; Arco-Aquitaine, 1967; Jones, 1969). This survey was expected to delineate the 'basin', should it exist this far south, and determine its relation to the Canning Basin and the Onslow Embayment of the Carnarvon Basin. The survey was intended to provide a comprehensive magnetic and gravity coverage of the area as a complement to the seismic data, and was also expected to help in synthesis of previous seismic work done by the B.O.C. of Australia and West Australian Petroleum companies in the area.

As the accurate determination of gravity at sea depends on precise navigation, much effort was expended on fixing the position and velocity of the ship. For example, to achieve an accuracy of one milligal in the gravity results, the ship's speed needs to be known to about 0.1 knot, and latitude to the order of one minute. A satellite doppler navigation system was introduced to give position fixes accurate to the order of 66 feet once every two to three hours, and a pulsed continuous-wave sonar doppler unit was expected to achieve 0.1 knot accuracy in shallow water and a somewhat lower accuracy in deep water when operating off water mass back-scatter. It was thought that v.l.f. derived position fixes would approach an accuracy of about half a mile when tied down to the satellite doppler fixes. Star fixes were taken at dawn and dusk when weather permitted, and radar fixes to land when near to the coast.

The seismic equipment was basically the same as in 1967: a 21,000-joule sparker energy source, a six-channel cable, a single-channel high-resolution cable, and a reserve single-channel cable. Recording was on an Ampex 14-channel FM magnetic tape recorder and visual monitoring was by means of two facsimile wet-paper recorders displaying the long and high-resolution cable outputs. Refraction profiling was added to the seismic work to obtain velocity determinations throughout the survey area. It is hoped that correlation of the refractors with known onshore stratigraphic horizons may be possible. Two air guns with a capacity of 300 cubic inches each and fired simultaneously were provided as an energy source for the refraction shooting and were expected to give greater depth of penetration than the sparker system. Sonobuoys were used as detectors. They were dropped overboard in suitable areas and telemetered data back to the ship as it continued to move on at 10 knots.

A La Coste and Romberg surface marine gravity meter was provided by the contractor for the survey. Unlike earlier La Coste meters which were gimbal mounted, this meter was mounted on a gyro-stablished platform. Corrections for cross-coupling errors were made by a simple analogue computer. Recording was by strip chart pen recorder and a digital magnetic tape system that was also used to record magnetic readings and ship's speed and heading at one-minute intervals.

The magnetometer used on the ship was a Varian proton-precession magnetometer using a phase-lock frequency multiplier to give direct read-out in gammas. The sensor was towed about 600 feet behind the ship to remove it from the magnetic effect of the ship's hull. An Elsec proton-precession magnetometer with strip chart recorder was stationed at Broome to monitor diurnal changes in the Earth's magnetic field. This unit did not function effectively for much of the survey, so most of the diurnal variation corrections will have to be obtained by extrapolation from Port Moresby and Mundaring geophysical observatories.

The Ray Geophysical Division of Mandrel Industries carried out the survey under contract to BMR. The contractor supplied as survey vessel, the M.V. Robray I, a 165-foot offshore supply boat, of a type common in the United States, with a gross tonnage of 200 tons and displacement of over 1000 tons. The geophysical equipment was installed in air conditioned areas of the ship, either in cabins or in a trailer mounted on the deck behind the main superstructure.

The survey lasted from 24 September to 17 December. The work was carried out over three cruises each of about 25 days' duration, using Broome as base. The area was covered moving from north to south. An office v.l.f. monitor and magnetic diurnal monitor were set up in Broome for the duration of the survey. Shortly after the commencement of the second cruise, the only bad storm during the period forced the Robray I to return to port. Fairly heavy seas were encountered for several days on the third cruise, otherwise the weather was generally good and did not significantly affect the survey operations.

Several officers of BMR have been involved in planning the survey and in the reduction and interpretation of results. The author or another officer was on board the ship throughout the survey, as BMR's representative. The contractor's reports of the survey will be issued later (Ray Geophysics, in prep.).

2. GEOLOGY

Geological knowledge of the offshore areas of north-west Australia is only slight. A survey of the several reefs and islands on the continental shelf by B.O.C. of Australia Ltd (1964) showed that all deposits were superficial and of recent origin, mainly cemented beach rock, and were of little value in determining the underlying geology. What knowledge is available is based mainly upon inference from bathymetric data and geophysical surveys over the continental shelf and upon extrapolation from onshore geology.

The continental shelf extends for 100 to 200 miles from the coast, and is marked at its outer edge by a line of shoals, some of which break the surface. Sea floor morphology suggested a basin inshore of the shoals running sub-parallel to the coast (Fairbridge, 1953b). A reconnaissance aeromagnetic survey indicated that up to 30,000 feet of sediments could exist in this basinal zone, and that the line of shoals appeared to be underlain by a structural ridge (Woodside, 1964; Shell Development, 1966a). Several seismic reflection surveys offshore by B.O.C. from 1964 to 1968 confirmed that upwards of 17,000 feet of sediments exist inshore from the Rankin Bank-Scott Reef line, but their age and correlation with onshore deposits is uncertain.

Before discussing the geology of the area in more detail, it is useful to summarise the regional geological setting (see Plate 3). The major geological provinces of north-west Australia are strongly influenced by, and usually orientated along, one of two prominent structural trends or lineaments that are roughly at right angles. In the north, the trends are north-east and north-west, but there is a gradual transition to an easterly and northerly orientation southwards. The Halls Creek Mobile Belt, the west coast of the Kimberley Block, and the inferred offshore basin and outer structural ridge all trend north-east, as does faulting within the Kimberley Block and the eastern margin of the Bonaparte Gulf Basin. The second major trend is exhibited by the north-eastern coast of the Kimberleys, the King Leopold Mobile Belt, the Fitzroy Trough or sub-basin, and the Pilbara Block. Features of a similar trend can be traced across the continental shelf for a considerable distance (Woodside, 1964; B.O.C. of Australia, 1967).

The tectonic trends appear to have been developed in Lower Proterozoic times when the only intense folding, faulting, and metamorphism occurred. Since then the major tectonic activity has been vertical adjustment of basement blocks by faulting along reactivated Lower Proterozoic fault lines. Most deposition has been in intracratonic basins bordering the older unstable areas. The basins are generally broad and asymmetric, controlled by hinge line faults and basement irregularities.

Several geological or structural units bound the survey area on the landward side, but the extent to which they encroach upon the continental shelf in uncertain (Plates 3 and 4). Their sedimentary and tectonic history are outlined in more detail below, followed by a discussion on the inferred geology of the shelf area. Although not always specifically mentioned, Condon (1964, 1967), Fairbridge (1953a, 1953b), Geological Society of Australia (1962), McWhae et al. (1958), Reynolds et al. (1963), Ryan (1965), Veevers (1967), Veevers and Wells (1961) and many B.O.C. of Australia reports have been heavily drawn upon.

Kimberley Block

The Kimberley Block covers an area of 60,000 square miles, and consists of sub-horizontal Upper Proterozoic and undifferentiated Proterozoic sediments and volcanics. The Palaeozoic-Mesozoic Bonaparte Gulf Basin bounds it in the north-east, but its north-west boundary has not yet been adequately defined. It is bounded in the south-east and south-west by highly metamorphosed rocks of Lower Proterozoic age.

The Upper Proterozoic sediments were unconformably deposited upon the Halls Creek Metamorphics of presumed Lower Proterozoic age when the area sank to become a nuclear basin. About 8000 feet of an arenite-volcanic sequence was laid down in lower Upper Proterozoic times, followed by tillite, dolomite, siltsonte, and arenite in the upper Upper Proterozoic. The volcanics and tillites are found only in the west. At the end of the Precambrian the region was raised and deeply dissected. Possibly Antrim Plateau Volcanics were extruded over some of the Block, but only small areas remain in the north-east.

Since Precambrian times the Block has been tilted and has risen and sunk, but actual deformation is slight. The rocks are gently folded into two broad basins. Adjacent to the mobile belts, folding is intense, but faulting is more prevalent than folding. In places, faults and jointing run for tens of miles. The fault trends are parallel to the bounding mobile belts. The majority of faults developed in the Precambrian, probably during the Lower Proterozoic, with reactivation in later times.

King Leopold Mobile Belt

The Canning Basin is separated from the Kimberley Block by a belt of highly metamorphosed, faulted, folded, and intruded rocks that form the King Leopold Mobile Belt. The belt covers an area of about 20,000 square miles and runs north-westerly from near Halls Creek to Yampi Sound; it may extend out across the continental shelf with a more westerly trend.

The oldest rocks exposed are Lower Proterozoic geosynclinal rocks of predominantly greywacke type with some carbonates and volcanics in a highly metamorphosed state, called the Halls Creek Metamorphics. The total thickness of strata is unknown. The rocks have been intruded by dolerite and gabbro, followed by the

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large-scale granitic intrusions of the Lamboo Complex and granitisation. Intrusion does not affect the overlying King Leopold Formation of Upper Proterozoic age. Considering the degree of folding and metamorphism, the Halls Creek Metamorphics and the granites are placed in the Lower Proterozoic. Isolated inliers of probably Upper Proterozoic rocks have been found in fault zones.

The axes of folding and major faults run parallel to the length of the Mobile Belt.

Canning Basin

The Canning Basin has a land area of 150,000 square miles, and may extend a considerable distance to seaward over the continental shelf. The Basin is bordered by the King Leopold Mobile Belt and Pilbara Block in the north-east and south-west respectively, but its margin is ill-defined in the south-east. Three major subdivisions may be distinguished with the basin: (a) Fitzroy Trough or sub-basin; (b) Broome Platform; and (c) Kidson Basin or sub-basin. Aeromagnetic and gravity surveys have shown several depressions within the platform area, much of which is not well known.

The basement appears to be predominantly Lower Proterozoic metamorphic and igneous rock except in the north-east, where sediments of Upper Proterozoic age occur. About 3000 feet of Upper Cambrian to Ordovician marine limestone, dolomite, shale, and sandstone occur over much of the Basin, locally thickening to over 6000 feet in sub-basins in the south-west. Devonian marine organic reefs and associated sediments interfinger with conglomerate, sandstone, calcilutite, and limestone breccia to form deposits up to 3000 feet thick within the Fitzroy Trough, followed by 6000 feet of Carboniferous marine calcarenite, sandstone, and siltstone. Until recently Devonian and Carboniferous deposits were believed to be absent elsewhere in the Canning Basin. However, drilling by West Australian Petroleum Pty Ltd (WAPET) has recently revealed a claystone-salt sequence followed by red sandstones and anhydritic limestone in the south (WAPET, 1966d) thickening to over 4000 feet towards the Kidson Basin (WAPET, 1966c). The deposits are tentatively interpreted as Silurian to Middle Devonian in age. Possibly peneplanation had removed Devonian deposits from elswhere in the south before the widespread deposition of Permian tillite, marine greywacke, conglomerate, limestone, and shale, and fresh water sandstone. About 3000 feet of these sediments are found in the south, thickening northwards to 14,000 feet in the Fitzroy Trough. Triassic mudstone and sandstone 1000 feet thick followed by 2500 feet of Jurassic-Cretaceous conglomerate, sandstone, siltstone, and shale were then laid down over most of the Canning Basin. Cainozoic deposits are mainly superficial.

The major structural features of the Canning Basin are the result of graben subsidence in the north, with less important block uplifts and tilting elsewhere. The main faulting is in a north-westerly direction in mobile zones along the sides of the Fitzroy Trough. Step-faulting has resulted in shelves at the edges of the main graben. This trend was maintained from the Proterozoic to the end of the Palaeozoic. Broad folding in the Mesozoic, however, was more east-west, with numerous associated north-south faults. As in other basins in the region, the folding has been ascribed to differential basement uplift rather than compressive forces.

Pilbara Block

An extensive area of sedimentary, metamorphic, and igneous rocks lying on the southern edge of the Canning Basin forms the Pilbara Block or Complex. Some authors have noted a threefold subdivision in the Precambrian of Western Australia (e.g. Fairbridge, 1953a). The uppermost Nullagine succession of unmetamorphosed conglomerate and sandstone, which is often glauconitic with thin dolomitic limestones and pyritic shales, overlies the Pilbara Block in part. It is believed to be Lower Proterozoic in age (Ryan, 1965), and is not considered further here.

The Pilbara Block proper consists of two fairly distinct successions. One is predominantly a volcanic facies with thin, metamorphosed conglomerates, dolomite, shale, and siltstone. The other consists mainly of clastic deposits (grit, quartzite, and shale). On the NULLAGINE 1:250,000 map area, these successions appear to be separated by an unconformity with the clastic facies overlying the volcanic facies (the Mosquito Creek and Warrawoona Systems respectively of Fairbridge, 1953a). To the west on the ROEBOURNE map area, however, similar successions are found to be contemporaneous, and the two facies types are interpreted as a horizontal facies variation (Ryan, 1965). Both successions have been placed in the Pilbara System of Archaean age (Ryan, 1964).

