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BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record No. 1969 / 40

Timor Sea Gravity, Magnetic, and Seismic Survey, 1967

Survey 3

by

B.F. Jones

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SUMMARY

An offshore sparker seismic, gravity, and magnetic survey has been made over the Australian continental shelf within the Timor Sea by the Bureau of Mineral Resources, Geology & Geophysics (BMR). To overcome the limitations of conventional navigation systems commonly used for geophysics - viz. short range and/or sky-wave interference at night - an attempt was made to navigate by range range methods in relative mode by reference to frequency-stabilised v.l.f. stations around the world and by use of the doppler principle in a sonar system. In spite of many difficulties an effective survey was achieved. Over 13,000 nautical miles of traverse was run during 70 days at sea.

The area of the survey may be subdivided into seven Regional Gravity Provinces; in some instances these express intra-basement density variations, in others tectonic movement and associated basement 'high' or sedimentary thickening. Faulting is the principal tectonic phenomenon on the continental slope. A number of anticlinal and diapiric features were observed.

Note: Full-size dyeline copies of the original seismic "Spark-array" sections may be purchased from:

Production Section
Government Printing Office,
Wentworth Avenue,
Kingston, Canberra, ACT 2604

A list of sections available, and prices, may be obtained from the Government Printing Office.

1. INTRODUCTION

The world-wide trend towards a change in accent from land to offshore areas in geophysical exploration for petroleum has been followed in Australia, where the volume of prospective sediments offshore is equal to that on land while the volume of post-Palaeozoic sediments offshore is about twice as large. This trend has been given particular impetus in Australia by the discovery of large oil and gas reserves in the offshore Gippsland Basin.

In 1965, the Bureau of Mineral Resources (BMR) carried out a reconnaissance gravity and marine seismic survey in the Timor Sea-Joseph Bonaparte Gulf area of north-west Australia (Smith, 1966; Geophysical Associates, 1966) to assist in the offshore exploration of the continent, and to show the feasibility of using surface-ship gravity meters for exploration purposes. The present (1967) survey is an extension to that work undertaken because of the success of the 1965 work in both gravity and seismic results. Continuous magnetic profiling also was done in 1967.

The survey area is shown in Plate 1 and has as its boundaries the 1965 survey area, the coastline, longitude 132° east, latitude 9° south, the 500-fathom isobath and latitude 13° 20' south. This area covers a part of the continental shelf which was known to contain deep sediments from previous seismic and aeromagnetic work, and so the survey was intended to provide gravity coverage and increase the seismic coverage on the continental slope as well as to act as a tool for synthesis of previous results. The full objectives are set out in Chapter 4.

The gravity meter used was an Askania Gss-2 mounted on a gyro-stabilised platform, with an analogue computer to continuously make cross-coupling corrections. The system and its performance are discussed in Appendix C.

The magnetometer used was a towed proton precession type; a second proton precession magnetometer was stationed outside Darwin to monitor diurnal charges in the Earth's field. As this second magnetometer did not record continuously over the survey period, some total field diurnal data were computed from the records of the Port Moresby Observatory. The equipment and its performance are described in Appendix E.

The seismic equipment consisted of a 21,000-joule "spark-array" source, a 6-channel streamer cable, a single-channel high-resolution cable, and a reserve single-channel cable. Recording was on FM magnetic tape with two facsimile recorders as visual monitors. The system is described more fully in Appendix D.

The measurement of gravity at sea requires extremely accurate navigation; for 1-milligal accuracy, for example, the ship's east-west speed in relation to the Earth must be known to about 0.1 knots and its latitude to about 1½ minutes (in the latitudes concerned in this survey). In the past, this sort of accuracy has been possible only with shore-based hyperbolic radio navigation networks such as Toran, which was used in the 1965 survey. These systems are, however, very expensive to install and operate, have a limited range, and typically operate only during daylight in the tropics. This survey, therefore, used a combination of v.l.f. radio navigation for position fixes and sonar doppler navigation for ship's speed (see Appendix B). Navigation was checked by celestial fixes, radar ranges, sightings on known land features where land was within sight, and by the use of anchored buoys at line intersections.

M.V. HAMME 180

The survey was carried out under contract to BMR by United Geophysical Corporation, who used the M.V. "Wyrallah", a 215-foot North Sea trawler type vessel of gross tonnage 1062 tons. Most of the geophysical instruments were housed in a converted refrigerated cargo area, and the gravity meter was mounted as near as possible to the ship's centre of motion.

The survey was conducted out of Darwin and the survey data were recorded during 70 days spent at sea between 23 September and 21 December 1967. The weather remained calm and sunny for most of the survey, and 13,050 nautical miles of line were completed. The lines are shown in Plate 1.

2. GEOLOGY

Knowledge of the geology of the north-western continental shelf of Australia is restricted to inferences drawn from geophysical and bathymetric data, extrapolation from onshore geological knowledge (particularly structural trends, stratigraphy, and nature of the basement), and from one stratigraphic well: Ashmore Reef No. 1. A discussion of geophysical results is given in the following chapter.

In the Timor Sea area, the continental shelf extends 200 to 300 miles out from the coast, and geophysical results show that it contains depths of 20,000 feet or more of relatively young sediments, probably mainly Tertiary and Mesozoic. The land area, which borders the shelf to the south and east, has remained relatively stable since Precambrian times and can be considered part of the Australian Precambrian shield. The shelf is terminated to the north-west by the Timor Trough (Plate 2), a north-east elongated feature which is up to 10,000 feet deep and which separates the Australian continent from the young orogen of the Timor-East Celebes Geosyncline.

Tectonic and structural trends, land area

The relevant land area has been conveniently divided into regional structural units by Traves (1955). These are:

1. Halls Creek Mobile Zone: A zone of Lower Proterozoic metamorphic and granitic rocks stretching from the vicinity of Halls Creek in a north-easterly direction to east of Port Keats, and probably as far as Darwin.

2. Pine Creek Mobile Zone: The Pine Creek Geosyncline, consisting of Lower Proterozoic sediments and granites, trending in a north-westerly direction from Katherine to Darwin.

3. King Leopold Mobile Zone: A zone of Lower Proterozoic sediments and metamorphics, intruded by granites, trending in a north-westerly direction to the north of Derby and Fitzroy Crossing.

4. Kimberley Block: An area of sub-horizontal Upper Proterozoic sediments, bounded in the south by the King Leopold and Halls Creek Mobile Zones and extending to the coast in the north.

5. Sturt Block: An area of sub-horizontal Upper Proterozoic sediments to the east of the Halls Creek Mobile Zone.

6. Bonaparte Gulf Basin: A basin of marine Palaeozoic and Mesozoic sediments bounded in the East by the Halls Creek Mobile Zone, in the south-west by the Kimberley Block, and probably extending to the continental slope in the north-west where it probably also contains Cainozoic sediments.

7. Canning Basin: A basin of marine Palaeozoic and Mesozoic sediments, with possible Cainozoic sediments offshore. It is situated south of the King Leopold Mobile Zone and has a deep trough of sediments, the Fitzroy Trough, extending along its northern margin adjacent to, and parallel with, the King Leopold Mobile Zone.

These units reveal striking trends which are, to some extent, paralleled by the offshore morphology (Plate 2). The Fitzroy Trough and King Leopold Mobile Zone, the south-west margin of the Bonaparte Gulf Basin, the north-east margin of the Kimberley Block, and the Pine Creek Mobile Zone trend in a north-west direction. The Halls Creek Mobile Zone, the eastern margins of the Bonaparte Gulf Basin (southern part), and gross segments of the coastline trend north-east. These two trends are also exhibited by major joint systems in the Kimberley Block and faulting in the Bonaparte Gulf Basin. These trends are primarily lineaments in the Precambrian rocks. The northern part of the eastern margin of the Bonaparte Gulf Basin and faulting and jointing immediately south of Darwin show a north-south trend.

Tectonic and structural trends, shelf area

Van Andel, Curray and Veevers (1961) and van Andel and Veevers (1967) have made studies of the sea bed morphology in the Timor Sea region. The trends of the Lévèque Rise and the West Londonderry Rise (Plate 2) parallel the north-west trend recognised onshore. The Sahul Rise, the southern part of the Malita Shelf valley, the edge of the continental shelf and the Timor Trough parallel the north-east trend. The northern part of the Malita Shelf Valley and a sea-valley between Bathurst Island and Van Diemen Rise parallel the northern trend. The system of rises (10-45 fathoms deep) encloses the Bonaparte Depression which has a mean depth of 65 to 70 fathoms and towards which the inclination of Pleistocene and post-Pleistocene terraces on the surrounding banks suggests that the downwarping of the depression was a recent process (or at least continued until recent times).

The shelf morphology in the Timor Sea region thus suggests the offshore continuation of the land tectonic trends; in particular the concept that the rises correspond to areas of relatively shallow Precambrian rocks and the Bonaparte Depression to a seaward extension of the Bonaparte Gulf Basin presents itself. This concept is generally confirmed by aeromagnetic and seismic results.

The trend of the Sahul Rise is continued to the south-west by a line of bathymetric "highs" which extends about 1200 miles: Ashmore and Hibernia Reefs, Scott Reef, Rowley Shoals, and Montebello and Barrow Islands. At its south end, the trend of the line parallels the trends of the Rough Range, Barrow, and Cape Range Anticlines; thus Boutakoff (1963) has suggested a structural origin for these bathymetric "highs". This line corresponds to indications of relatively shallow magnetic basement shown by aeromagnetic work, so Veevers (1967a) has named the inferred basin, which lies inshore from the line, the Cartier Furrow. The Cartier Furrow is thus postulated as a sediment-filled furrow, at least 800 miles long, which trends north-east and lies on the shelf with its axis inshore from the line of bathymetric "highs". It will be seen later that the results from Ashmore Reef No. 1 will throw some doubt over the validity of Veevers' magnetic interpretation but in the broad sense his concept may be correct, particularly in the Palaeozoic. He considers that the Bonaparte Gulf and Canning Basins are onshore extensions of the Cartier Furrow and cites the similarity of contemporaneous deposits in these basins as additional evidence, although the Furrow must contain more and younger sediments than the basins to explain the indicated magnetic basement depths of 20,000 feet.

Stratigraphy - introductory remarks

Seismic and aeromagnetic surveys (see next chapter) have shown the existence of a large area of thick sediments offshore. In considering the possible stratigraphic succession in these areas, the most relevant evidence comes from Ashmore Reef No. 1 well, the onshore part of the Bonaparte Gulf Basin, and possibly the island of Timor. The geology of the Canning Basin and the Arafura Basin, although these do not directly border the survey area, is of indirect importance.

Stratigraphy, Bonaparte Gulf Basin

The geology of the Bonaparte Gulf Basin as then known was discussed rather fully by Traves (1955). Considerable geological and geophysical exploration has been carried out since then and Drummond (1963) has reviewed and re-interpreted the geology of the Basin (Reynolds et al., 1963). More recent contributions by Veevers et al. (1964), Kaulback and Veevers (1965), Veevers and Roberts (1966, 1966a, 1967), and Roberts and Veevers (1967) and the drilling of six wells have caused further revision of the stratigraphy. The following table and discussion is a summary of present knowledge based on all of this work. The data apply only to that put of the basin which is on land.

TABLE 1

STRATIGRAPHIC COLUMN, BONAPARTE GULF BASIN AND ADJACENT AREAS

Age	Stratigraphic Unit	Description	Thickness
Lower Proterozoic	Halls Creek Metamorphics	Metamorphosed sediments, sandstone, quartzite, slate, phyllite, schist and volcanics	-
	Lamboo Complex	Intrusives into and granitised Halls Creek Metamorphics - granite, gneiss, granodiorite	-
U N C O N F O R M I T Y			
Upper Proterozoic	King Leopold Formation	Sandstone and quartzite	1500' +
	U N C O N F O R M I T Y		
	Possibility of volcanics (Mornington Volcanics)		
	Warton Beds	Sandstone and shale (with dolomite)	4000' +
	U N C O N F O R M I T Y		
	Possibility of Walsh Tillite		
	Mount House Beds and Victoria River Group	Sandstone, shale and limestones with some dolomite	2000' 3000' +
U N C O N F O R M I T Y			
Lower Cambrian	Antrim Plateau Volcanics	Basalts, agglomerates, and tuffs	up to 3300'
	U N C O N F O R M I T Y		
	Blatchford Formation	Dolomite and quartz sandstone	400'
Middle Cambrian	Tarrara Formation	Shale, sandstone, dolomite	200'-1300'
Lower Palaeozoic (Carlton Grp) (U. Mid. Camb. to Lower Ord.) (4000' +)	Hart Spring Sandstone	Sandstone, limestone, shale	500' +
	Skewthorpe Formation	Limestone, shale, and sandstone	600' +
	Pretlove Sandstone	Sandstone	400' +
	Clark Sandstone	Glauconitic sandstone	600' +
	Pander Greensand	Greensand and sandstone	500' +

F A U L T E D - P R O B A B L E U N C O N F O R M I T Y			
Middle Palaeozoic (C.D. Group) (Up.Dev. to Low. Carb.) (8000')	Cockatoo Formation	Sandstone, cross-bedded	4000'
	Burt Range Formation	Shale, siltstone, sandstone, and limestone	2000'-4000'
	Enga Sandstone	Sandstone	800'
	Septimus Limestone	Limestone and calcareous	400'
	Zimmerman Sandstone	sandstone	
	Milligans Beds and Bonaparte Beds	Dark shale with interbedded sandstone and siltstone	5600'
	Tanmurra Formation	Sandstone, calcarenite, limestone oolite	1000'
	Point Spring Sandstone	Sandstone, with some limestone	600'
D I S C O N F O R M I T Y			
Upper Carboniferous	Border Creek Formation	Sandstone, with conglomerate	1000'+
U N K N O W N			
Permian-Triassic	Keep Inlet Beds	Sandstone, with conglomerate	?
	U N K N O W N		
	Port Keats Group	Sandstone, shale, and limestone with coal	5800'
D I S C O N F O R M I T Y			
Mesozoic	Mullaman Group	Clay and sandstone (laterite cap)	100'-1000'
????????????			
Tertiary	White Mountain Formation	Siltstone, chert and marl	370'

The Bonaparte Gulf Basin is an area of Palaeozoic sediments covering about 8000 square miles on land adjacent to Joseph Bonaparte Gulf (Plate 2). It is bounded on land by the Precambrian rocks of the Kimberley Block and the Halls Creek Mobile Zone, and has a seaward extension on to the edge of the continental shelf which probably contains the major part of the volume of sediments in the Basin. The known stratigraphy of the Basin is restricted to the land area and is a record of repeated marine invasion followed by uplift and denudation. During Palaeozoic time, there were three such invasions, in which considerable sedimentation took place with a possible total thickness of the order of 15,000 feet. There have probably been further widespread transgressions during Mesozoic and Tertiary times, but only isolated remnants of these sediments remain on land.

The basement rocks of the Bonaparte Gulf Basin probably consist of types from three different groups of rocks. Lower Proterozoic metasediments of the Halls Creek Metamorphics and granitic rocks of the Lamboo Complex crop out in the Halls Creek Mobile Zone and probably underlie the Palaeozoic sediments along the eastern margin of the Basin, adjacent to the Halls Creek Mobile Zone. Upper Proterozoic sandstone, quartzite, shale, limestone, and dolomite are exposed on the Sturt and Kimberley Blocks and most likely extend under the Basin in the parts away from the Halls Creek Mobile Zone. In Lower Cambrian time, a large thickness of volcanic rocks consisting of basalt, agglomerate, and tuff of the Antrim Plateau Volcanics was extruded. These volcanic rocks cover a large area of the inland plateau country, and although there are only limited outcrops of them around the margins of the Bonaparte Gulf Basin, they could well form the basement to a large part of the Palaeozoic sediments of the Basin.

The earliest Palaeozoic sediments known in the general area are the Middle Cambrian shales and limestones of the Ord Basin, a small basin to the south of the Bonaparte Gulf Basin and separated from it by the Halls Creek Mobile Zone (Plate 2). However, these sediments have not been found in the Bonaparte Gulf Basin, although their equivalent may be present in the deeper parts of the Basin. Along the south-western margin of the Bonaparte Gulf Basin, the Upper Proterozoic sediments and the Antrim Plateau Volcanics are unconformably overlain by about 400 feet of late Lower Cambrian dolomitic quartz sandstone and siltstone and dolomite (Blatchford Formation) and by 200 feet (possibly up to 1300 feet) of early Middle Cambrian shale, sandstone, and dolomite (Tarrara Formation). This sequence is overlain by a marine sequence of 3000 to 4000 feet of upper Middle Cambrian to Lower Ordovician sandstone, with minor shales and limestones, which have been named the Carlton Group. The top 1000 feet of the section becomes glauconitic and finishes with 500 feet of greensand.

The Middle and Upper Ordovician, Silurian and Lower Devonian are not represented by 5000 feet of shallow-water quartz sandstone, conglomerate and carbonate (Cockatoo Formation), overlain by 1000 feet of reef limestone (Ninbing Limestone), and 1100 feet of equivalent lagoonal carbonate and sandstone.

The marine depositional period which began in the Upper Devonian continued into the Lower Carboniferous, which is represented by a marine platform succession 600 feet thick and an equivalent 10,000-foot sequence of basinal sediments. The platform succession (Burt Range Formation, Enga Sandstone, Septimus Limestone, Zimmerman Sandstone, Milligans Beds, Utting Calcarenite, Burvill Beds, Waggon Creek Breccia, and Point Creek Sandstone) contains quartz sandstone, calcarenite and shale; the basinal succession (Bonaparte Beds, and Tanmurra Formation) contains siltstone and shale with minor sandstone and limestone.

The beginning of a paralic episode that continued through the Permian into the Lower Triassic is marked by Upper Carboniferous quartz sandstone, siltstone, and conglomerate a few hundred feet thick (Border Creek Formation) which disconformably overlie the Lower Carboniferous.