The volcanic sequence is found predominantly in tightly folded belts around the peripheries of the extensive granitic domes, while the clastic sequence is mainly in less intensely folding basinal areas. Metamorphism is restricted mainly to the margins of the granitic domes and is generally of low grade. Wide zones of gneiss and metasomatised country rock surround the domes. Throughout the area, the volcanic succession is folded and strongly affected by the large granite domes while the clastic succession is little altered or intruded. Despite this apparent correlation, there is no direct evidence to suggest that the granite intrusions preceded deposition of the clastic sequence.

Carnarvon Basin

The Carnarvon Basin is an epicontinental feature of Proterozoic to Tertiary age, with a landward area exceeding 50,000 square miles. It is bounded by the Pilbara Block to the east, but its seaward extent is unknown. Shallow basement ridges separate the Basin from the Perth Basin to the south. It is postulated that a basement ridge separates the inferred offshore basin from the Carnarvon Basin, but there is no direct evidence for this. Several sub-basins occur within the main basin.

Proterozoic to Palaeozoic sandstones up to 8000 feet thick are found in the southern part of the Basin, and may be overlain by Silurian limestones. Marine sandstone, limestone, shale, and conglomerate of Middle Devonian to Lower Carboniferous age overlie the Lower Palaeozoic sediments. There is more than 7000 feet of these apparently conformable deposits. During the Permian an unconformable sequence of glacial deposits about 4500 feet thick was laid down and was succeeded by about 1000 feet of limestone, sandstone, and greywacke, followed by 4000 feet of alternating carbonaceous shales and sub-greywacke, and finally by 2500 feet of sandstone with some siltstone. Relatively thin marine Cretaceous sediments are the major Mesozoic deposits except in the far north, where a thick sequence of Jurassic clastics was deposited in the Onslow sub-basin.

Barrow Island and its surrounding area is in the Onslow Embayment or sub-basin, which is separated from the main Carnarvon Basin by the Yanrey and Chinty basement ridges (Spence, 1961). Recent regional geological studies, intensive marine surveys, and drilling have shown that the northernmost part of the Carnarvon Basin is primarily a Mesozoic province with a separate history from the predominantly Palaeozoic provinces to the south (WAPET 1964, 1965, 1966b), and has an affinity with the offshore Mesozoic-Teritary depression extending along the coast to the Sahul Shelf and beyond. The geological section typically contains 100 to 1000 feet of Tertiary calcarenite, 2000 to 5000 feet of Cretaceous siltstone with minor calcilutite and limestone, and upwards of 5000 feet of Jurassic sandstone and siltstone (WAPET 1967a, 1967b).

The Palaeozoic sediments were laid down in a series of structurally controlled basins in the Precambrian surface. Differential sinking of the basins continued during deposition. All structures point to large-scale downwarping of basement blocks, with no evidence of compressive forces.

The Shelf area

As mentioned in the introductory remarks to the geology, interpretation of the offshore geology is primarily based upon a correlation of bathymetric features, seismic and aeromagnetic surveys, and similarity with continental features. Some stratigraphic evidence is available from the Barrow Island, Ashmore Reef, Legendre, and Dampier wells, but this is sparse control for an area that stretches almost 1000 miles.

The outer edge of the continental shelf is bounded by a series of shoals exposed at Rowley Shoals, Scott Reef, Ashmore Reef, and Sahul Banks. Offsets in the bathymetric contours occur south of Ashmore Reef and north-east of Sahul Banks, which could be caused by faulting (see Plates 4 and 6). In the south the bathymetric rise appears to correspond to the anticlinal trend of the Rough Range-Barrow Island structure. An aeromagnetic survey by Woodside (1964) has been interpreted as indicating a basement 'high' from Rowley Shoals to the Ashmore Reef area. Ashmore Reef itself corresponds to a structural 'high' at the base of Tertiary level. Van Andel and Veevers (1965) believe the bathymetric ridge to have been exposed for much of the Tertiary era.

However, the Ashmore Reef well shows that a thickness of sediments in excess of 11,000 feet was laid down fairly continuously throughout the Mesozoic and Cainozoic eras. The apparent absence of Lower Cretaceous or appreciable Jurassic sediments sets the Ashmore Reef area apart from both Timor and the Carnarvon Basin (B.O.C. of Australia, 1968b). The well results show that intra-section volcanics of Jurassic age are the probable cause of the interpreted magnetic basement 'high'. The well was abandoned at 12,843 feet below sea level while drilling in Jurassic sediments, so magnetic basement must be below that depth and could be much deeper. The magnetically defined basement ridges under Scott Reef and Rowley Shoals may have a similar intra-sediment origin. There is no information on where the transition occurs from anticlinal ridge as found in the south to sedimentary 'thick'as found at Ashmore Reef. The whole concept of a basement ridge paralleling the edge of the continental shalf may be erroneous.

The shelf dips gently seaward from the coastline for about 100 miles before dipping fairly steeply to depths of the order of 200 to 300 fathomas, then rises abruptly along the line of shoals about 150 miles from shore (Plate 6). This depression on the shelf inshore of the shoals has been interpreted as corresponding to a sedimentary basin (Fairbridge 1953b, Boutakoff 1963, Veevers 1967). Surveys by B.O.C. of Australia (1965, 1966, 1967, 1968c) confirm the existence of a considerable development of sediments in this zone. The sediments are inferred to be Mesozoic to Tertiary in age though there is no direct evidence to indicate the age of the deeper section. On a regional scale the sediments form a wedge, thick along the edge of the shelf and thinning towards the shore. The southern extremity of the wedge appears to be the Onslow Embayment of the Carnarvon Basin, while the northern end is to the north of Cobourg Peninsula (Shell Development, 1966b). Apart from the aeromagnetic interpretation (Woodside, 1964) which should be considered doubtful following completion of the Ashmore Reef well, there is little direct evidence for a sedimentary basin offshore, and sedimentary wedge would be a better term.

Veevers (1967) has postulated that an offshore basin exists that is co-extensive onshore with the Canning Basin and Bonaparte Gulf Basin. It would seem simpler, however, to consider the Canning Basin and offshore area as the former is predominantly Palaeozoic with fairly thin, uniform, flat-lying Mesozoic deposits, while the latter shows a considerable thickening in the Mesozoic-Tertiary section in a north-westerly direction.

The results of an aeromagnetic survey by WAPET (1966a) suggest that the onshore features of the Canning Basin may continue offshore for some distance, but presumably the features must dip beneath the sedimentary wedge. The Woodside (1964) aeromagnetic survey was interpreted as indicating an offshore extension of the King Leopold Mobile Belt with only a thin sedimentary cover draped over it. WNW arches and faults in the Rankin Bank area also suggest an extension out to sea of the onshore tectonic trends (B.O.C. of Australia, 1967). A series of bathymetric rises paralleling the land trends can be followed across the continental shelf (van Andel et al., 1961). All of these tend to negate the ideal of a basinal feature paralleling the coastline.

The relation between the offshore area and the Proterozoic Kimberley Block is ill-defined. A rise in the average Bouguer anomaly value along the north-west margin of the Block suggests there could be a basement rise at depth (Whitworth, in prep.). Whether or not Proterozoic sediments extend beyond the ridge has not been determined. Similarly the boundary between the Pilbara Block and the shelf area has never been defined.

3. PREVIOUS GEOPHYSICS

Some surveys have been carried out by B.O.C. of Australia, WAPET, and Woodside within the area of interest. Most of the work by WAPET has been confined to the onshore Canning Basin and areas around Onslow and Barrow Island. The offshore surveys by B.O.C. of Australia started as reconnaissance surveys in the shoal and reef areas and have gradually concentrated around Rankin Bank and Ashmore Reef, culminating in the drilling of the Ashmore Reef, Legendre, and Dampier wells.

Aeromagnetic surveys

A reconnaissance survey by Woodside (Lakes Entrance) Oil Co. Ltd. out of Derby, Wyndham, and Darwin covered the fringing reefs of the continental shelf (Woodside, 1964). Navigation was by dead reckoning and photo identification of the exposed reef areas, which proved adequate for such isolated reconnaissance lines. The results suggested that the Fitzroy Trough terminates a few miles offshore. However, the data have been alternatively interpreted as indicating the presence of volcanic plugs rather than shallow basement, with the trough continuing further out to sea (B.O.C. of Australia, pers. comm.). The King Leopold Mobile Belt appears to extend out over the shelf with a more easterly trend at a depth of 2000 to 5000 feet. Inshore of the line of shoals, the sedimentary section is interpreted as being about 25,000 feet deep, but shallowing to about 10,000 feet under the Rowley Shoals, 15,000 feet under Scott Reef, and 5000 to 7000 feet under Ashmore Reef and Cartier Island. At Ashmore Reef this magnetic depth estimate correlates with intra-section volcanic beds found in the well at 7200 feet. As the Ashmore Reef well reached a total depth of 12,843 feet, magnetic basement must be at a still greater depth under the reef. Browse Island, Adele Island, and Churchill Reef appear to be in the deep section of the basin. Intermediate magnetic horizons possibly also exist at Rowley Shoals, Adele Island, and Scott Reef as at Ashmore Reef. The general indication is that a trough perhaps 30,000 feet deep parallels the coast about 100 miles offshore, and is bounded by an outer basement ridge about 15,000 feet deep that seems to support the reefs. This ridge, if real, may not be continuous.

West Australian Petroleum Pty Ltd made an offshore aeromagnetic survey along the edge of the Canning Basin (WAPET, 1966a). Lines were flown parallel to the coast in bands so that anomalies suitable for depth determinations were adequately defined. The Napier Platform was indicated as extending across PENDER and YAMPI 1:250,000 map areas with an easterly strike at a depth less than 5000 feet. The Fitzroy Trough appears to be about 12,000 feet deep and may shallow offshore (see above). The Broome Swell and La Grange Platform appear to extend for some distance across the continental shelf. However, the La Grange Platform is thought to be deep and cut by a basement swell near Cape Bossut into two depressions, which may contain significant thicknesses of Mesozoic rocks. The Samphire Depression is interpreted as being fault bounded, and does not appear to extend offshore. The survey did not extend sufficiently far out to sea to allow the relation between the Canning Basin and offshore 'basin' to be determined.

Two surveys have been conducted over the northern end of the Carnarvon Basin. A combined aeromagnetic and radiometric survey by BMR in 1959 (Spence, 1961) showed that a shallow basement ridge (the Yanrey Ridge) exists along the eastern shore of Exmouth Gulf. A deep embayment was indicated between this ridge and the Chinty Ridge to the east. A survey by WAPET (1968) indicated that north-east of Barrow Island the basement is shallow until 30 miles offshore; further offshore it deepens to perhaps 10,000 feet. South of Barrow Island, depths of over 25,000 feet are indicated in the west, shallowing to about 5000 feet over the Yanrey Ridge before deepening again to 20,000 feet in the Onslow Embayment east of the ridge. Some of the non-magnetic sediments in the embayment may be Precambrian in age.

Gravity surveys

There are few marine gravity observations within the survey area. Two lines measured by Tokyo University during the International Indian Ocean Expedition cross the area but the results are not yet available (Tomoda et al., 1964). While on a cruise around the Australian coast in 1967, the U.S. survey ship Oceanographer skirted around Barrow Island, but again final results are not yet published. A Lamont Geological Observatory oceanographic survey ship was also operating in the same region during 1967. At the moment, the data are still being analysed.

BMR's 1967 Timor Sea marine survey borders the area to the north (Jones, 1969; United Geophysical Corp., 1968). A series of Bouguer anomaly 'highs' and 'lows' run essentially parallel to the major inferred structures in the Ashmore Reef area. The Reef area coincides with a local gravity 'high' despite the considerable thickness of Mesozoic-Tertiary sediments, suggesting that it may still form a basement 'high' relative to the inferred offshore basin. The inferred basin correlates very roughly with a fairly extensive relative Bouguer anomaly 'low' that is disturbed by several Bouguer anomaly maxima along its axis. A similar Bouguer anomaly maximum occurs within the Joseph Bonararte Gulf (Smith, 1966), and has been interpreted as density variation within the basement. However, analysis of the amplitude, shape, and gradients of this feature by A.J. Flavelle (pers. comm.) suggests that the cause of the feature is fairly shallow and may possibly be within the sedimentary section. Dense Tertiary limestones or thick beds derived from volcanic source material might therefore be a possible cause of these gravity 'highs' within the basin.

Most of the landward part of the area has been covered by at least reconnaissance gravity surveys (e.g. Flavelle & Goodspeed, 1962; WAPET 1966e; Flavelle, in prep.,; Whitworth, in prep.). Over the Kimberley Block, the Bouguer anomaly features are undulating with low relief. A general irse in Bouguer anomaly value along the north-west coast suggests that the Lower Proterozoic rocks form a buried swell under the islands.

In the Fitzroy Trough area the Bouguer anomaly features are intense, completely at variance with the known generally thick sedimentary section. Intrusions within the Trough and density variations within the underlying King Leopold Mobile Belt appear to be the major contributing factors to these features. Over the platform areas of the Canning Basin, the Bouguer anomalies are less intense but still show a marked north-westerly strike that is not in evidence in the surface geology. The positive ridge extending inland from MANDORA to TABLETOP 1:250,000 map areas and possibly as far as BENTLEY may be caused by a sub-basin Lower Proterozoic mobile belt that marks the edge of the ancient West Australian Sheild. This feature may continue offshore.

There are very few observations on the Pilbara Block, but several surveys have been made over the North West Cape area. The Bouguer anomaly rises as the Mesozoic section thickens offshore. This has been interpreted as an isostatic effect rather than due to density variation in the sediments (Vale & Jones, 1967). The Onslow Embayment corresponds to a poorly defined Bouguer anomaly 'low' feature, and on Barrow Island the gravity featues are normally correlated with the structure.

Seismic surveys

A considerable number of land surveys have been carried out by BMR and by WAPET and their associates in the Canning and Carnarvon Basins (e.g. Smith, 1955, 1961; Vale et al., 1953; WAPET 1966f, 1967c, 1967d), mainly over local structures. Several wells have been drilled primarily for stratigraphic purposes (e.g. WAPET 1959a, 1959b, 1960a, 1960b, 1966d).

Offshore, much of the survey area has been sampled by reconnaissance seismic surveys. Detailed work has been carried out over anticlinal structures at Barrow Island, Rankin Bank, and Ashmore Reef.

In 1964, B.O.C. of Australia Ltd carried out reconnaissance surveys from Rankin Bank to Cootamundra Shoals (B.O.C. of Australia, 1965). Lines were shot over the known reef and shoal areas in an attempt to elucidate the underlying structures. Considerable folding and faulting occur in the Rankin Bank area. The most prominent feature defined was an anticlinal structure running parallel to the coast. A general increase in sedimentary thickness to the north-west was detected. Deep structure could not be detected as sea bed multiples made interpretation difficult. Between Rowley Shoals and Samphire Marsh, the reflection quality was good and showed an almost featureless north-west dipping section with an indication of an unconformity at about 2500 feet near the coast. There was no evidence of any major structural feature or of the nature of the base of the shoals. To the north, the regional picture was of gentle dips and little folding and faulting. A possible basement 'high' occurred near Ashmore Reef, while to the south-east the basement dipped north-west; otherwise the limits of the basin remained undefined.

The Montebello-Mermaid Shoal marine survey (B.O.C. of Australia, 1966) defined three parallel Permian and pre-Permian anticlinal trends around the Rankin Bank, with probable local closures. South-west of Rowley Shoals a locally thick sedimentary section was indicated. From the shoals to Adele Island, the onshore tectonic trends continued seawards for about 100 miles. Between Adele Island and the Sahul Shelf, there is a NE-trending sedimentary 'thick'. This appears to be associated with a more or less continuous structural ridge on the northern edge of the Sahul Shelf over which the sedimentary beds lie unconformably. It is suggested that this ridge could be basement. Sea bottom multiples still proved troublesome, and a high degree of common-depth-point stacking appeared necessary.

The following year a more detailed study was made of selected areas in the Rankin-Troubadour survey (B.O.C. of Australia, 1967). Around Troubadour Banks, which is to the north of the present survey area, two main reflectors were detected whose geological significance is uncertain. Refraction shooting indicated that Horizon A occurs in a zone with velocity of about 12,000 ft/s, but no refractor appears to be directly correlated with the horizon. The lower Horizon B represents the most prominent reflector in the deeper section and has a velocity of about 15,000 ft/s. It shows gentle unconformity with the overlying strata. In the Sahul Banks-Ashmore Reef area three levels were mapped, which are not necessarily related to horizons in other areas. Horizon A correlates with the base of the Oligocene, Horizon B is probably the base of the Upper Cretaceous, and Horizon C is a deeper phantom horizon. Horizon B is just above an unconformity, and a 16,000-ft/s refractor is believed to be just below the unconformity. Horizon B appreaches Horizon A towards Ashmore Reef. A large NE-trending anticline forms the north-west limit of the Bonaparte Gulf Basin, and more than 15,000 feet of sediment occur within the Basin. Ashmore Reef seems to be caused by deep structure rather than a large coral reef. No evidence of high velocities across the Reef was detected, and a sea floor velocity of 6500-7000 ft/s is common. Four major reflecting horizons were mapped around the Rankin Banks. Data quality was better than in 1965, and the reflectors were shown to be unconformable. Two anticlinal zones were delineated in the upper horizons. A deep syncline with superimposed anticline was detected between this outer anticlinal zone and the coast at the deepest Horizon D level. A series of local closures occur on the ridge, caused by a north-westerly cross-trend of faulting that could be a residual effect of the Canning Basin strike. A 15,000-ft/s refractor occurs just above Horizon C.

The 1967 Ashmore Reef survey showed the northerly trending anticlinal structure under the reef to be asymmetric at Horizon B, culminating about six miles northeast of the centre of the reef (B.O.C. of Australia, 1968a). North-westerly closure is enhanced by faulting. At Horizon A the crest is less intense, and is displaced south- eastwards from the Horizon B apex. Significant faulting at the shallow level is restricted to the north-east side of the structure. The results indicate that Ashmore Reef formed over the southerly culmination of an anticlinal trend extending to the north-east. The structure is flanked to the south and east by a trough in which there is considerable thickening in the A-B interval.

The Scott-Cartier survey confirmed the existence of a broad, faulted anticlinal fold along the regional trend at Sahul Banks (B.O.C. of Australia, 1968c). A dome appears to culminate under Woodbine Banks while Cartier Island seems to be a high area on a broad, low-relief fold. Some reflection time anomalies in this area correlate with the bathymetry, suggesting the presence of high-velocity reefs. Refracted first breaks give a velocity around 7500 ft/s which does not entirely explain the time anomaly. A velocity of 9500 ft/s would be required for the sea bed velocity to completely remove the anomaly. Only in the Scott Reef area were high near-surface velocities detected. Within the lagoon a velocity of 16,500 ft/s was found at the uppermost Horizon I level. Near-surface velocities were about 9000 ft/s, but some velocities as high as 14,000 ft/s were measured. However, refraction shooting within and outside the lagoon indicated essentially the same depth for the deepest refractors of 16,500 and 17,000 ft/s respectively. This suggests that the time anomalies are possibly the result of reef-like structures but that the structures do not exist at depth. The Rankin Bank anticlinal trend continues to the north-east. Faulting parallel to the trend is inferred. The high relief of two elongate domal structures in the southern part of the area is suggestive of diapiric movements. The upper horizons appear to wedge out in the south-east against the continental slope.

Surveys by Arco (1966) and Arco-Aquitaine (1967) in the Timor Sea and Sahul Banks area confirm the general interpretation provided by the B.O.C. surveys. The existence of a deep triangular basin predicted by an aeromagnetic survey (Australian Aquitaine, 1966) was confirmed. A 'high' trend appears to limit the basin along the edge of the continental shelf. In the north, outcrops or buried reefs distorted the horizons. The general sea bed velocity was about 6000 ft/s rising to 8000 ft/s over reefs. Some apparent diapiric structures were mapped. In the deep section the horizons appear conformable, but thinning of horizons occurs in the updip areas. Some beds are present only in the centre of the basin.

In the south-west, WAPET has carried out seismic surveys over Barrow Island and the adjacent continental shelf (WAPET, 1964, 1966b). Barrow Island is a gentle anticline in Tertiary limestones similar to those exposed on North West Cape. Onshore, shallow basement is indicated, deepening to perhaps 20,000 feet under the Island. A 12,500 ft/s refractor, probably from the basal Cretaceous unconformity, shows about 1000 feet of north-eastern dip in the north and a suggestion of an east-plunging anticlinal nose in the centre of the Island. The absence of a recorded higher-velocity refractor was interpreted as indicating very thick Jurassic sediments (WAPET, 1964).

The Barrow Island wells confirmed the thick Mesozoic section indicated by the refraction survey (e.g. WAPET, 1965). East of the Island, a major north-south fault with downthrow to the west cuts out the Jurassic section, and the Cretaceous overlies highly faulted Palaeozoic rocks. Further to the east, another large fault cuts out the Palaeozoic section, and the Cretaceous sediments directly overlie Precambrian rocks. Most of seismic reflection structures appear to be controlled by faulting. Some structures are under or near islands, suggesting that the islands in the area may be caused by anticlinal structures at depth. Structures at the Lower Cretaceous level appear to be found along old down-to-the-west faults that allowed the formations to fold or slump into the downthrown areas (WAPET, 1966b).

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4. THE NAVIGATION SYSTEM

The navigation system has been briefly outlined in the introduction to this Record. As the value of the survey results, especially the gravity work, is dependent upon the accuracy of determining the ship's position and velocity at any time, it is worth discussing the navigation system in more detail.

For surveys of a reconnaissance nature, rough figures for accuracy desired would be ± 1 mile in position, and ± 0.1 knot in velocity. With navigation methods normally used in marine seismic work, this accuracy can be easily achieved, but the cost is high and usually work can only continue during the daylight hours. As high costs defeat the purpose of reconnaissance surveys, a lower-accuracy system that permits continuous operation at less cost would be the optimum.

In 1967, a v.l.f. navigation system was introduced to BMR surveys with this aim in mind. The accuracy achieved was of the order of ± 2 miles and ± 0.2 knots when averaged over fairly long intervals of time. Short-term velocity variations could not be detected. Although a Marquardt continuous-wave sonar doppler unit was provided to try to measure the velocity fluctuations, the system did not achieve the accuracy claimed for it.

For the 1968 survey, a satellite doppler system was introduced to provide effectively absolute fixes once every two to three hours with a quoted accuracy better than 0.1 mile. Using these fixes to tie down the v.l.f.-defined traverses, it was expected that a positional accuracy of better than one mile would be possible. An Edo Western Corporation pulsed sonar doppler system was expected to be significantly better than the Marquardt unit used the year before. Ship's log, radar, astro fixes, and sun fixes were used to provide back-up on the more sophisticated navigation techniques. The different navigational tools are discussed below.

Satellite doppler system

The U.S. Navy satellite navigation system uses up to four satellites in nominally polar orbits. The system provides a position fix every two to three hours on the average. Basically, the technique determines the slant range from ship to satellite at a specified instant by measuring the doppler shift in the satellite's transmitted frequency over a period of two minutes. By determining two such slant ranges the ship must be at the intersection of the two surfaces of revolution defined by the slant ranges and the surface of the Earth. In fact, a minimum of three ranges must be determined using two frequencies to remove bias frequency and ionospheric refraction effects.

The solution determining the ship's position is laborious and fairly complicated, and as the ship's position must be determined quickly for it to be of much use as a navigation aid, a digital computer is required. The contractor provided an I.T.T. AN/SRN-9 radio navigational set, a Digital Equipment Corporation PDP8/S computer, and a teletype unit for this purpose.

Satellite passes below 10 degrees or more than 75 degrees above the horizon are classed as unreliable. Of the acceptable passes, some may be rejected before computation because of excessive noise interfering with the doppler count or an erratic refraction count. Following computation, some further editing based upon doppler count residuals is possible, followed by recomputation.

Certain precautions must be taken during reception of the satellite signal. The ship's course and speed must not be changed during this time, which can last up to 18 minutes. Although reception and computation are carried out almost automatically certain important data must be hand fed into the computer. The data include the approximate position of the ship, height of the receiving antenna, and the ship's course and speed during the fix. Errors in determining or feeding in these data can lead to errors in the ship's position.

V.l.f. navigation system

The v.l.f. radio navigation is a world-wide system that works by effectively determining the range of the receiver from various low-frequency radio transmitters by phase comparison with a local standard oscillator. Frequency-stabilised transmissions in the range 10 to 30 kHz are propagated in a duct between the Earth's surface and the ionosphere. Radio transmission suffers little attenuation in this frequency band and has a world-wide range, but is affected by diurnal variations in the state of the ionosphere. Navigation using this system is effected by commencing from a known point and determining the changes in phase of two or more transmissions relative to a very stable local oscillator, usually an atomic frequency standard, and recording the comparisons in cycles or microseconds.

There are many stations that transmit in the v.l.f. range, but most of these are not frequency stabilised, do not transmit continuously, or are too weak to receive in Australian waters. The following stations are reasonably good:

ALDRA (OMEGA station), Norway - 10.2 and 13.6 kHz

GBR, England - 16.0 kHz

HAIKU (OMEGA station), Hawaii - 10.2 and 13.6 kHz

NPG, Jim Creek, U.S.A. - 18.6. kHz

NPM, Hawaii - 23.4 kHz

NWC, North West Cape, Australia - 22.3 kHz

TRINIDAD (OMEGA station), TRINIDAD, B.W.I. - 10.2 and 13.6 kHz.

Determination of the ship's position by phase changes relative to these stations is influenced by the diurnal variation in propagation mentioned previously. The major effects of the variation is a change in propagation velocity from day-time to night-time, and a decrease in signal amplitude at dawn and dusk, sometimes with a complete loss of signal. The variation may be computed from a priori considerations or determined empirically for the survey area. As diurnal characteristics are almost unknown in the Australian area, a shore v.l.f.

monitor is used, and it is assumed that the diurnals so determined are also applicable at the survey ship's position. With a satellite doppler system a somewhat coarser shipboard diurnal can be determined; this provides a test of the assumption.

BMR provided two Tracor 599Q and one 599G receiver for both ship and shore monitor station. The 599Q receivers measure phase in cycles and are capable of receiving up to four OMEGA stations simultaneously (as these stations operate at the same frequency on a time-shared basis) or one v.l.f. station. The 599G receiver records in microseconds and receives only one station.