Isolated outcrops of clastic rocks have been described from the Keep Inlet area by Associated Australian Oilfields (1955) and are referred to as the "Keep Inlet Beds". These presumably overlie the Border Creek Formation and are considered to be Upper Carboniferous to Permian. They consist of calcareous quartz sandstone with pebbles and boulders, which are considered (Glover et al., 1955) to be of glacial origin. North of Queens Channel, about 6000 feet of sandstone, siltstone, and shale, with coal, crops out in a belt extending from Fossil Summit to Point Blaze. Their age probably extends from Lower Permian to Lower Triassic. On the eastern edge of the Basin, they overlie Precambrian rocks unconformably, but their relation to the Palaeozoic formations in the southern part of the Basin, including the Keep Inlet Beds, is unknown. They have been named the Port Keats Group, and Drummond (1963) has tentatively placed the Keep Inlet Beds in this group also.

Sediments of Mesozoic age have a wide distribution in the northern part of the Northern Territory. They occur over a wide area to the south of Katherine, and also at Darwin and on Melville and Bathurst Islands. Noakes (1949) gave the formal name Mullaman Group to these sediments in the Katherine-Darwin region, and recognised two formations, a younger marine formation and an older lacustrine formation. On Melville and Bathurst Islands, the sequence reaches a thickness in excess of 1000 feet. The youngest known rocks of the Bonaparte Gulf Basin occur as small outliers south-east of Port Keats Mission. These consist of a thin veneer of laterite, limonite clay, and sandstone, with a basal conglomerate, the total thickness being of the order of only 100 feet. Traves (1955) and Drummond (1963) have tentatively assigned these sediments to the Mullaman Group.

An isolated outcrop of 370 feet of marine siltstone and sandstone of probable Tertiary age, the White Mountain Formation, occurs at White Mountain in the Ord Basin (Traves, 1955). This deposit is difficult to explain (van Andel & Veevers, personal communication), but may mean a widespread Tertiary transgression.

Drilling in the Bonaparte Gulf Basin has not been extensive so far. At the turn of the century, several coal bores were drilled along the coast from Port Keats to Cliff Head. Port Keats No. 4 and Anson Bay No. 2 reached about 1500 feet in Permian sediments. Cliff Head No. 1 reached granitic basement at 728 feet.

Six oil exploration bores have been drilled in the Bonaparte Gulf Basin. Spirit Hill No. 1 (Westralian Oil Ltd., 1963), drilled to 3003 feet in overlying a sequence of dolomite, limestone, dolomitic sandstone, and Lower Carboniferous Burt Range Formation. Slight oil traces were obtained in the shale, suggesting that it may be a potential source rock for petroleum. Bonaparte No. 1 (Alliance Oil Development, 1964a) was drilled in the north-west part of the Basin to a total depth of 10,530 feet. It penetrated 7480 feet of Bonaparte Beds, including 5850 feet of the lower shale unit, and then passed through 3050 feet of Lower Carboniferous to Upper Devonian sandstone, siltstone, and shale. The Bonaparte Beds were considered to provide excellent source rocks for petroleum, and as these were interbedded sandstones, it could also form the necessary traps. This was confirmed by Bonaparte No. 2 (Alliance Oil Development, 1965), five miles south of Bonaparte No. 1, which penetrated a similar but slightly thinner section of Bonaparte Beds and produced gas at rates up to 1,540,000 cubic feet per day from a thin sandstone member in the Bonaparte Beds. A (see below)

Kulshill No. 1 (Australian Aquitaine, 1966a), sited about 12 miles south of Port Keats, has given the most complete section of the Lower Permian known in the Basin. The Lower Carboniferous sequence encountered was comparable to that encountered in the Bonaparte wells. The total depth of 14,416 feet included about 6000 feet of Permian, 6100 feet of Lower Carboniferous and 2000+ feet of Upper Devonian, in which the drilling was stopped. Several minor oil and gas shows were found in the Lower Permian and the upper part of the Lower Carboniferous but no flows were obtained. Kulshill No. 2 (Australian Aquitaine, 1966b) was drilled about three miles south of No. 1 where the section was structurally higher. It encountered 5000 feet of Lower Permian and 1300+ feet in the Lower Carboniferous, reaching a total depth of 6432 feet in the Lower Carboniferous Bonaparte Beds. Oil traces were found in the Microconglomeratic Shale Member of the Lower Permian Kulshill Formation (Port Keats Group) and in the upper member of the Lower Carboniferous Bonaparte Beds. The shows were not as extensive or as common as in Kulshill No. 1 and failed to flow again, being restricted to impermeable strata. Moyle No. 1 (Australian Aquitaine, 1966c) was drilled about 23 miles east of Port Keats Mission to a total depth of 1767 feet. It passed from the Lower Permian into a tholeiitic gabbro at 1698 feet. The gabbro gave an absolute age determination of 1400 to 1500 million years (Proterozoic) and may be in the form of a regional sheet. No gas or oil traces were found in this well.

Stratigraphy, Canning Basin

The stratigraphy of the Canning Basin is included because it has a seaward extension onto the shelf south of the survey area and may thus be relevant to the survey area (see Veevers' Cartier Furrow concept).

Insert missing line at A above
the south-east part, encountered 800 feet of shale of the Milligans Beds,

The Canning Basin has an area, on land, of about 150,000 square miles. The basement consists of Lower Proterozoic igneous and metamorphic rocks overlain by Upper Proterozoic sediments and intrusives.

The stratigraphic sequence of the Phanerozoic section (Veevers & Wells, 1961) starts with some 3000 feet of widespread Lower and Middle Ordovician shallow marine limestone, dolomite, siltstone, shale, and sandstone. Eight thousand six hundred feet of Upper Ordovician to Middle Devonian red beds evaporites, dolomite, and limestone, discovered by drilling in 1965 (Koop, 1966; Johnson, 1966; Singleton 1965; and Johnstone et al., 1967) overlie these. A major marine transgression in the Middle and Upper Devonian gave some 5000 feet of marine carbonate reef complexes, conglomerate, and calcareous siltstone in the northern part of the basin (Napier Platform) (Playford & Lowry, 1967), with equivalent thick deeper marine siltstone, shale, sandstone, and dolomite southward, in the Fitzroy Trough, and very thin, probably terrestrial, plant and fish-bearing quartz sandstone in the north-east of the Basin. The Lower Carboniferous is represented by 1500 feet of Lower Carboniferous limestone and siltstone (Thomas, 1960) with deeper marine (Shannon, 1966) and terrestrial equivalents (Veevers, Roberts, White & Vermutes, 1967). From the Upper Carboniferous to the Lower Triassic, three and a half rhythmic alternations of shallow marine and estuarine deposition can be recognised: 5000 feet of Upper Carboniferous paralic sandstone, siltstone, shale, and minor evaporites; 14,000 feet of Permian glacigene paralic sandstone, siltstone, tillite, and limestone and 1000 feet of Triassic paralic shale and sandstone. A veneer, probably nowhere thicker than 2500 feet, of Middle Jurassic to Lower Cretaceous shallow marine sandstone, conglomerate, siltstone, shale, and fresh-water sandstone, covers a large part of the Basin. In Tertiary times the Canning Basin was largely a land surface, only the coastal fringes being intermittently submerged.

To date, only 20 wells have been drilled to 4000 feet or more in the Basin. Minor shows of hydrocarbons have been found in the Ordovician limestone and Devonian reef rocks, but the only oil recovered is a very small quantity from Lower Carboniferous sandstone (Reynolds, 1965).

Stratigraphy, Arafura Basin

This name is applied to an outcrop of Upper Proterozoic to Cambrian and Mesozoic sediments bordering the south coast of the Arafura Sea in the north-east of the Northern Territory (Rix, 1963). The land area is only 4000 square miles with a maximum depth of magnetic basement (top of Lower Proterozoic) between 5000 and 10,000 feet. The basement of the Basin consists of Archaean and Lower Proterozoic metamorphic and igneous rocks overlain by Middle and Upper Proterozoic sedimentary rocks. The margins of the Basin are marked by the Proterozoic-Cambrian Wessel Group, 5000 feet of shallow marine lutites, arenites, and carbonates. A very thin Mesozoic section overlies the Wessel Group on land. This section is composed of Lower Cretaceous epicontinental sediments: leached siltstones with a thickness of 200 feet. Aeromagnetic and seismic evidence (see next chapter) show that the Arafura Basin extends offshore to the north under the Arafura Sea where depths to magnetic basement are estimated at up to 20,000 feet. Seismic evidence, however, shows that only 1000 feet or so is Mesozoic, the inference being that the rest consists of thick, folded Upper Proterozoic rocks, although there is a possibility that some Palaeozoic rocks may be present. To the west, the "Mesozoic" section appears to thicken rapidly north of Cobourg Peninsula reaching a maximum depth of 15,000 feet north of Melville and Bathurst Islands. It seems likely that the "Mesozoic" section will here start to include Palaeozoics under the Mesozoic and this area can be considered as part of the north-east extension of the offshore Bonaparte Gulf Basin, the section thickening to the west and to the north (the Mesozoic is only a couple of thousand feet thick on Bathurst and Melville Islands and would seem to lie on basement - a 20,000-ft/s refractor).