<u>Sonar doppler system</u>

The speed of a ship may be determined by transmitting a beam of ultrasonic sound forward and downward from the ship, and measuring the doppler frequency shift in the signal reflected back from irregularities on the sea bottom. Pitch, roll, and heave of the ship introduce spurious velocity changes, so two beams are used, one pointing forward and one backward at an angle of about 30 degrees to the vertical, and the difference in doppler shift is used. Two similar beams to port and starboard enable the ship's sideways drift to be determined.

The system on the ship was an Edo Western Corporation 'Navtrack' unit, using pulsed waves to give improved signal-to-noise ratio over the simpler continuous wave technique. The time of reception relative to the instant of transmission could be varied up to the equivalent of 100 fathoms, so guaranteeing a bottom reflection signal. An accuracy of one percent was claimed, while in deep water the system was said to work off water mass back-scatter at a somewhat reduced accuracy.

The great advantage of the method, when operating off bottom reflection, is that water currents do not affect the velocity determination. The ship's true forward and sideways speed over the bottom are measured when operating in this mode.

<u>Electromagnetic ship's log</u>

The ship's speed through the water was measured by a Chesapeake E.M. log unit. A voltage is electromagnetically induced in an underwater sensor proportional to the velocity of the water flowing past it. A digital display was available for speed, while distance travelled was registered on a mechanical counter.

<u>Radar fixes</u>

Two Decca radar units were available for use on the ship's bridge. Range expanders were not available. Radar fixes provide a useful adjunct to the more usual navigation techniques when close to land and fixed points at sea, such as drilling rigs or buoys. Accuracy is variable depending upon the sharpness of the reflector and accuracy of available hydrographic charts. Based upon internal consistency, land radar fixes are estimated to be correct to the order of 0.3 miles.

Astro and sun fixes

Star fixes were shot every day at dawn and dusk by Department of the Interior surveyors, weather permitting. Multiple determinations on several stars distributed around the compass give a far higher accuracy than the standard sextant shot carried out at sea. Internal consistency suggests an accurancy of ± 0.7 miles.

Sun shots were made at noon, when possible. Latitudes to an accuracy of about half a mile are obtainable by this method.

Buoys

A number of NE-SW tie lines were run across the east-west traverse lines. In deep water the positions of the intersections can only be estimated, but in shallow water buoys were dropped and anchored at preselected points to act as a reference point on the later traverses. The intersection points are used to check the internal consistency of the navigation network and for removal of gravity misclosures.

The buoys were of simple, inexpensive construction, consisting of an aluminium rod passing through a polyurethane float with a radar reflector at one end and a counterweight at the other. A nylon mooring line was attached to a concrete block and sea anchor to prevent the buoy from drifting.

Raydist

Raydist Type 'N' was provided for part of the survey by courtesy of B.O.C. of Australia Ltd. Three nets are available along the coast of the north-west shelf, but only one is occupied at any time. Accuracy depends upon position within a net, but is generally better than 200 feet. Close to the transmitters, 24-hours-a-day operation is possible, but at the extremities of the net only daylight operation is feasible because of sky-wave interference at night.

5. OBJECTIVES

The major objective of the survey was the continued reconnaissance of the continental shelf of Australia. Since 1965, when these surveys started, the number of geophysical methods used has increased considerably as has the sophistication of the equipment used. Continuous gravity, seismic reflection, and magnetic profiling was carried out. Seismic refraction profiles using sonobuoys were shot about once every three days.

The results of all the differing geophysical investigations are of little value without knowing the ship's position with reasonable accuracy at all times. For gravity work, the ship's velocity must be known with high accuracy. The cost and accuracy of navigation systems can vary by several orders of magnitude. High accuracy is rarely achieved without high cost. The system adopted for the 1968 survey was the result of a compromise between cost and effort involved, area covered, accuracy relative to station interval, and several other imponderable factors. More time and effort were put into the navigation data collection and reduction than any other system; perhaps three-quarters of the total effort on the survey went into finding the ship's velocity and position.

Particular stress was accordingly placed upon the maintenance of quality control on all data collection systems. The highest possible accuracy consistent with the aims of the survey was aimed for, rather than rapid reduction of data of a lower quality. As new instruments and techniques are continually being introduced into this type of survey by BMR, assessments of suitability, potential, and accuracy of these new systems are a necessary part of the survey. These perhaps could be termed geophysical objectives. The geological objectives generally cover the elucidation of geological problems and investigation of unknown areas. The objectives of the survey are summarised below.

Geophysical objectives

1) To continue to assess the performance and reliability of the v.l.f. navigation system (vide Ingham, 1968; Jones, 1969). Satellite fixes and line intersections will be used in the final reduction to determine the overall accuracy of the system. The independent fixes at roughly two-hourly intervals will permit a check of the reliability of the diurnal correction obtained at the shore station.

2) To assess the performance and reliability of the pulsed continuous-wave sonar doppler unit manufactured by Edo. The system is claimed to operate off bottom at greater depths than the Marquardt system used in 1967.

3) To assess the performance and reliability of the I.T.T. satellite doppler system using a PDP/8 digital computer. Accuracy under way is lower than when at anchor, and estimates of the system accuracy when operating at 10 knots are needed.

4) To determine the overall accuracy of the gravity data. Line intersection values are used for this purpose. The accuracy of the position and velocity determinations probably influences the final accuracy more than uncertainty in the averaging and drift within the La Coste and Romberg meter.

5) To continue the assessment of seismic data quality obtained with the Chesapeake cable at speeds up to 10 knots. It was intended to carry out common-depth-point stacking of the six-channel output, for areas where reflection quality was poor, as a separate project after the survey finished.

6) To test the suitability and usefulness of the sonobuoy refraction technique, by shooting continuous refraction profiles in suitable areas to try to obtain velocities at least down to the major reflectors. This was expected to allow more reliable correlation of reflecting horizons within the area and possibly with identified horizons onshore.

7) To tie into previous seismic surveys in the area to allow co-ordination and compilation of the results.

Geological objectives

1) To map the offshore 'basin' that is postulated to exist parallel to the edge of the shelf. In particular, to investigate the continuity of the 'basin' and the main structural features within it, including the thickness of sediments and the major reflecting horizons.

2) To determine the continuity of the King Leopold Mobile Belt and Pilbara Block across the continental shelf.

3) To investigate the seaward extension of the Canning Basin and whether it is intimately involved with the offshore basin, dips beneath the offshore feature, or terminates on the shelf.

4) To determine whether the Onslow Embayment is a feature continuous with the offshore 'basin'.

5) To further the determination of the structural relation between the shelf area and the Kimberley Block.

6) To study the nature of the structural ridge inferred to run along the edge of the continental shelf, particularly with regard to its magnetic and gravity expression.

7) To see whether the volcanic plugs thought to exist in the seaward extension of the Fitzroy Trough can be detected by seismic and gravity methods.

8) To run several traverses across the edge of the continental shelf to advance the determination of its nature and structural significance, and to endeavour to position the transition area between continental and oceanic crust.

6. OPERATIONS

In general, the programme consisted of a series of east-west traverses nine nautical miles apart, with NE-SW tie lines roughly 100 miles apart (Plate 2). The survey consisted of three cruises of roughly 25 days' duration. The first cruise covered the northernmost part of the area from Ashmore Reef to Adele Island. The second cruise covered the area from Adele Island to Broome, and the final cruise covered the area from Broome to North West Cape.

The survey vessel Robray I arrived in Australian waters on 26 August 1968. The seismic and v.l.f. equipment provided by BMR was installed in the ship at Brisbane while other necessary outfitting was taking place. The ship left Brisbane on 3 September, and made a series of gravity ties at Mackay, Townsville, Cairns, and Darwin on the way to Broome, arriving there on 20 September. The trip around the coast was used as a shake-down cruise to ensure that all systems were operating satisfactorily, and that contract personnel were familiar with the equipment and its operation.

The first cruise commenced on 24 September. On 25 September the six-channel cable was lost due to a breakage at the rear of the first active section. A three-day search found no trace of the cable, so the survey was resumed on 28 September. The boat arrived in Broome on 20 October at the end of the cruise.

After a nine-day field break, the boat left Broome for the second cruise on 29 October. Very heavy seas forced the boat to return to Broome on 1 November. After the storm abated, the boat resumed surveying on 2 November. Engine maintenance and transfer ashore of the electronics instrument supervisor to carry out urgent repairs on the shore v.l.f. monitor caused some modification of programme. An extra loop southwards from Cape Leveque to the vicinity of Broome was run. The cruise ended on 28 November.

The last cruise commenced on 29 November and ended on 17 December. Fairly heavy seas between 9 and 16 December caused the programme to be modified. The spark-array system was damaged by seas coming from the port beam, and an attempt to run the third long line over the edge of the continental shelf was postponed for some two days.

7. SYSTEM PERFORMANCE

At the moment only preliminary results at one-hourly intervals are available. Some analysis of these data preparatory to final data reduction has been made. The most significant results are outlined briefly below, mainly so that the reader may see the accuracy and limitations of the various survey techniques and to act as a guide to further work of this type.

Navigation

Once again, as navigation is the most fundamental work, upon which the quality of the survey as a whole rests, it will be discussed in some detail.

Satellite doppler system. The inherent accuracy of the method depends on how well the path of the satellite is known. In part this depends upon how well the Earth's gravity field is known. This form of error becomes more significant in the southern hemisphere because of lack of data. The accuracy when the ship is stationary is of the order of ± 300 feet, as shown by multiple readings taken in Broome harbour (Ray Geophysics, in prep.). Under way, accuracy is reduced by uncertainties in the ship's velocity. An error in the fix of 0.2 nautical mile per knot error in boat speed has been quoted (B.O.C. of Australia, 1969). However, a few tests carried out on the 1968 survey suggest that errors could rise as high as 0.8 nautical miles per knot, and appear to occur mainly in longitude (V. Ingham, pers. comm.).

V.l.f. navigation system. The overall performance as a navigation system has been disappointing. Diurnal variation has been erratic, particularly from transmitter NPM, and a characteristic pattern was not well defined. The long-term variation on ship and shore has been inconsistent, both between channels and between ship and shore. The erratic variation from channel to channel indicates that it is not erratic atomic frequency-standard drift, while the differences between ship and shore negate the possibility of varying transmitter frequencies. It does not seem likely that the diurnal variation would very significantly over the survey area. The two most likely causes are interference within the receiver by transmitter NWC because of its proximity and high power, or incorrectly adjusted cardioid aerials.

Preliminary analysis indicates that useable position fixes are obtainable on an empirical basis by adjusting the ship range lane values to give correct positions at satellite fixes with linear adjustment between fixes, and ignoring shore diurnal values. Once reasonable positions can be obtained, the results can be reanalysed and the cause or causes of the erratic diurnals can probably be deduced.

Sonar doppler. The Edo Western unit did not achieve the specifications claimed of one percent accuracy in velocity or of working off water mass back-scatter in water deeper than 100 fathoms. Sensible velocities were not obtained in deep water. In shallow water, velocity values were consistently obtained but there was a systematic error increasing from about 0.5 knots in 20 fathoms of water increasing to around 1.0 knots in 100 fathoms as deduced by comparisons between satellite doppler and sonar doppler average velocities between satellite fixes by V. Ingham. Analysis of Ingham's abstracted figures indicates that the standard deviation of the sonar doppler average velocities is of the order of 0.2 to 0.6 knots (see Table 1). The value of the data is somewhat limited by the small number of observations available, but there is little doubt that the scatter is real.

The systematic error increasing with depth, and the high scatter in velocities, which are believed to be instrumental in nature rather than real changes in boat speed, have considerably reduced the value of the sonar doppler unit in determining small-scale fluctuations in the ship's velocity and hence Eotvos correction.

E.M. log. The Chesapeake ship's log became inoperative on 5 November, and stayed that way for the remaining half of the survey. For the first half of the survey the mechanical counter that registers distance travelled operated satisfactorily but the velocity output to the electronic Nixie tube display appeared to have too short a time-constant. The velocity value was almost unreadable as variations of over one knot occurred in the display in a few tenths of a second.

Buoys. During the survey 87 buoys were dropped at intersections, but only 23 were recovered. Maximum recovery occurred when the buoys were dropped in shallow water and revisited within 10 days (Ray Geophysics, in prep.). Loss of most of the buoys was ascribed to strong and unpredictable currents and a severe storm during the second cruise. Disintegration of some of the buoys suggests that a more robust buoy is necessary.

Raydist. Final positions determined by Raydist have only just become available, and have yet to be studied. A study of the shipboard computed values indicates a systematic variation relative to satellite doppler fixes of about 2300 feet and a standard deviation of about 1000 feet (Ray Geophysics, in prep.). It is expected that Raydist will give fixes accurate to the order of 200 feet on a relative basis, but the absolute accuracy depends upon the net geometry and other factors. The comparison of the final values should allow a reasonable estimate of the accuracy of satellite fixes while the ship is moving.

Gravity

The performance of the gravity meter during the survey appears generally satisfactory. During the first cruise, the digital recording system had a locked bit in the unit position resulting in only odd milligal values being recorded. The photo-cell lamp in the beam servo-mechanism failed during the first field break and the beam jammed hard against the stops. Upon replacement, the meter continued to function normally, but had suffered a large datum shift. An engineer from the manufacturer was flown from the U.S.A., and readjusted the meter to close to its original value.

The drift during the survey was negligible but, as in 1967, an unexplained high drift was experienced at the end of the survey. Moreover, the gravity ties made into ports along the coast from Brisbane to Broome show erratic differences up to 1.7 milligals. Technically those erratic values should be defined as meter drift, so a further look at the port values would seem necessary. During the survey a progressive gravity misclosure map was maintained using the values found at line intersections (Plate 5). Where buoys were recovered the differences at the intersections were relatively exact, but where the intersection points had to be estimated, errors in position are necessarily included in the gravity values. One would therefore expect slightly higher errors in gravity in deep water. The mean misclosure at intersections was 1.37 milligals, corresponding to a standard deviation of about 1.6 milligals.

Magnetic

The ship magnetometer operated satisfactorily throughout the survey. Some slight interference was experienced during transmission on the Raydist radio communications set on the third cruise but this was quickly cured. The shore magnetometer was either inoperative or excessively erratic for most of the survey. For about the first 20 days the sensor heads kept cracking, presumably because of overheating. Perhaps for the first 40 days, noise generated by nearby transmitters made the magnetic readings obtained almost valueless. When removed to a less noisy site near the v.l.f. monitor station, the pen recorder kept breaking down, mainly because of sand getting into the gears.

Failure of the shore monitor magnetometer has seriously downgraded the quality of the shipboard magnetic readings. A mean misclosure of 25 gammas at traverse line intersections was obtained, when it had been expected that a value of 2.5 gammas would be achievable. It may prove possible to compute reasonable magnetic diurnals using the magnetic values obtained at Port Moresby (TPNG) and Mundaring (WA) geophysical observatories.

Seismic

A big setback was experienced in the seismic work when the six-channel Chesapeake cable was lost shortly after the start of the survey. The cable broke at the rear of the first active section, and was the second breakage experienced with this particular cable. Despite there being a buoy attached to the rear end of the cable, a three-day search by the Robray I and by plane failed to find any trace of the cable. As the cable was lost in deep water, it is possible that it sank.

The loss of the multi-channel cable seriously affected the overall quality of the seismic reflection work. Using the single-channel cable, the record quality was generally fair. In shallow water, however, multiple reflections and ringing interfered greatly with the reflections and caused loss of the multiple reflection problem was much reduced, and events could be followed for many tens of miles. Continuity was lost over the edge of the continental shelf, because of diffractions and side reflection off the steep slopes and disturbed sedimentary sequence. In deep water, reflection quality

line missing. See below

Insert the following missed line at the point marked above

...continuity of events most of the time. In water deeper than about 100 fathoms...

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was good despite the very low energy return.

Only a few hours' seismic record was lost during the survey because of equipment malfunction, except when the cable was lost. Some time was lost because of breakdown of the recorders but this must be expected under continuous operation. One cause of lost record was moisture getting into the electrode sockets and wiring of the spark-array system. The heavy current pulses vaporised the moisture and blew the wiring apart.

The sonobuoy refraction system operated satisfactorily considering that the method was new to all parties concerned. The air-gun energy source gave useable refraction data out to about eight miles, usually farther in deep water. Even using the sparker as energy source was useful when there were shallow, high-velocity refractors. A maximum range of about three miles was obtained with the sparker. Some problems were experienced with the sparker. Some problems were experienced with ship-generated noise swamping the incoming signal. This was removed by using a narrower filter band, 20-47 Hz instead of 0-47 Hz.

8. RESULTS

Preliminary reduction of the gravity and magnetic data was made on the boat for each hourly position. As the one-hour points are roughly 10 miles apart, features of wavelength less than about 20 miles cannot be detected. Therefore the preliminary results are essentially regional in nature. The Bouguer anomaly contours have been matched with the contours on the land surveys to give continuity of features already recognised. The survey area has been divided up into provinces, or zones, that demonstrate a consistent internal pattern of Bouguer and magnetic anomalies (Plates 7 and 8).

The continuous seismic refraction profiles were analysed and a rough depth to the main refractors was computed (B.O.C. of Australia, 1969). A qualitative attempt has been made to define velocity regimes more or less on the basis of the velocity depth distribution (Plate 9). The seismic structural trends are discussed within that framework later. Major reflection events were followed on the seismic sections and timed at one-hourly intervals. Profiles have been drawn up at 1:250,000 scale using a time scale of one second per inch. While the more continuous events were picked where possible, no definite horizon could be followed throughout the survey area.

A brief outline of the more significant results is given below, and an interpretation of these features is attempted in the next chapter.

Gravity

Based upon the gravity and magnetic data, thirteen provinces have been defined (Plate 8). A larger grouping of the provinces is possible based upon the Bouguer anomaly values, within which three major zones may be observed.

In the north-east there is a zone of broad, generally undulating Bouguer anomalies that constitute Provinces I to III. Province I is a Bouguer anomaly rise with a series of minor culminations paralleling the edge of the Kimberley Block, while Province II forms a platform-like area with some intense minor features offshore from the Fitzroy Trough and King Leopold Mobile Belt. A long-wavelength relative Bouguer anomaly 'low' centred on Browse Island forms Province III.

The second zone is formed by Provinces IV to VII which generally show high Bouguer anomaly gradients. All of these provinces are along the edge of the continental shelf, and the high gradients are almost certainly caused by isostatic effects as the crust thins out toward the ocean. Province VII shows much lower Bouguer anomaly values than the other provinces within the zone, and is indicative of an area of unusual crustal development.

The most obvious feature of the third zone is the intensity of the Bouguer anomaly pattern and its continuity from the Canning Basin out across the continental shelf. This zone includes Provinces VIII to XIII. Provinces X to XII appear to be extensions of gravity provinces found onshore, while Provinces VIII, IX, and XIII

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appear to be wrapped around the periphery of the Pilbara Block.

Magnetic

A somewhat similar pattern to the gravity features is exhibited by the magnetic anomaly features. In the north, the magnetic features are broad and of low amplitude with a generally indeterminate trend. To the west of the Canning Basin, the features are intense and show a remarkable parallelism to the gravity features. This seems to suggest a common origin to the two types of feature, gravity and magnetic, in this area.

The larger magnetic anomaly features usually show a dipole-like pattern, generally with the positive feature to the north of the negative feature. Anomalies of this type appear to fall upon the flanks of the associated Bouguer anomaly features. The short-wavelength, low-amplitude features do not generally demonstrate such a dipole pattern, possibly because of the filtering effect of station spacing. However, they may have a different origin from the larger features, as they appear to coincide with similar small-wavelength, low-amplitude Bouguer anomaly features.

Seismic

It is convenient to outline the velocity regimes determined on the basis of the refraction profiles first, and then use these regimes as a framework within which the major structural trends may be discussed. The regimes are based upon 34 widely scattered refraction profiles, so their boundaries (Plate 9) are necessarily poorly defined (B.O.C. of Australia, 1969).

Regime 1 is along the north-west coast of the Kimberleys and is an area of shallow, high-velocity refractors. The velocity reaches about 20,000 ft/s within 2000 to 4000 feet of the surface.

Offshore from the Fitzroy Trough a single profile is used to speculatively outline the shallow, very-high-velocity Regime 2. The seismic reflection data have also been used to help define this area. The only velocity determination gives a velocity of 20,000 ft/s at less than 1000 feet.

The third zone, Regime 3, covers a very large area along the outer part of the continental shelf. Velocities are low and typically reach 10,000 ft/s within a depth of 3000 feet. However, there is considerable variability throughout the regime.

To the south-east of Regime 3 there is a fairly narrow zone running from the Barrow Island area to near Broome, where the velocity increases rather more rapidly. A velocity of 10,000 ft/s is generally reached within the first 1000 feet, and this is used to define Regime 4. Again there is some variability within the regime.

Regime 5 occurs on the south-east side of Regime 4, and demonstrates similar properties to Regime 3. It is a low-velocity regime where 10,000 ft/s is reached within 3000 feet of the surface.

It seems to show a gradual increase in velocity at that depth towards the south-east, reaching about 15,000 ft/s near the coast.

The very-high-velocity, shallow-refractor zone of Regime 6 occurs near Port Hedland. Similar to Regime 2, it is defined by a single refraction profile, which in this case gives a velocity in excess of 20,000 ft/s at a depth of 100 feet.

Turning to the seismic reflection work, an attempt was made by the B.O.C. geophysicist on the boat to follow the near-top Cretaceous unconformity. Where necessary, this was done as well as possible by constructing a phantom horizon. Later study suggests that the phantom horizon as presented (Plate 10) is better interpreted as near-base Tertiary (B.O.C. of Australia, 1969). As events were reasonably conformable just below this level, it is considered that the horizon is generally representative of the Upper Cretaceous. Most of the following brief discussion is based upon structures evident at the near-base Tertiary level, and for convenience the same nomenclature as used by B.O.C. of Australia (1969) has been adopted here.

On a regional scale the near-base Tertiary horizon shows a monoclinal dip to the north-west. The dips are low near the coast but increase rapidly near the edge of the shelf. Continuity of the horizon into deeper water is uncertain as the seismic sections are greatly disturbed by diffractions and side reflections at the continental shelf edge. Several reflectors can be followed on the few lines that are in deep water, but the lines are too far apart to allow correlation between each other, and the disturbed zone prevents correlation with reflectors on the shelf.

Faulting is fairly common along the main structural trends. The throw of the faults is generally indeterminate, and as the faults cannot be traced with any confidence from line to line, correlation of events is sometimes difficult. In shallow water the reflections are complicated by ringing and multiple reflections. In deep water the multiples are easily distinguished and present no problems. The reliability of features detected is therefore higher in the western half of the survey area than in the eastern half.

On a smaller scale than the regional features, nine major structural trends were detected at the near-base Tertiary level; within these trends, about 40 local features and closures can be discerned (Plates 9 and 10). In Plate 9, trend A for example is represented by the group of letters A; each letter A marks one of the local features within the major structural trend. Some of the results of previous seismic surveys by B.O.C. of Australia have been used to help delineate local features in the Rankin Bank, Rowley Shoals, and Scott Reef areas. Only four of the major structural trends (A,B,G,and H, Plate 9) and about 18 of the local features within them were known prior to this survey.

Three large-scale platforms have been defined, in the Browse Island and Lacapede Island areas, and to the west of Broome. Minor closures and embayments occur within the platforms. In the north, the thickness of Tertiary sediments increases rapidly to the west of the platform areas, frequently with anticlinal trends along the periphery of the platform. In the south, thickening is more gradual until the edge of the shelf is reached. Deep embayments occur along the edge of the shelf at Rowley Shoals and Scott Reef.

The nine major structural trends will now be considered in more detail. Five trends occur within or border Regime 3 (Plate 9). Three of these - G, D, and H - are along the edge of the continental shelf. G and D correspond roughly to Scott Reef and Rowley Shoals respectively, while the most prominent structure within trend H coincides with a ridge in the sea floor. Correlation of these trends with magnetic and Bouguer anomaly features is poor. The platform-like area centred on Browse Island has several shallow structures upon it (trend F), while to the south-west, trend C is found around the periphery of the platform centred on the Lacapede Islands. The C trend coincides with a series of small-amplitude positive Bouguer and magnetic anomaly features at the boundary between Regimes 2 and 3.

Trends A, B, and E fall within Regime 4, and are parallel to its major axis. Trends A and B run north-eastward from the Barrow Island area; their structural relief attenuates northward and may pass into the structural nosing of trend E to the west of Broome. The three trends parallel intense gravity features, which near Broome are associated with intense magnetic features.

Trend I runs westward from the coastal region on MANDORA 1:250,000 map area to north of Roebourne within Regime 5. Although the area is one of intense Bouguer and magnetic anomaly features, these do not show any direct correlation with the seismic structure.

In two areas, pre-Tertiary horizons could be seen in the seismic sections. Immediately to the west of Broome, these beds show extreme folding and faulting at a depth of about 0.7 seconds. By extrapolation from onshore data, these horizons would be in the Palaeozoic or early Mesozoic (B.O.C. of Australia, 1969). Farther south, to the west of the Samphire Depression, the lines near the shore also show intensely folded and faulted beds down to a reflection time of about 2.0 seconds. A continuous reflector rarely exists, but a zone of reflections can be followed several miles out to sea until it becomes lost in the ringing and multiples from the higher levels. This zone of reflections is placed in the Palaeozoic by correlation with onshore well data.

As mentioned previously, several reflectors can be seen in the deep-water sections out beyond the edge of the continental shelf. The age of these horizons is uncertain, but it is thought that they could be Tertiary. One of the most important features found was to the west of Barrow Island in more than 500 fathoms of water. Line 144 (see Plate 2) detected an anticline 60 miles wide with 2000 feet of relief, as well as two smaller anticlines closer inshore but still beyond the continental shelf (Plate 11). A deeper, discontinuous horizon not shown in Plate 11 was considerably faulted. Some of the faults appear to be of reverse type, and possibly thrust faults occur.