Stratigraphy, Ashmore Reef No. 1 Well

This well was drilled by B.O.C. of Australia Limited in 1967 (Burmah Oil Co., 1968) at 12° 10' 49.7" south, 123° 05' 10.6" east. It was drilled into a faulted anticline which culminates just north-east of Ashmore Reef on the outer edge of the continental shelf. As it was the first offshore well drilled in north-western Australia and because of the remoteness of its locality the results are extremely important.

The following stratigraphic sequence was encountered (adapted from Burmah Oil Co., 1968).

TABLE 2

STRATIGRAPHIC SEQUENCE, ASHMORE REEF NO. 1 WELL

Age	Formation	Depth	Thickness
Quaternary/ Pliocene	Foraminiferal limestone and calcarenite	160'-1053'	893'
U N C O N F O R M I T Y			
Early middle to late lower Miocene	Increasingly forminiferal, some crystalline limestone	1053'-2635'	1582'
D I S C O N F O R M I T Y			
Early lower Miocene	Limestone, crystalline to foraminiferal. Calcilutite, argillaceous	2635'-3062'	427'
Oligocene	Intebedded marl and shale	3062'-4009'	947'
D I S C O N F O R M I T Y			
Eocene-Paleocene	Gradational series of carbonates	4009'-6543'	2534'
Paleocene-Upper Cretaceous	Gradational series of marl, limestone, and calcilutite.	6543'-7956'	1413'
U N C O N F O R M I T Y			
Upper Jurassic	Shale, sandstone, and calcarenite	7956'-8102'	146'
	Volcanic beds (basaltic)	8102'-9143'	1041'
U N C O N F O R M I T Y			
Upper Triassic	Upper clastic beds	9143'-11980'	2837'
	Carbonates	11980'-12703'	723'
	Lower clastic beds	12703'-12843' (T.D.)	143'+

The ages given in Table 2 are from palynological, palaeontological, and micropalaeontological studies except for the volcanics, on which a radioactive determination was made.

The 5300-foot interval representing lower Miocene to Upper Cretaceous is dominantly marine and probably represents the most complete time-rock sequence known for this period in the Indo-Pacific region. The sequence above the volcanics resembles the infra-neritic sediments on Timor (see next section) of the same age (B.O.C., pers. comm.). The sequence is, however, different from both Timor and the Carnarvon Basin in the apparent absence of Lower Cretaceous and appreciable Jurassic sediments. The thick sequence below the volcanics, the upper Triassic clastics, shows south-easterly sedimentary dip. This sequence is certainly a shallow-water deposit, perhaps deltaic. Thus, a clastic source area north-west of Ashmore Reef must be postulated; however, the time-equivalent sequence in Portuguese Timor is lithologically very different and shows no evidence of significant amounts of clastic material.

Ashmore Reef No. 1 found no liquid hydrocarbons and only minor indications of methane from the volcanic beds down. The presence of the volcanics, whose areal extent is unknown, is not considered to rule out the petroleum prospects of older sediments in the area. Potential reservoir rocks present were porous Miocene rocks (if a cap rock is present - there is none at Ashmore Reef), a calcarenite facies in the Eocene-Paleocene, and the upper portion of the upper Triassic.

Reinterpretation of the seismic results in the area following drilling indicates that the sequence from Palaeocene to early lower Miocene is regionally thick at Ashmore Reef, so the area was in a regional "low" at these times. The uplift which produced the structure is thus post-early lower Miocene.

Stratigraphy, Timor

There is a great contrast between the long and monotonous geological history of mainland north-western Australia and the disturbed geological history of Timor, Roti, and the other islands of the Outer Banda Arc, which border the Timor Trough on the north-western side. They form part of the highly complex orogen that is the Timor-East Celebes Geosyncline. After Lemoine (1959), the stratigraphy and structural history of the island of Timor may be summarised as follows. A tectonic complex, probably autochthonous (Permian and Triassic flysch with interrelated palaeozoic limestone) and parautochthonous (Jurassic and Cretaceous limestone), is overlian by an overthrust complex of metamorphic rocks, sediments, and volcanics (Permian schist, Jurassic radiolarian jasper, Jurassic and Cretaceous slate, Miocene limestone, conglomerate, and tuff, and lower Miocene reef limestone and tuff), eruptive rocks of Mesozoic and Miocene age, and a thick, tectonically chaotic marl and shale sequence with lenses of massive limestone. During the Miocene, intense deformation accompanied by overthrusting took place. In the Pliocene, a post-orogenic series of coarse clastics (molasse) was formed, and at the end of the Tertiary the island was eroded to sea level and invaded by the sea, while reefs grew up along its margins. Rapid uplift started in the Pleistocene, which brought the island to its present height, while the Timor Trough subsidised. This uplift is probably still continuing. According to van Bemmelen (1949), the island and its neighbours form part of the outer Sunda orogenic arc, while the Timor Trough represents the fore-deep separating it from the Australian continental block. The structural trends of Timor in general are parallel to the axis of the island.

Audley-Charles (1965, 1966a) has concluded, after a study of the Permian and Mesozoic systems of Timor and north-western Australia (the Canning and Bonaparte Gulf Basins), that the spatial relation of these two land masses has remained relatively constant through the Permian and Mesozoic. Mineralogical considerations and evidence of large-scale slumping indicate that the autochthonous Permian rocks of Timor were probably derived as detritus from the Kimberley region, Timor occupying a shallow shelf area. During most of the Mesozoic, the palaeogeographic evidence is interpreted by Audley-Charles as indicating that Timor and Australia were separated by a wide, shallow sea. Crustal downwarping in the Upper Cretaceous resulted in the formation of a major geosyncline centred on Timor. The area between Timor and Australia (including Ashmore Reef, see above) would have become an infra-neritic zone at this time. The Timor Trough was formed, according to Audley-Charles (1966b), during the lower Eocene, when this deep-water zone contracted and moved south and Timor emerged as an island.

Oil and gas occur in two sets of formations (Boutakoff, 1968): in the Permian-Triassic and Jurassic outcrops which are autochthonous updomings forming the central backbone of the island, and in Miocene-Pliocene intramontane troughs which occur on the south coast and extend offshore. All known oil and gas occurences are in autochthonous formations.

Stratigraphy - a synthesis

The Phanerozoic sediments of the Bonaparte Gulf and Canning Basins are known to extend offshore and to be continuous with the sediments that mantle the continental shelf along the whole of north-west Australia. The Bonaparte Gulf and Canning Basins can thus be considered as two onshore extensions of the larger north-west-trending body of thick sediments (the Cartier Furrow of Veevers, 1967a). Veevers points out that the geological unity of the two land basins is indicated by this continuity of offshore structure and by the similarity of contemporaneous deposits in the basins. He discusses this similarity through time in detail. The onshore Phanerozoic rocks show an almost continuous record of deposition except in the Cainozoic, and the Cainozoic is possibly represented offshore. The Phanerozoic sediments were deposited in three environments: on epicontinental marine shelves with shallow (platform) and deeper (basinal) parts during the Middle Cambrian to Middle Ordovician, Upper Devonian and Lower Carboniferous, Middle Jurassic to Lower Cretaceous, and at the present time; on paralic platforms, intermittently continental and marine, during the Upper Carboniferous to Triassic; and on continental platforms in the interval Upper Ordovician to Middle Devonian.

The outer shelf area, as evidenced by Ashmore Reef, contains sediments, deposited in an infra-neritic environment since the Lower Cretaceous, which do not occur on the mainland. They do, however, resemble sediments on Timor, so that the geology of the outer shelf area may be more genetically related to Indonesia in more recent times.

3. PREVIOUS GEOPHYSICS

Aeromagnetic surveys

Timor Sea-Bonaparte Gulf Basin area. An aeromagnetic survey was carried out by the Bureau of Mineral Resources over the Bonaparte Gulf Basin and a large part of south-eastern Joseph Bonaparte Gulf in 1958. The results of this survey (Quilty, 1966) are given as depth-to-magnetic-basement estimates and generalised form lines which show a depression plunging to the north with depth estimates up to 20,000 feet below sea level within the Gulf. These results confirmed the surface geological interpretation of the Bonaparte Gulf Basin deepening to the north under Joseph Bonaparte Gulf.

Woodside (Lakes Entrance) Oil Co. Ltd. (1964) carried out a survey from Derby, Wyndham, and Darwin in 1963. The computed form lines and depths, in general agreement with the survey by the Bureau of Mineral Resources, indicated the possibility of a deep basin trough in the centre of the Joseph Bonaparte Gulf and extending north-west into the Bonaparte Depression (a bathymetric feature). Some magnetic basement depth estimates were greater than 20,000 feet. The western margin of the Basin appeared to trend in a north-west direction from Cambridge Gulf at about 25 miles from the coast. There was an indication that the eastern margin swings sharply eastwards for about 40 miles at Bathurst Island before resuming its northerly trend.

Associated Australian Oilfields N.L. (1963) carried out an aeromagnetic survey in 1963, which covered the whole of O.P. 83 to the west of Darwin. The survey consisted of a series of east-west lines ten miles apart which were flown on dead-reckoning with visual ties to the coastline on their eastern ends. There was no possible correlation of the magnetic readings from line to line, but from the few erratic depth estimates made for the eastern part of the survey, there was an indication that the basement deepens to the west, that is seawards.