In shallow water it is difficult to clearly define any but the regional seismic structures because of multiples. However, in water depths greater than 100 fathoms upon the continental shelf many local structures can be seen, particularly near the shelf edge. Reefs are fairly common in a band that includes Rowley Shoals, Scott Reef, and Ashmore Reef. The reefs appear to have been buried by later sedimentation. An example is given in Plate 11. The sedimentary structures have the appearance of giant forest beds that can be followed for a few miles before being cut off by later beds. This zone reaches a considerable thickness at the edge of the shelf, and the general appearance is one of a continental shelf being actively built out towards the ocean during Tertiary times; reefs were established only to be continually overwhelmed by sedimentation.

CORRELATION TABLE

PROVINCE	GRAVITY	MAGNETIC	REGIME	SEISMIC	TREND
I	An area of relatively high B.A. with minor undulations.	Indeterminate trend of magnetic anomalies	1	High velocity, shallow refractor	
II	B.A. platform with local fairly intense B.A. highs. Bounded by series of small B.A. highs	Minor magnetic anomalies surround the province	2	Very high velocity, shallow refractor bounded to W by trend C	C
III	Broad, shallow B.A. depression	No significant magnetic features	3	Trend F occurs in centre of platform area around Browse Island.	F G
IV	Regional B.A. gradient to northwest local highs in north at Ashmore Reef	Minor magnetic anomaly features only		Low velocity zone	
V	Gradual increase in B.A. to northwest. Local highs correlated with magnetics	Ring-like structure to magnetic features		Trends D, G, and H parellel edge of continental shelf	D
VI	Steady gradient out towards ocean. No distinctive features	No significant magnetic anomaly features			
VII	Area of anomalously low B.A. considering depth of water	Minor magnetic anomaly features only			
VIII	Intense Bouguer anomaly ridge with northeasterly trend	Almost no magnetic feature at all			H
IX	Bouguer anomaly low paralleling Province VIII	Two positive magnetic anomaly features	4	High velocity, shallow refractor Trend A, B and E parallel axis of zone	B A
X	Continuation of Fitzroy Regional Gravity Complex of Complex of Canning Basin	No magnetic features			

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CORRELATION TABLE (Cont'd)

PROVINCE	GRAVITY	MAGNETIC	REGIME	SEISMIC	TREND
XI	An offshore extension of Munro Regional Gravity Platform	Intense magnetic features with westerly trend	5	<u>Low velocity zone similar to Regime 3</u>	E
XII	Northwest end of intense B.A. feature called Ankatell-Warri Regional Gravity Ridge	Northwest trending intense magnetic anomaly features	5	Trend does not appear to correlate with observed feature	I
XIII	Series of intense B.A. highs and lows that can be followed on-shore	Several intense magnetic features	6	<u>Very high velocity, shallow refractor</u>	I

9. PRELIMINARY INTERPRETATION

The preliminary results have been outlined in Chapter 8. Provinces have been defined on the basis of gravity and magnetic results, and regimes mainly on the basis of the seismic refraction results but influenced by the reflection data. To help bring this information together, a correlation table has been drawn up showing the inter-relation of the various parameters. As can be seen from the correlation table, the seismic velocity regimes generally coincide with groupings of the gravity and magnetic provinces. The seismic structural trends usually coincided with the borders of the provinces. The cause of these inter-relation can only be postulated, but such theories can be of great help for advancing future exploration.

The following discussion is made in terms of provinces, as these appear to be the most useful units. It is believed that in most cases the provinces delineate the major structural blocks in the area. This belief may be erroneous for Provinces IV to VII, which are greatly influenced by isostatic effects along the edge of the continental crust.

Province I

The seaward boundary of this province, defined as the Archipelago Gravity Rise on land (Whitworth, in prep.), is uncertain but appears to be just within the survey area. The province shows a general rise in the average Bouguer anomaly value, with local undulations. Magnetic anomaly features are almost completely absent on the regional scale, but very local intense anomalies were observed close to the coast. The province corresponds to Regime 1 where velocities around 20,000 ft/s were detected at shallow depths.

The gradual rise in Bouguer anomaly may indicate a shallowing of the metamorphic basement (Whitworth, in prep.). As the Proterozoic sediments in the Kimberley Block are around 30,000 feet thick, it seems unlikely that the basement would rise by 25,000 feet along the coast to a depth of a few thousand feet without producing significant Bouguer and magnetic anomaly features. The shallow refractor is therefore probably intra-sedimentary. A possible explanation is that the high-velocity refractor is an intra-sedimentary volcanic layer and may be an extension of the Mornington Volcanics exposed farther to the east. The local, sharp magnetic features are consistent with this interpretation.

Province II

A Bouguer anomaly platform forms Province II to the west of Cape Leveque. Some fairly intense local relative Bouguer anomaly 'highs' which are associated with magnetic anomaly 'highs' occur within the platform. A series of small Bouguer anomaly 'highs' are found around the periphery of the province. These 'highs' correlate with minor magnetic features and the seismic features of Trend C. The province coincides with the very high shallow velocity of Regime 2 defined by the seismic reflection and refraction results.

The peripheral gravity, magnetic, and seismic features suggest that the province forms a structural block, and that differential vertical movement relative to the surrounding areas has caused the features. The more intense magnetic and gravity features within the platform are in an area where sediments are thought to thin over the King Leopold Mobile Belt (Woodside, 1964), and would tend to strengthen that hypothesis.

Province III

A broad Bouguer anomaly 'low' about 150 miles across is centred around Browse Island. The feature has an amplitude of about 25 milligals, and does not exhibit any difinite trend. There are no significant magnetic anomaly features within the province. The area is platform-like at the base Tertiary level, and the minor Trend F structures occur within it. One refraction profile indicated that there are at least 10,000 feet of low-velocity sediments in the area.

The lack of magnetic feature combined with the Bouguer anomaly depression suggest a thickening in the sedimentary section in the Browse Island area. The refraction work tends to confirm this. As the region is a platform at the base Tertiary level at a depth of perhaps 2000 feet, the thickening presumably occurs in the Mesozoic or Palaeozoic section, or both. This appears to be the only part of the survey area where the geophysical evidence suggests a basinal structure. Elsewhere the evidence is consistent with the seismic implication of regional thickening of sediments north-westward from the coast to beyond the edge of the continental shelf.

Province IV

The northern part of this province was first defined by Jones (1969) as the Ashmore Regional Gravity Gradient. It runs in a north-easterly direction from around Scott Reef to north of Ashmore Reef. The province shows a fairly steady positive Bouguer anomaly gradient towards the north-west, with a few local positive features in the Ashmore Reef area. However, no local features are evident around Scott Reef. Only minor magnetic features occur within the province. The Scott Reef area corresponds with the fairly broad structures of Trend G.

The rapid rise in Bouguer anomaly values to the north-west is undoubtedly caused by crustal thinning at the edge of the continental shelf. The absence of anomalous magnetic and gravity features over the Scott Reef area suggests that a basement ridge does not exist, or at least not one of major dimensions. A reasonable cause of the seismic structures under Scott Reef and Ashmore Reef is therefore not readily deduced. One possible cause is decollement in which the upper sediments have slipped towards the ocean. This, however, would cause a structural 'high' only in the upper layers, upon which the reef structures were later built.

Province V

This province, showing a more gradual rise in Bouguer anomalies to the north-west than province IV, stretches from the Scott Reef area to south of Rowley Shoals. A series of small positive Bouguer anomaly features on the western flank of the province are usually associated with positive magnetic features. There is an intense Bouguer anomaly depression off the edge of the shelf on map D50/16, which appears to be associated with a bathymetric ridge in deep water. A series of magnetic anomaly features forms a ring-like structure about 100 miles in diameter centred roughly on Mermaid Reef, the northernmost reef of the Rowley Shoals. The line of structures in Trend D coincides roughly with the bathymetric ridge on which the Rowley Shoals lie, but there do not appear to be any associated gravity and magnetic features.

As at Scott Reef, the gravity and magnetic data indicate that a basement ridge probably does not exist under the Rowley Shoals. The gravity and magnetic features on the south-east border of the province do not appear to have associated seismic structures, unlike those farther north which correlate with trend C. The ring-like magnetic feature cannot be interpreted at our present state of knowledge. Although there is no positive evidence in favour of it, a possible explanation is a ring-structure with subsidence of the central area.

Province VI

The province is characterised by a steadily increasing Bouguer anomaly value out to sea. No significant gravity, magnetic, or seismic features occur within the province.

The gravity pattern is almost certainly the result of isostatic crustal thinning towards the ocean.

Province VII

This province is outlined only by a few lines to the west and south-west of Barrow Island. A Bouguer anomaly 'low' exists to the north of North West Cape, but its extent is uncertain. A Bouguer anomaly minimum is poorly defined on the long lines to the west of Barrow Island, with more positive values farther out to sea. This area corresponds to a zone of considerable thickness of sediments, which is folded into an anticline 60 miles wide with a vertical relief in excess of 2000 feet. No significant magnetic anomaly features occur within the province.

The gravity 'low' near North West Cape could be interpreted as an offshore extension of the Onslow Embayment of the Carnarvon Basin, though the correlation is tenuous considering the paucity of data. The area to the west of Barrow Island is anomalous. There is at least 5000 feet of sediments in a zone of relatively deep water, and there could be more than 10,000 feet. The Bouguer anomaly values are much lower than would normally be expected for an area so far from the edge of the continental shelf. The lines that define the seismic structure passed over a huge bathymetric rise covering more than 20,000 square miles. This bathymetric rise appears to correspond with an area of continental-type crust that has 'foundered', sinking to a depth of about 500 fathoms.

Province VIII

A prominent arcuate Bouguer anomaly ridge 60 miles wide and 250 miles long with a roughly north-easterly strike runs from north of Barrow Island to the Rankin Banks. Several culminations occur along its length. Despite the intensity of the gravity ridge, suggestive of dense intrusives, there is little associated magnetic feature. The seismic Trends H and B occur along the province's north-west and south-east flanks respectively.

The province forms a peripheral feature to the Pilbara Block, reminiscent of a bounding mobile belt. However, lack of magnetic effect would tend to negate an intra-basement source for the gravity feature. Nevertheless, the seismic structures along the flanks suggest a structural block that has undergone structural movement, and there is aeromagnetic evidence for a horst-like structure to the west of Barrow Island (WAPET, pers. comm.).

Province IX

A NE-trending Bouguer anomaly depression parallels Province VIII to the east. Unlike the gravity ridge, there are two fairly intense positive magnetic anomaly features within the province. The province corresponds with the southern part of Regime 4, and seismic Trend A occurs along its northern flank.

If Province VIII corresponds to a horst structure, then by analogy this province could be associated with a sedimentary depression. As mentioned previously, the evidence is conflicting. There is no evidence in the Tertiary section for a basinal feature, and the lack of magnetic features over the gravity ridge and their presence over the gravity depression tend to make the horst-graben interpretation unacceptable. The gravity 'low' could possibly be caused by a zone of granitic intrusions within the basement, but the lack of obvious dipole magnetic anoamly features again makes acceptance of this hypothesis difficult. At the present time, a reasonable explanation for Provinces VIII and IX has not been found.

Province X

This province is thought to be an extension of the onshore Fitzroy Regional Gravity Complex of Flavelle (in prep.). The boundary with Province II is arbitrarily defined. The seaward part of the province consists of a low-amplitude Bouguer anomaly 'low' with a westerly trend. There are no significant magnetic anomaly features within the province.

The data are difficult to interpret. The low amplitude could be a result of thick, uniform sediments masking basement effects. However, thick sediments occur in the Fitzroy Trough onshore and considerable gravity relief is still shown. Why the Bouguer anomaly values are generally higher than in Province XI despite the presumably greater sediment thickness is also a puzzle.

Province XI

Several intense Bouguer and magnetic anomaly features with a westerly trend form Province XI. This is an extension of the Munro Regional Gravity Platform (Flavelle, in prep.) where the trend is more north-westerly. The major magnetic features occur on the flanks of the central Bouguer anomaly ridge with a positive feature on the north flank, negative on the south. The nosing feature of seismic Trend E coincides roughly with the axis of the province.

The correlation between magnetic and gravity anomalies indicates that the cause of the gravity feature also exhibits a considerable susceptibility contrast with the surrounding rocks. On land, the sedimentary structures are generally flat-lying and show little correlation with the Bouguer anomaly features. The evidence suggests two possible explanations: intrusive bodies within the sediments (or basement), or horizontal density and susceptibility constrasts within metamorphic rocks in the basement. It is felt that the second interpretation is the more likely.

Province XII

The province consists of a broad Bouguer anomaly ridge with intense local culminations within it. It may be traced for over 500 miles onshore as the Anketell-Warri Regional Gravity Ridge (Flavelle, in prep.), with a striking north-westerly trend. The larger northernmost culmination has associated magnetic anomaly features showing the familiar dipole pattern. The base Tertiary level is fairly shallow throughout the province.

The province probably outlines an ancient mobile belt separating the West Australian Shield from the Canning Basin. It is believed that the mobile belt was active from Lower Proterozoic to early Cambrian times (Flavelle, in prep.).