Associated Australian Oilfields N.L. (1964) also carried out a reconnaissance survey over Bathurst and Melville Islands (O.P. 8) in 1963, with groups of three east-west lines one mile apart, groups 8 miles apart. This indicated that magnetic basement was between 1000 and 3000 feet deep under the islands, but the control did not allow a contour map to be drawn. The basement appears to correspond to the refractor, tentatively identified as Proterozoic, that underlies the Cretaceous (Oil Development N.L., 1962c).

The most extensive aeromagnetic survey in the area was carried out for Arco Ltd and Australian Aquitaine Petroleum Pty Ltd in 1965 (Arco Ltd and Australian Aquitaine Petroleum, 1965). This survey covered all of PE 221 H and O.P. 151 (1 and 2); that is, most of the area bounded by the Timor Trough, 129° east longitude and 14° south latitude. This survey was done using a digital caesium vapour magnetometer and achieved an accuracy of total intensity measurement probably an order of magnitude better than the other work. The programme consisted of a square grid of bands of lines oriented at 060° and 330°, the interval between lines being two miles and between bands, 24 miles. Some supplementary lines were flown to Timor across the Timor Trough. This survey succeeded in outlining the Bonaparte Gulf Basin offshore, confirming and enlarging the results of the BMR work of 1958. Several possible faults and structures were indicated along the flanks of the Basin.

The total picture, presented by aeromagnetic results, of this area then is of a large offshore sedimentary basin, shaped as an inverted triangle, with its axis pointing into Joseph Bonaparte Gulf. The shape shows good agreement with the Bonaparte Depression. The indicated depth of sediments in the middle of this basin exceeds 20,000 feet. It is not clear whether magnetic basement represents the Proterozoic or the Cambrian Antrim Plateau volcanics.

<u>Offshore Canning Basin and outer shelf area</u>. The Woodside survey mentioned above also included reconnaissance lines which covered the fringing reefs of the continental shelf. Shallow anomalies a few miles offshore from the Fitzroy Trough were interpreted as marking a termination of this feature although the presence of volcanic plugs masking true basement is certainly not precluded. The King Leopold Mobile Belt appears to extend offshore, though with a more westerly trend, at a depth of 2000 to 5000 feet. Indicated magnetic basement is generally about 25,000 feet deep over the shelf and shallows under the outer edge of the shelf to 12,000 feet under the Rowley Shoals, 15,000 feet under Scott Reef, and 5000 to 7000 feet under Ashmore Reef and Cartier Island. The presence of basic volcanics penetrated between about 8000 and 9000 feet in Ashmore Reef No. 1 well, however, implies that "magnetic basement", is here an intermediate horizon and that the depth to economic basement is much greater. Thus the relatively shallow depths indicated for the other reef areas are suspect and a substantial amount of the evidence for Veevers Cartier Furrow becomes doubtful. Nevertheless, the general picture remains one of a north-east-trending area of thick sediments, 25,000 feet deep, about 100 miles offshore along the shelf, possibly with an outer bounding ridge, 15,000 feet deep, under the reef.

<u>Arafura Sea area</u>. Shell Development (Australia) Pty Ltd (1965) flew a reconnaissance survey over O.P.s 127, 128, 140, and 156 in 1965 covering much of the offshore Arafura Basin with north-south lines 12 miles apart. The results showed that magnetic basement deepens towards the north and north-west of the offshore Arafura Basin from about 5000 feet on the Arnhem Land coast to over 30,000 feet about 80 miles north of the coast. The northern limit of the deep basement was not found. Magnetic basement is probably the top of the metamorphosed Lower Proterozoic. Seismic evidence (see below) indicates that over the main part of the basin this thick section is

likely to be mainly Upper Proterozoic with little or no Palaeozoic and a couple of thousand feet of Mesozoic rocks. The thickening to the north-west, north of Bathurst and Melville Islands, is probably mainly due to thickening of the Mesozoic section, with perhaps the appearance of Palaeozoic rocks. Once again, the depth to magnetic basement here is over 30,000 feet.

Gravity Surveys

From 1923 to 1938, the Netherlands Geodetic Commission carried out a large number of gravity readings at sea using pendulum equipment in submarines (Vening Meinesz, 1948). These readings include a coverage of the Indonesian Archipelago, and Vening Meinesz (1948, 1954) has made an interpretation of the isostatic anomaly pattern of this area in terms of crustal movement and buckling. He describes a belt of negative "isostatic" gravity anomalies which coincide with the outer area of the Indonesian Archipelago, i.e. running through the islands west of Sumatra, a submarine ridge south of Java, through Timor, the Tanimbar islands, the Kai Islands, to Ceram. This outer arc is accompanied by an inner arc of mostly volcanic character over Sumatra, Java, and the smaller Sunda islands up to the Banda Islands. The belt of negative anomalies coincides with the islands and areas where strong folding and overthrusting of the surface layers has taken place, probably in the Miocene epoch (the outer Sunda orogenic arc). Vening Meinesz proposes that during the lateral compression of the crust, as indicated by the folding and overthrusting, the crust has been down-buckled and brought to a lower position than that corresponding to isostatic balance, and therefore has given rise to the present belt of negative anomalies.

There has been some gravity work carried out in Timor Island (Teixeira, 1964; Ritsema, 1956), and Lemoine (1959) makes reference to large positive Bouguer anomalies (+160 mgals), measured along the north coast and negative Bouguer anomalies (-20 mgals) along the south coast, which he asserts are in contradiction to Vening Meinesz's results. However, reduction of Vening Meinesz's results to Bouguer anomalies instead of isostatic anomalies, shows that there is no gross inconsistency with the Bouguer anomalies measured on the Island.

During 1960-61, the Institute of Geophysics of the University of California took part in the Scripps Institute of Oceanography's "Monsoon expedition" to the Indian Ocean by operating a marine surface gravity meter (Helfer et al., 1962). A traverse was run from Darwin to Timor, and the broad results show an increase in free-air anomalies from small negative values near Bathurst Island up to +60 mgals over the outer shelf area. The values near Timor are in general agreement with the values obtained by Vening Meinesz. These exhibit a strong gradient of 2 mgal per mile across the Timor Trough with values decreasing towards the island of Timor. A minimum is reached about 20 miles from the south coast of the Island, although the small increase at the north-west end of the profile is only slightly greater than the order of accuracy of the survey and may therefore not be significant.

From a consideration of the results of all these surveys in the vicinity of Timor, it appears that there is a strong negative Bouguer anomaly running parallel to the south coast of the Island about 20 miles offshore, that is, about midway between the Timor Trough and the Island.

The profiles obtained on the "Monsoon expedition" also show a steep gradient of about 2 mgal per mile between longitudes 130° and 130° 30'. This gradient is most probably associated with the eastern margin of the Bonaparte Gulf Basin, and consequently is in general agreement with the conclusion from the aeromagnetic surveys on this margin. A minimum occurs at about longitude 129° 45' and latitude 11° 50', and then there is a steady increase in gravity to the north-west towards the edge of the continental shelf.

Several regional and detailed gravity surveys have been made on the Australian mainland along the eastern and southern coastal areas of Joseph Bonaparte Gulf, by the Bureau of Mineral Resources and the various leaseholders. BMR has also made underwater gravity surveys along the coastal waters between Darwin and Wyndham and between Cape Arnhem and Darwin (Williams & Waterlander, 1959a, b). Bigg-Wither (1963) has prepared a compilation and review of these gravity surveys, along with other geophysical surveys in the area. He points out that many ties are of doubtful accuracy.

In 1965, BMR made a surface marine gravity meter survey in the southern part of the offshore Bonaparte Gulf (Geophysical Associates, 1966; Smith, 1966). The meter used was a gimbal-mounted LaCoste and Romberg, corrections for horizontal accelerations being made from the outputs of two accelerometers mounted in fore-and-aft and port-starboard orientations. Accuracy was checked with a LaCoste and Romberg underwater meter at the beginning and end of each day's run, and adjustments to the surface data were made. Positioning was by Toran, which could be used only for about 8 hours each day because of sky waves, thus restricting the gravity work to these hours. Assessment of the accuracy of the survey from line intersections gave a standard deviation of the differences of 3 milligals. The results of the survey are shown in Bouguer anomaly contours included in Plate 3.

The most striking feature is the large north-south-trending positive anomaly, the Wickham Regional Gravity High (after Smith, 1966, and elsewhere called the Keep Inlet anomaly) in the centre of Joseph Bonaparte Gulf. This feature is at least 120 miles long and has a relief of about 100 milligals: from a crest of +75 milligals to flanking minima of -30 milligals on the east and -20 milligals on the west. The eastern minimum strikes north, and the western, north-west. The aeromagnetic and seismic results show that the large positive anomaly lies over the deep axis of the Bonaparte Gulf Basin, so that the anomaly does not reflect a basement depth change. It was formerly considered to be related to an intrabasement density change, but recent depth computations (A.J. Flavelle, pers. comm.) indicate that it is more probably caused by a volume of relatively dense material within the sedimentary section. The trends of the flanking minima correlate well with the basin margin trend measured by seismic and

and aeromagnetic results. Along the eastern coast of the Joseph Bonaparte Gulf, the Bouguer anomaly contours have a general north-easterly trend, with a tendency to swing northward in the north, and with generally positive values inland and negative values seawards. Thus, there is general agreement with the geological concept of this margin of the Bonaparte Gulf Basin.

In 1967, BMR conducted a reconnaissance helicopter gravity survey extending from Arnhem Land to the Kimberleys (Whitworth, 1968). The results of this survey are integrated into Plate 3.

Seismic surveys

Bonaparte Gulf Basin - land surveys. A number of seismic surveys have been carried out in the Port Keats and Keep River areas, mainly investigating structure in the Palaeozoic section. A short refraction survey has also been carried out on Bathurst Island. A compilation and review of the work up to 1962 has been made by Bigg-Wither (1963). The following summary briefly describes the surveys in chronological order.

BMR made the first seismic survey in the Bonaparte Gulf Basin in the Carlton and Keep River area in 1956 (Robertson, 1957). Tenement holders began work in 1960 with a survey in the area south-east of Port Keats (A.A.O., 1961), and in the Spirit Hill area (Westralian, 1960). In 1962 a survey was made on the Lower Keep River Plains (A.A.O., 1962b), and another between the Keep River area and the Ninbing area (Oil Development, 1962a). This last survey, the Carlton Seismic Survey, showed a closed structure, based on poor results, on which Bonaparte No. 1 was drilled in 1963-64.

A survey, which was mainly refraction work although three test reflection spreads were shot, was carried out on Bathurst Island in 1962 (Oil Development, 1962c). A high speed refractor (17,000 to 20,000 ft/s) was found at depths ranging from 1000 feet in the east to 3000 feet in the west. This refractor corresponded to a strong reflection which is assumed to represent the top of the Proterozoic section and magnetic basement.

The Ninbing-Burt seismic survey was completed in 1963 (Alliance, 1964c) and was tied to the Carlton survey, revealing a north-south fault and suggesting a closed structure to the south-west of Bonaparte No. 1. Australian Aquitaine Petroleum (1963) carried out an extensive survey at Pearce Point in 1963.

Alliance Oil Development (1964b) carried out a third survey in the Bonaparte No. 1 area in 1964. Using multiple coverage methods this confirmed the north-south faulting found in 1963, but showed that the suspected closed structure did not exist. It also showed that the structure on which Bonaparte No. 1 was drilled culminated farther south and structurally higher than suspected.

Australian Aquitaine Petroleum (1964c, 1964d) carried out two further surveys in 1964. The Kulshill survey (1964c) was aimed at improved results in the area of the 1963 survey (Point Pearce).

A structural high, the Kulshill High, was detailed and shown to be part of a north-south trend. Probable closure was demonstrated on this feature. A major north-south-trending fault was found about 10 miles east of the Kulshill High, downthrown to the west. The second survey was the Legune seismic survey (1964d), south of Keep River Inlet, where poor results showed a very thin sedimentary section dipping to the north-west.

Australian Aquitaine Petroleum (1965) conducted a survey (Skull Creek) in 1965, west of Keep River Inlet. Poor results were obtained even with some 6-fold C.D.P. shooting. Refraction shooting showed basement, a 21,000-ft/s refractor, to be about 8000 feet deep.

Anacapa Corporation (1965) conducted an experimental programme in the area of the Bonaparte wells at the start of the Tanmurra seismic survey. This indicated that with 12-fold C.D.P. shooting, marginally usable results could be obtained, although the 65 miles of line subsequently shot provided poor to unusable results. A general north dip with some faulting was shown.

To obtain further detail in the Kulshill area, Australian Aquitaine Petroleum (1966d) conducted the Moyle River seismic survey in 1966. This confirmed the major north-south fault found in 1964 and found minor "spur" faults associated with it on both sides. They used both single coverage and 6-fold shooting, but obtained generally poor reflection results. Refraction results were good, however. A refractor with a speed of 18,600 to 21,000 ft/s was found in most places and is considered to be Proterozoic basement. Several structural "highs" were delineated against the faults.

In 1967, Australian Aquitaine Petroleum (1967) conducted another reflection survey, with one refraction line, west of Keep River Inlet. Results with 6-fold stacking and deconvolution were poor to fair in quality but showed a regionally north-dipping basement (Proterozoic), with north-south-trending folds and two fault systems: north-south and east-west.

Seismic reflection results on the land part of the Bonaparte Gulf Basin have, then, yielded generally poor results, even with high-multiplicity shooting. Refraction results vary greatly in quality. Basement is usually represented by a refractor with a velocity of about 20,000 ft/s, shallower refractors sometimes being recorded. Seismic methods have outlined faults and several structural "highs"; some of these have been drilled to give shows of hydrocarbons, but none are commercial at this time.

<u>Offshore Bonaparte Gulf Basin</u>. For the purpose of discussing the seismic results, this includes the area inside the rises along the continental margin to the north, west of Bathurst Island and the mainland to the east, and north of the Kimberley Block to the south and west.

In 1961, Associated Australian Oilfields (1962a) conducted a marine seismic survey along the east coast of Joseph Bonaparte Gulf, off the Port Keats area (in O.P. 162). This survey showed an increasing thickness of sediments to the north-west. Indications of two structural reversals were found.

In 1964, Australian Aquitaine Petroleum (1964a, b) carried out two marine surveys; one to the north of the previous survey (Flat Top Bank Survey in O.P. 83) and one to the south (Queens Channel survey in O.P. 162), both being tied to the previous work. Three-fold coverage was used for both these surveys; it gave generally good reflection quality north of 14° 20' south latitude, and poorer but usable results south of this. The Queens Channel survey suggested a depth of sedimentary section of 7000 to 9000 feet. The Flat Top Bank survey in the north confirmed the thickening of the basin to the west. One horizon which could be correlated throughout the area deepened from 0.4 seconds to 1.85 seconds reflection time westward in a distance of about 40 miles.

In 1965 the Bureau of Mineral Resources (Smith 1966, Geophysical Associates 1966) did a combined gravity and seismic "spark array" survey covering 3600 line miles, composed mainly of east-west lines about ten miles apart. This survey covered most of the marine area east of 127° east longitude and south of 12° south latitude. The 12,000-joule sparker system used gave mostly good results down to about 1.6 seconds two-way time. It was demonstrated that a large Permian and Mesozoic sedimentary basin exists in the Joseph Bonaparte Gulf and extends to the north and north-west into the Timor Sea, containing at least 10,000 feet of post-Permian sediments. Reflection quality was poorest in the deeper parts of the basin. Three main reflections were recorded, called the M, P_1, and P2 horizons. The strongest and most widespread of these was the P_1 horizon which was followed throughout the area except where it became so deep (1.2 to 1.6 seconds reflection time) that it was obscured by noise. This reflection was tied to the 1962 A.A.O. survey, and through that survey could be tied to one of the Port Keats coal bores where it correlates with the top part of the Permian strata at about 800 feet. This is about 200 feet below the conformable transition from Permian to Triassic which has been recognised in the bore. The P_2 horizon is conformable with, and about 0.2 seconds below, the P_1 horizon, and is also a Permian horizon. The shallower M horizon, probably Mesozoic, is not conformable with the P_1 horizon, there being a considerable thickening between the two towards the centre of the basin. The survey found some faulting and folding around the margins of the basin, but none in the central deep area. A line of faulting and folding which trends north-west paralleling the coast and basin margin was found along the south-western margin of the basin. In this zone, about sixty miles from the coast, three or possibly four structures were found which had the appearance of diapirs or intrusive plugs. No definite gravity anomaly was observed over them.

After completion of the BMR survey, Arco Ltd and Australian Aquitaine Petroleum (1965a) ran a long reconnaissance loop over the Timor Sea with the same equipment, but the equipment was too low-powered to achieve the desired penetration in the apparently deeper parts of the basin to the north and north-west of the BMR survey.

In 1965 and 1966 Anacapa Corporation (1965a, 1966) conducted the West Bonaparte Gulf and the Medusa Banks seismic surveys in PE127H, the western half of Joseph Bonaparte Gulf. The first of these surveys was for reconnaissance and showed that the sediments thickened to the north-east with possibly 25,000 feet of Palaeozoic to Mesozoic sediments. It also indicated several folds, faults, and two large structures with possible closure. The structural trends parallel the general strike. The second survey extended the reconnaissance and detailed several structures using three-fold and some six-fold coverage. Five horizons were mapped and several closed structures were revealed. Some of these appear to be associated with deeper intrusions. In addition, two shallower features possibly represent intrusive plugs or salt diapirs.

All subsurface structural "highs" found appear to be associated with bathymetric "highs". Up-dip thinning and pinch-outs were found also.