Province XIII

A series of intense positive and negative Bouguer anomaly features occur within this province. Some, but not all, of the positive gravity features appear to be correlated with magnetic features. The area corresponds to the shallow-high-velocity Regime 6, and ?basement is very shallow throughout the area.

The province corresponds approximately with the presumed offshore extension of the Pilbara Block. The intense gravity 'low' features onshore are probably caused by granitic intrusions, and a similar explanation of the offshore features is reasonable. The positive Bouguer anomaly features could be caused either by dense igneous bodies or by zones of intensely metamorphosed rocks, the latter being more consistent with the known geology.

10. CONCLUSIONS

Interpretation of ~~the~~ preliminary results on a regional scale has provided a picture of the geology of the North-west Continental Shelf that is considerably at variance with previously conceived ideas (e.g. Fairbridge, 1953b; Boutakoff, 1963; Veevers, 1967). The final results may alter the interpretation in detail, but it is felt that the broader conclusions will remain unaltered.

These are:

1) There appears to be little evidence for a basement ridge along the edge of the continental shelf extending from the Barrow Island area to the Sahul Banks. Possibly a basement ridge occurs to the west of Barrow Island, but it is interpreted as a feature on the periphery of the Pilbara Block.

2) The only area where there appears to be reasonable evidence for an offshore basin paralleling the coast is around Browse Island. Elsewhere the results indicate a sedimentary wedge thickening towards the edge of the continental shelf.

3) Despite these somewhat negative results, the survey has revealed five new structural trends within which are about 22 closures or nosing features that warrant further attention by oil search operators. Many intra-section reefs occur along the edge of the shelf; these may also be worthy of further study.

4) In the central part of the survey area, the onshore tectonic features extend offshore almost to the edge of the continental shelf. The King Leopold Mobile Belt and Canning Basin appear to be buried under an increasing depth of Tertiary deposits away from the coastline.

5) In the south-west the tectonic trends, as shown by the gravity and magnetic results, bound the Pilbara Block, which appears to extend out towards the edge of the continental shelf. These trends could be relics of ancient mobile belts formed around the periphery of the West Australian Shield.

6) A large area of anomalously thick crust has been found beyond the edge of the continental shelf to the west of Barrow Island. A large bathymetric rise in the area appears to demarcate an area of continental-type crust upon which there is several thousand feet of sediment that demonstrates normal shallow-water-type faults and folding.

Several problems have been outlined by the preliminary interpretation, which are being studied further. Although provinces showing common internal magnetic and gravity characteristics can be defined, simple theories to explain the origin of some of the provinces do not come to mind. The most intense Bouguer anomaly and dipole magnetic anomaly features can be explained in terms of likely intra-basement density and susceptibility constrasts. However, the smaller features are difficult to explain. The small features generally show positive correlation; i.e. the magnetic and Bouguer anomaly features are both positive or both negative, and do not show a dipole pattern.

The reduction of data for the final results has pin-pointed a considerable number of areas where the data collection and reduction techniques could be imporved:

1) Errors in the satellite doppler fixes are not yet assessed. The final accuracy of fix depends primarily on velocity control, which still needs improvement. Final assessment requires an estimate of the error in position for unit velocity error for all fixes, and the velocities used in the satellite fixes should be compatible with the derived interval velocities.

2) There are still considerable gaps in our knowledge of v.l.f. radio wave propagation. Further analysis is needed of the 1968 survey data to try and fill these gaps, particularly concerning diurnals and variation in diurnal with position. Tighter data quality control than applied on this survey is necessary.

3) The sonar doppler equipment still does not reach the accuracy requirements necessary for this type of work, or the specifications given for the equipment in the manufacturer's literature. The Edo Western system had an accuracy of five percent. It clearly had inherent faults in system design, which are now being rectified. Manufacturers are now claiming that 0.1 percent accuracy is possible. Accurate calibration and control is essential to approach such accuracies under operationsl conditions.

4) Back-up in depth is required in the navigation system if 24-hours-a-day operation is to be maintained. Ship's log and engine revs need to be continuously monitored and recorded despite the more sophisticated and more accurate navigation equipment on board. Complete duplication of some systems could possibly be the best approach.

5) Complete digital recording of all observed parameters has been shown to be essential by this survey. To make optimum use of such a system, on-board facilities for checking the input to the digital system are required.

6) To achieve maximum accuracy in navigation, gravity, and magnetic figures, all traverse line intersections need to be relocatable with an accuracy at least equalling the best on-board navigation system. A range expander (preferably digital) for the radar system and a more robust form of buoy that will survive at sea for periods greater than one month are required. A more self-contained compact cruise pattern to reduce the period before return to a marker buoy is also desirable.

7) A six-channel cable capable of being towed at 10 knots is almost essential to obtain useful reflection information in shallow-water and poor-reflection areas. Combined with this, increase in sparker energy would give greater depth of penetration. At the moment, almost no useful information at reflection times greater than about one second is obtained in shallow water.

8) The sonobuoy refraction system could be considerably improved with attention to detail. This includes use of low-frequency transducers, improved transmitter frequency response and aerial design, and a preamplifier at the base of the receiver aerial.

9) Other possible improvements are variations in the gear ratios of the helical drive motors of the E.G. & G. recorder to allow refraction shooting without changeover of the helix motors, changes in the paper-drive speed to give improved section presentation, and running the sparker and cable at a depth of one quarter wave-length to use ghost reflection interference constructively.

TABLE 1

DIFFERENCE BETWEEN SATELLITE AND SONAR DOPPLER VELOCITIES

(averaged between satellite fixes)

Water Depth	Number of Observations	Mean Difference	Standard Deviation
15	1	1.12	-
20	10	0.56	0.52
25	24	0.54	0.35
30	24	0.51	0.27
35	25	0.57	0.34
40	20	0.44	0.51
45	17	0.60	0.49
50	17	0.72	0.40
55	14	0.75	0.38
60	7	0.92	0.53
65	13	0.88	0.23
70	6	1.06	0.27
75	6	0.73	0.18
80	10	0.75	0.50
85	5	0.64	0.58
90	2	0.84	0.14
95	3	1.07	0.36
100	2	0.16	0.75
105	-	-	-
110	1	0.96	-

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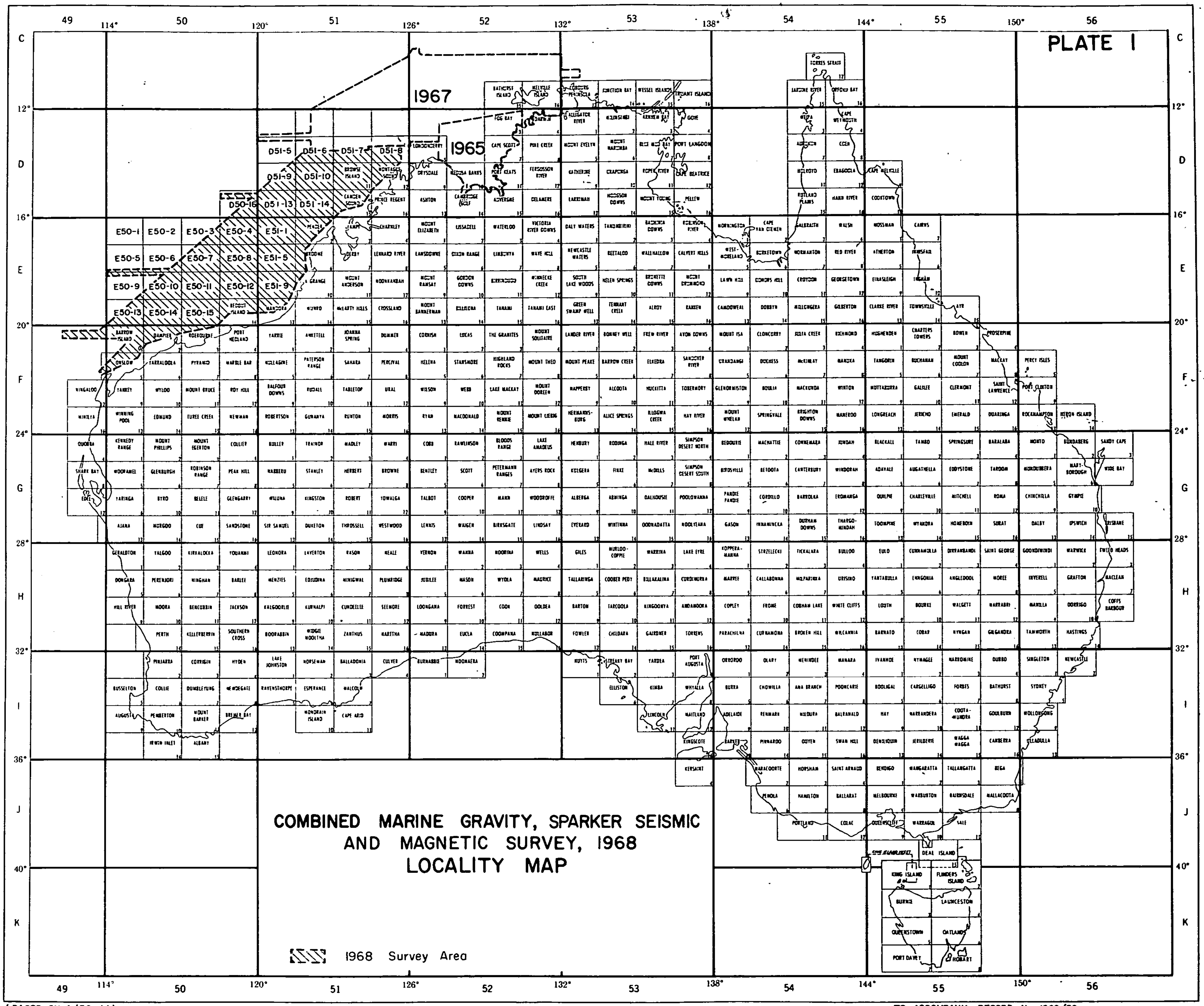


(BASED ON A/80-14)

TO ACCOMPANY RECORD No. 1969/99

A/B2-34

PLATE 2

Yampi 1:250,000 Map area

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968
TRAVERSE PLAN

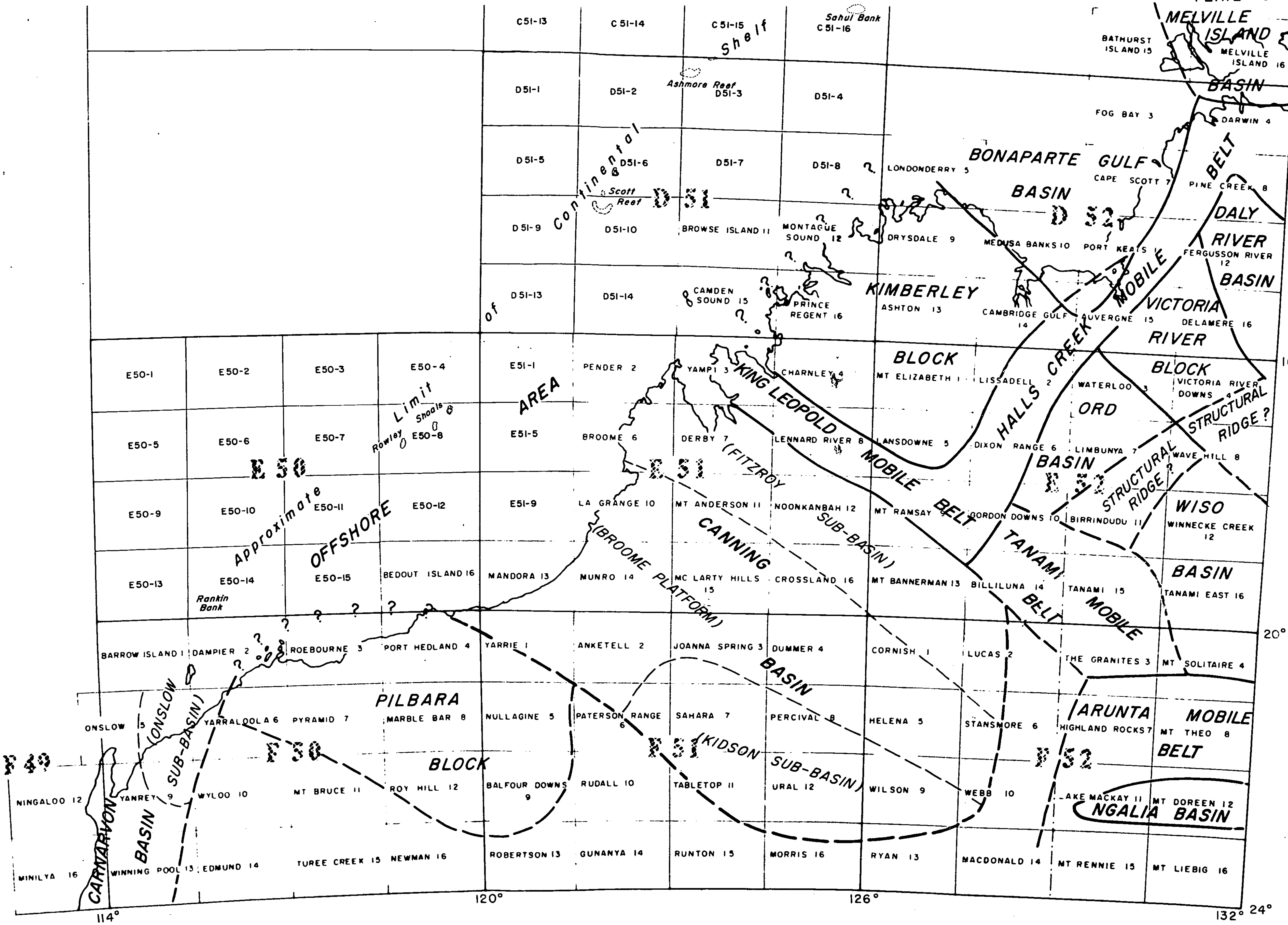
SCALE
40 20 0 40 80 MILES

- - - - - 1967 WORK
FIRST CRUISE 1968
SECOND CRUISE 1968
THIRD CRUISE 1968
REFRACTION SPREADS

TO ACCOMPANY RECORD No. 1969/99

WA/B8—4

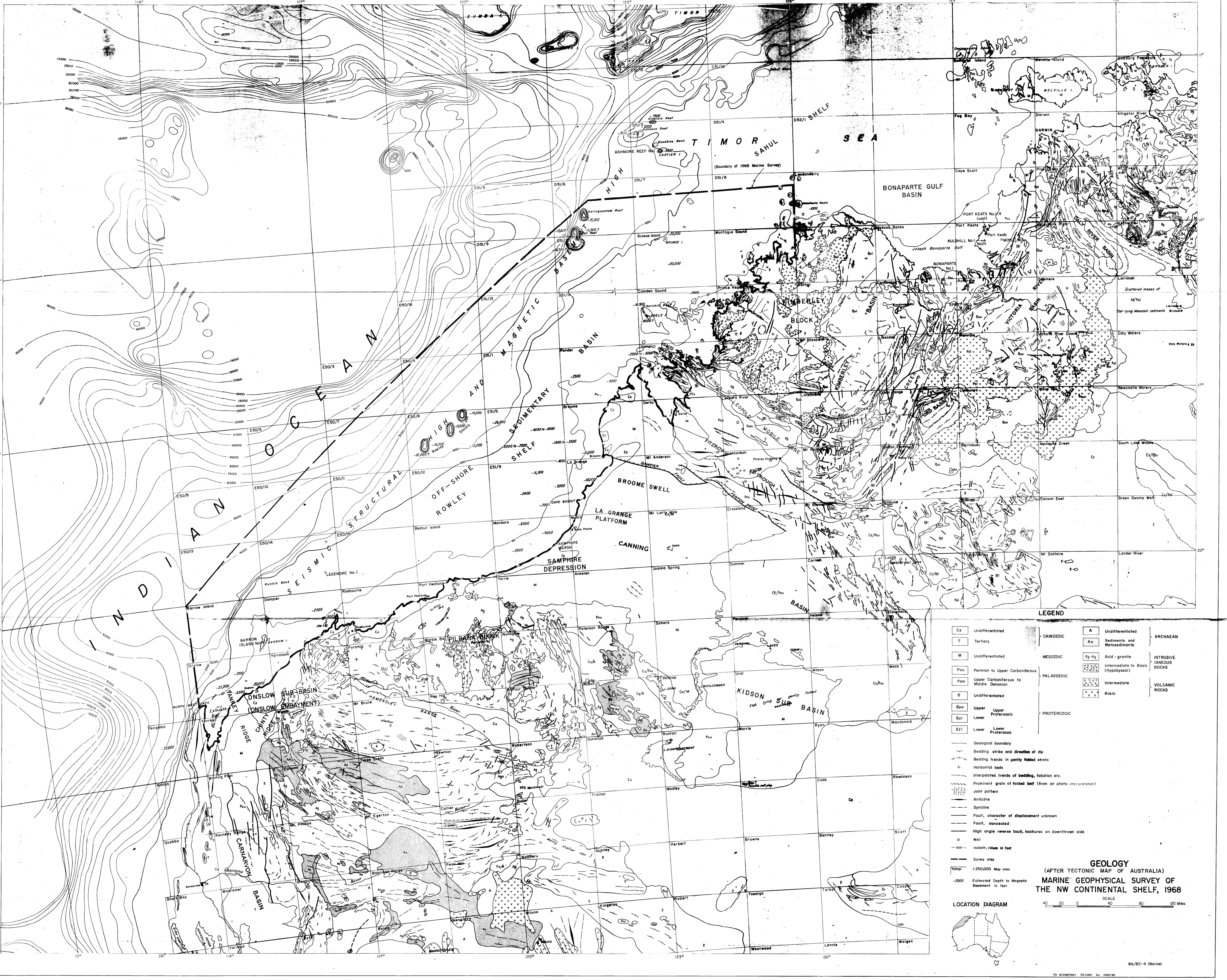
PLATE 3



MARINE GEOPHYSICAL SURVEY OF
THE NW CONTINENTAL SHELF 1968
GEOLOGICAL UNIT BOUNDARIES

TO ACCOMPANY RECORD No. 1969/99

WA/B8-7



TO ACCOMPANY RECORD No. 1969/99

LEGEND

Loop misclosure, milligals

Yampi 1:250,000 Map area

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968 GRAVITY LOOP MISCLOSURES

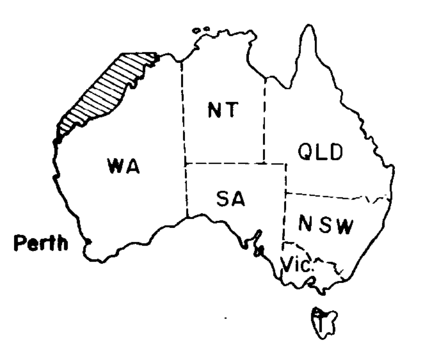
SCALE

40 20 0 40 80 MILES

- 1967 WORK
- FIRST CRUISE 1968
- SECOND CRUISE 1968
- THIRD CRUISE 1968
- REFRACTION SPREADS

TO ACCOMPANY RECORD No. 1969/99

WA/B8-4-1



Survey area

Yampi 1:250,000 Map area

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968

WATER DEPTH

SCALE

40 20 0 40 80 MILES

Contour Interval 100feet
Note: Interval change at 2000 feet

Yampi 1:250,000 Map area

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968
MAGNETIC CONTOURS

SCALE

40 20 0 40 80 MILES

DEC.17, 1968

CONTOUR INTERVAL . 100 gammas

TO ACCOMPANY RECORD No. 1969/19

WA/B8-5

PLATE 8

LEGEND

Munro	1:250,000 map area
▲	Isogal primary station
△	Isogal secondary station
▥▥▥	Province boundary

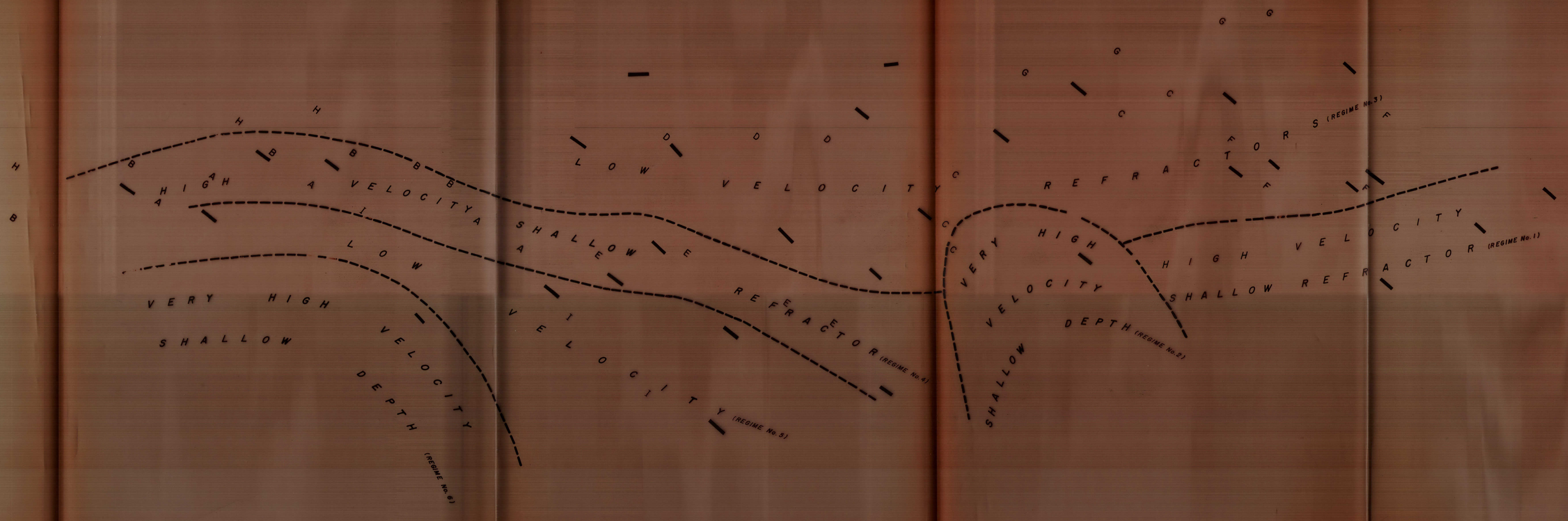
MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968

PRELIMINARY
BOUGUER ANOMALIES
AND
GRAVITY PROVINCES

SCALE
40 30 20 10 0 40 80 MILES

TO ACCOMPANY RECORD No. 1969/99 WA/B2-3-1(marine)

PLATE 9



Regime boundary

A Seismic trends, as referred to in text

Refraction profile site

REFRACTION VELOCITY REGIME BOUNDARIES

TO ACCOMPANY RECORD No. 1969/99 WA/B2-22

Yampi 1:250,000 Map area
▲ Isogal primary station
Δ Isogal secondary station

—0·6— Seismic contour, two-way reflection time in seconds, corrected for depth of water. Contour interval 0·1 sec.

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968

CONTOURS SHOWING NEAR— BASE TERTIARY— HORIZON

SCALE

40 20 0 40 80 MILES

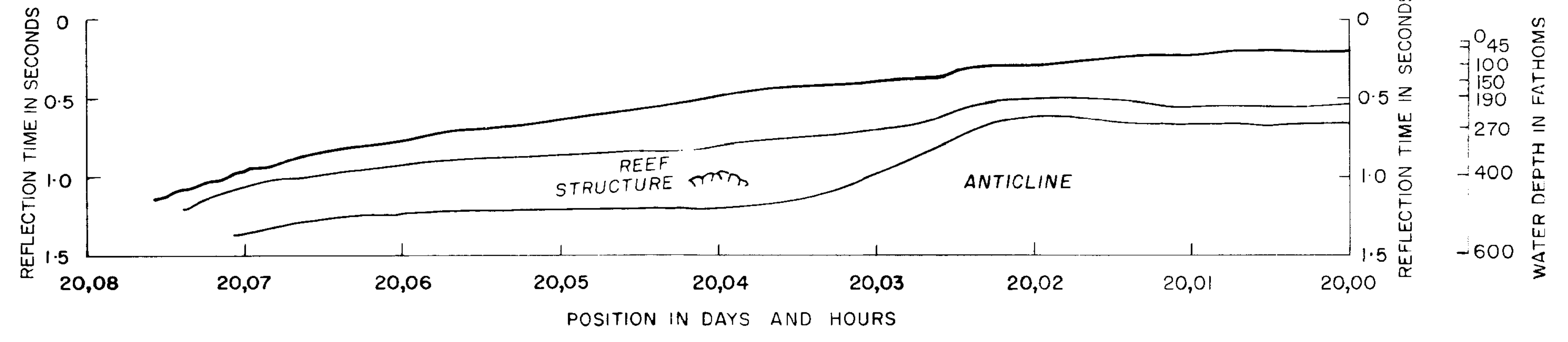
TO ACCOMPANY RECORD No. 1969/99 **WA/B2—20**

Lines 44 and 144 show typical seismic reflection results obtained in water depths greater than 100 fathoms.

Line 44 off the Kimberley coast; the shelf slopes more or less continuously and gently to the western end of the line where the wrinkled and more steeply dipping surface marks a realistic edge of the shelf in 350 fathoms of water. The section shows an anticline in 100 fathoms of water, and a reef structure in about 190 fathoms.

In the case of line 144 to the west of Barrow Island, the shelf is relatively flat and the main break occurs at around 100 fathoms. The line shows an anticline of enormous dimensions (60 miles wide, 2000 ft of relief), in about 450 fathoms of water, as well as two smaller ones closer inshore. All three lie beyond the continental shelf.

LINE 44



LINE 144

LEGEND

- Water Bottom
- Reflection Horizons

DEEP WATER SEISMIC REFLECTION SECTION SKETCH

SCALES (approx)

HORIZONTAL 10 0 10 20 30 40 MILES

VERTICAL 5000 0 5000 10,000 15,000 20,000 FEET (for sediments)

Vertical exaggeration about 10:1 for sediments at 10,000 ft/sec
" " " 20:1 for bathymetry at 5 000 ft/sec

TO ACCOMPANY RECORD No. 1969/99

WA/B3—3