During 1966, Arco Ltd and Australian Aquitaine Petroleum (1966) conducted the extensive Sahul Shelf seismic survey using a 130,000-joule sparker source. This survey covered PE221H and O.P. 151 (parts 1 and 2); i.e. most of the shelf area of the Timor Sea west of 129° east longitude. This outlined the overall configuration of the basin and confirmed the interpretation of the aeromagnetic results, showing the basin to have a triangular shape with its apex pointing towards Joseph Bonaparte Gulf. The basin appears to be limited along the edge of the continental shelf by a high trend. Several large structures were found; most of them were near Joseph Bonaparte Gulf, where the best results were obtained. Several horizons were mapped, some of limited areal extent. From shallowest to deeper the principal ones were: 1a, 1b - a probable Tertiary unconformity; 2a, 2b - Mesozoic; 2 - Mesozoic unconformity (Cretaceous?); 3 - Mesozoic (?); 4a, 4 - Upper Permian to Triassic; 5 - probable base of Upper Permian; 6 - Proterozoic basement (recorded over a limited area near the southern shore). Horizons 2, 4, and 5 were chosen after a regional interpretation of all previous work and correspond to horizons M, P_1, and P_2 of Smith (1966). Several closed high structures were mapped. Six structures were found, which may be diapirs or intrusive plugs, including those previously found by BMR. They seem to be generally related to faults and are characterised on the seismic sections by moderate to very sharp breaks underlined with diffractions on the deep horizons. They are generally asymmetrical with one side steeper than the others. No deep reflections cross them, and shallow reflections show domes, sometimes faulted, over them. They have certainly been intruded since the Permian. Record quality on this survey was fair to good in Joseph Bonaparte Gulf but deteriorated to the north-west where "singing" and rough bottom topography became problems. The energy source was insufficient for the deeper parts of the basin. Some digital processing trials (including deconvolution) showed appreciable improvement by "singing" cancellation. During this survey, a single line run out to about the deepest part of the Timor Trough showed step faulting down into the Trough. The faulting appears to be young, consistent with Audley-Charles' estimate of an Eocene age for the trough.

At about the same time as the above survey was being made, Australian Aquitaine Petroleum (1966e) made a complementary survey in the adjoining O.P. 83 and O.P. 2 areas, east of 129° east longitude. They used three-fold coverage "Flexotir" and obtained good results. A small sparker was used for shallow control. The survey was called Cape Hay-Cape Ford. The horizons mapped were numbered 2 to 8, horizons 2 to 5 corresponding to those of the same number mapped on the Sahul Shelf survey. The results confirmed the regional picture of the basin; they showed the general WSW dip in the northern part of the survey area, where smooth tectonics were a feature, and general WNW dip in the southern part, which is affected by sharp local features including one "high" over a possible intrusion west of Pearce Point. In the Queens Channel area an anticline with a small amount of closure was confirmed.

In late 1966, Arco Ltd and Australian Aquitaine Petroleum (1967) conducted further experiments in sources and processing on one of the lines of the Sahul Shelf survey in their Sahul Bank project. Comparisons were made between results from the sparker, "Flexotir" and conventional dynamite shooting, all digitally recorded and processed. They concluded that the dynamite source gave the best penetration and reflection character, and that digital processing (stacking and deconvolution) gave significant improvement, particularly regarding cancellation of "singing", although the processing parameters have to be chosen for small areas and do not apply over more than a few miles of line.

A single north-south line west of Bathurst Island shot with air guns and digitally recorded, was run for Canadian Superior Oil (1967) in 1967. Digital deconvolution and 12-fold stack were applied. Only one good event was recorded - horizon A - which was very strong and probably correlates with Arco and Aquitaine's horizon 2. It is possibly associated with the basal Cretaceous unconformity. This horizon shows a northerly dip from 0.650 seconds (two-way time) at 13° south to 1.4 seconds at 12° south. In the context of other surveys, the true dip is probably to the north-west. Some small reversals were found. It is such an efficient reflector that deeper penetration was extremely poor and an associated "multiple" further complicated the deeper picture. Some segments were observed, however, down to 2 seconds and they indicated unconformity with horizon A and some reversals. The possibility of some Permian-Triassic representation cannot be positively excluded but seems likely.

The first digital recording in the eastern half of the Bonaparte Gulf Basin was carried out in the Hyland survey by Australian Aquitaine Petroleum (1968) in 1967. Most of this work was done in O.P. 162, south-west of Port Keats, but a reconnaissance grid extended to the north of O.P. 38, west of Bathurst Island. The shooting was done with dynamite, and 6-fold stacking and deconvolution were applied. This gave more penetration and better quality than the Cape Hay-Cape Ford survey, and basement (horizon Z - Proterozoic) was recorded over the northern half of the area - at reflection times to 4 seconds, horizon 7 corresponds to a 19,000-ft/s refractor. A smooth basement ridge trending north-west from Fog Bay to the north of O.P. 83 was mapped. The north-south-trending Moyle River fault trend continues offshore near Cape Dombey and is shown in the basement contours as far north as Cape Scott; it appears as a steep west dip, and basement is soon lost to the west of this feature. East of this and from a line joining Cape Scott to the north-west corner of O.P. 83, a shallow section comprising mainly Cretaceous and possibly Tertiary sediments presumably lies on the Proterozoic. This area shows no interesting structures. West of this divide, older beds appear and horizons 2 to 6 are mapped. The latter area also contains several structures, some of which were found on earlier surveys and some of which appear to be associated with possible intrusions. These dome structures are usually associated with faulting. There is also a north-west-trending series of plunging anticlines, for example the Emu Anticline extending offshore from the Port Keats-Hyland Bay area.

A small detail sparker survey (the Lesueur survey) was carried out for Arco and Australian Aquitaine Petroleum (1967a) in the central part of the offshore Bonaparte Gulf Basin in early 1967. This provided details of the structure found in the Sahul Shelf survey in 1966 in addition to finding two new closed structures. A seventh intrusive type structure was also found.

The Sahul Rise survey (Arco and Australian Aquitaine Petroleum 1968) conducted over the northern section of the offshore Bonaparte Gulf Basin (north half of O.P. 151-2 and north and west half of PE221 H) in 1967 was the first large-scale attack with powerful seismic techniques on the poor-record area here. Some 4500 miles of line was shot, mostly with 6-fold conventional seismic using about 50 pounds of explosives per shot. A small amount of shooting with two air guns was also tried, using both 6-fold and 12-fold stacking, but the results were not quite as good as those from the conventional work. All the data were digitally recorded and later deconvoluted. Although the survey was mainly reconnaissance over the northern and western part of the leases, some follow-up detail work over structures within Joseph Bonaparte Gulf was included. Penetration to 5 seconds (two-way time) was generally achieved. In the southern part, horizons 2, 3, 4, 5, and 6, equivalent to those picked on the Sahul Shelf survey, were mapped in addition to several other deep horizons. In the northern part, horizons 4, 2, and 2a were the principle markers of which one (2a) was mapped on the Sahul Shelf survey. The section appears to be very thick in the northern part, where deep horizon 4 was followed throughout. Two roughly perpendicular structural trends were found: an old north-west trend and a more recent north-east trend. Several structures and anticlinal trends were found in the northern and north-western part of the area. These are concentrated on the regionally high strip which coincides with the Sahul Rise bathymetric feature. Further detailed work will be necessary to confirm closure on these. Faulting is common towards the edge of the shelf, and its trend follows the edge of the shelf (that is, north-east). A large fault downthrown to the south trends north-east under the southern part of the Malita Shelf Valley.

In summary, the seismic results from the area confirm the regional interpretation based on both magnetic and gravity results. The Sahul Rise, Londonderry Rise, and Van Diemen Rise are generally high and the Bonaparte Depression corresponds to the thickest zone of sedimentation. There are many features located on the south-western and south-eastern flanks of the Bonaparte Depression which appear to be intrusive in nature on the seismic sections. The Sahul Rise area is characterised by poor seismic results.

Arafura Sea. For the purpose of this discussion, the Arafura Sea area is taken to be that on the continental shelf north of Bathurst and Melville Islands, Cobourg Peninsula, and Arnhem Land.

The first marine seismic work in this area was a short reflection programme carried out in 1965 by Anacapa (1965a), the Dundas Strait survey. This survey, just off the north-east coast of Melville Island, showed a regional north dip in this area.

Shell Development (1966, 1967, 1967a) have carried out three surveys in the Arafura Sea: the Arafura Sea survey in late 1965, and the Lynedoch Bank and Money Shoals surveys in 1966-67. These together covered O.P.s 128, 127, and 140. Three main horizons have been mapped and are, from shallowest to deepest: A, B, and C. Horizon C is a prominent unconformity and is shallow over most of the area but deepens rapidly to the north and west to a probable depth of the order of 20,000 feet in O.P. 128, north of Melville Island. In the east, where it is shallow, it probably represents the base of the Mesozoic, by analogy with the geology on land in the Arafura Basin. It overlies folded strata which are probably, once again by analogy with the geology, Proterozoic. The fact that aeromagnetic data indicate basement depths of up to 30,000 feet here thus implies that most of this great thickness is made up of non-magnetic Proterozoic rocks. Refraction profiles in many places show refractor velocities of about 20,000 ft/s associated with the unconformity, and so support the idea that Proterozoic sediments underlie it, although in some parts, velocities of about 15,000 ft/s indicate that, in places, some folded Palaeozoic rocks may be present. To the west, where horizon C deepens, it seems probable by analogy with the Bonaparte Gulf Basin that some Permian-Triassic sediments will be represented above it. In fact, this deep section can be considered an extension of the Bonaparte Gulf Basin. Above horizon C, the section appears to be conformable and mainly featureless, only two structures having been found: an unclosed nose corresponding to Money Shoals on the surface, and a probably unclosed "high" under Lynedoch Bank. This contrasts with the highly folded section beneath horizon C, where closed structures almost certainly exist. The northern extent of the deep area of post-horizon C section has not been established. Mainly three-fold conventional coverage was used on the Arafura Sea and Lynedoch Bank surveys and gave fair to good results; ringing was a problem, particularly in water depths over 50 fathoms. Notch filtering to remove the ringing was tried on the latter survey, with disappointing results. Some digital recording was done on this survey also, and trials of processing indicated that deconvolution both before (short operator) and after (long operator) stacking gave the best results. The Money Shoals survey was done with a sparker to fill-in less critical areas.

Outer shelf region. This is taken to include the area of relatively shallow bathymetry along the continental margin and includes, for convenience, all of the continental shelf areas south of 14° south latitude.

Burmah Oil Company (1965, 1966, 1967, 1968) has carried out four stages of a reconnaissance programme covering the outer part of the continental shelf, where aeromagnetic results indicate a relatively shallow magnetic basement compared with the inner shelf (including the Bonaparte Gulf Basin) areas. These surveys were conducted in 1964 (Cootamundra Shoals, O.P. 105, and North Western Shelf Survey) 1965 (Montebello-Mermaid Shoals survey), 1966 (Rankin-Troubador survey), and 1967 (Scott-Cartier survey), each adding more detail over the same areas. The results from tenement areas O.P. 108, O.P. 159, and O.P. 158, north of the offshore Bonaparte Gulf Basin, will be considered first.

The southern extremity of work associated with O.P. 108 is only 30 miles west of the north-west tip of Bathurst Island. A good reflector found here at a depth of about 4000 feet may correspond to the good reflector associated with the high-speed refractor (17,000 to 20,000 ft/s) at about 3000 feet deep in the west of Bathurst Island (Oil Development, 1962c). If this is so, then it probably represents Proterozoic basement. The concept is supported by aeromagnetic data. This reflector deepens to the north to 11,500 feet at about latitude 10° 13' south. North of latitude 10° south the regional dip of the deep section appears to be south-east so that this probably represents part of the northern boundary of the Bonaparte Gulf Basin; this agrees with results in the Sahul Rise area. The deepest part of the basin lies south of O.P. 158 and O.P. 159, and these tenements appear to be on a relative "high", although at least 7000 feet of sediments underlies them. The deepest continuous event mapped - horizon B - is gently unconformable with the overlying section. It corresponds to a 15,000-ft/s refractor. Regional dip into the Timor Trough to the north is indicated for the shallower horizon A. The broad structural features in the area follow the trends of the bathymetry closely. An area of fault closure appears to exist in one place in O.P. 159. The area presents severe ringing problems in many places. The Rankin-Troubadour survey was recorded with both analogue and digital recorders, and deconvolution and time variant filtering was applied after stacking. These techniques gave better results, so the Scott-Cartier survey used similar recording techniques but without deconvolution.

Results from the area from Sahul Banks to Ashmore Reef will now be discussed. Two continuous horizons have been mapped. The shallower, A, corresponds to a 12,000-ft/s refractor and ties to Oligocene-Palaeocene-Eocene unconformity at Ashmore Reef. The B horizon ties to the Paleocene-Upper Cretaceous/Upper Jurassic unconformity at Ashmore Reef. These horizons do not necessarily correspond to those of the same name in the previous Burmah Oil Company work just discussed. Dip segments from deeper than horizon B show the presence of interesting pre-B structure and imply a thick sedimentary section. Sahul Banks lie over a broad faulted north-east-trending anticline which has local areas of closure.

Ashmore Reef, where an additional small detail survey was carried out prior to drilling (Burmah Oil Company, 1967a), lies over a faulted north-south elongated dome which culminates at a point six miles north of the east island of the reef complex. Ringing is a problem in this area.

The nearby Woodbine Banks-Cartier Island region has also been mapped at the same A and B levels as above. Although more detailing is needed here, Woodbine Banks have been shown to lie on the apex of a dome and Cartier Island on a broad, low-relief anticline which possibly trends north-east.

At Scott Reef a broad, north-east-trending regional anticline was shown to exist, and at least 16,000 feet of section is indicated under the lagoon.

Further to the south a general increase in the depth of sediments from the shore line to the continental margin is indicated. However, offshore from the Fitzroy Trough and the Broome Swell, there are north-west trends indicating an extension of these features offshore. At least 15,000 feet of section is probably developed under the outer shelf. Results in the immediate area of the Rowley Shoals were poor, but there may be structural "highs" associated with them.

In the Rankin Bank area there is a series of north-east-trending folds. A second longer-wavelength series trending more east-west (continuing the trend of the southern margin of the Canning Basin) produces several structural closures.

4. OBJECTIVES

The broad objective of the project was to continue the reconnaissance and regional geophysical survey of the continental shelf of Australia commenced in 1965. The geophysical methods used were to be those that could be reasonably combined in a single boat operation. The selected methods were to conform with technical practicability and a low cost rate, bearing in mind the limited budget and the area to be covered. The 1965 survey had combined gravity and seismic profiling. The present survey added total magnetic intensity recording, and it is hoped that future surveys will add refraction seismic and sidescan sonar.

Navigation can be a high cost element. The 1965 survey employed a phase comparison radio system (Toran) but sky wave interference limited its use. The present survey used a system relatively independent of shore stations and employed v.l.f. phase comparison observed for stations distributed around the world, and sonar doppler measurements.

The instruments and techniques used for this survey are relatively new to exploration, particularly in Australia. This applies particularly to the marine gravity meter in the form used, and to the v.l.f. and sonar doppler navigation techniques. An immediate prime objective of the survey was, then, to investigate their suitability and future potential as exploration tools in a regional survey of the continental shelf area of Australia. Particular stress was accordingly placed on assessing the accuracy of the navigation and gravity results obtained. In fact the measurement of the accuracy of the data was to be considered no less important than the data themselves. The objectives of the survey were divided into two categories: geophysical and geological.

Geophysical objectives

(1a). To investigate the performance and reliability of the Askania Gss-2 marine gravity meter and its peripheral equipment. To this end it was envisaged that about 100 line intersections at accurately known points would be made. For gravity it was deemed preferable that the intersections be made in areas of low gravity gradient as much as possible.

(1b). To investigate the quality of the seismic data and the depth penetration obtainable with the "spark array" equipment, in particular whether, with the Chesapeake cable, the quality of results would be as good when the ship was running at a high enough speed for optimum operation of the gravity meter. The outlining of zones of various reflection quality was to assist in planning the equipment for future surveys.

(1c). To tie to previous seismic surveys in the area and attempt to co-ordinate their results with each other and with the present survey.

(1d). To assess the performance and reliability of the v.l.f. navigation technique in Australian waters. The main technique intended here was to record four stations simultaneously to give a multiplicity of "fixes" for each boat position. Also, once again, line intersections at known points were to allow assessment of the data and adjustment of the results. In addition, visual fixes were to be made wherever possible on topographic features of accurately known geographic position.

(1e). To assess the performance and reliability of the Varian V4970 proton precession magnetometer.

(1f). To assess the performance and reliability of sonar doppler navigation.

Geological objectives

(2a). To further investigate the seaward extension of the Bonaparte Gulf Basin, and outline the Basin's margins, general form, sedimentary thickness, stratification features, structural features, and behaviour at the edge of the continental shelf.

(2b). To investigate the offshore extensions, where they exist, of other structural units on the mainland; for example, the Precambrian trends.

(2c). To investigate the north-easterly-trending basin which lies completely offshore along the continental margin of the north-west of Australia, and its relation to the Bonaparte Gulf Basin.

(2d). To investigate the relation between the continental shelf, the Timor Trough, and the island of Timor. A line was planned to cross the Timor Trough in both directions as a contribution to this purpose.

(2e). To investigate the relation between the Bonaparte Gulf Basin and the Arafura Basin to the east.

More particular geological objectives were:

(2f). To investigate the nature of the diapiric or intrusive structures which have been found on several seismic surveys in the Bonaparte Gulf; to see if they have any gravity or magnetic expression.

(2g). To investigate Lynedoch Bank and Goodrich Bank in the Arafura Sea. A seismic survey by Shell (1967) had indicated a positive structural expression under Lynedoch Bank; by analogy the same may be expected of Goodrich Bank, although no work had been done near there.

(2h). To investigate the gravity and magnetic expressions of Ashmore Reef, Sahul Bank, and other bathymetric "highs" which previous seismic work have shown to correspond to structural "highs".

(2j). To investigate the geological significance of the D'Artagnan Shoals, which are shown as the culmination of a bathymetric ridge which runs west off the continental shelf of Australia near Scott Reef.

5. PROGRAMME

Intended programme

The programme planned to achieve the objectives consisted of a series of east-west lines spaced nine nautical miles apart with north-south tie-lines about two degrees of longitude apart. The nine nautical mile spacing was chosen so that meaningful 5-milligal contouring could be carried out on the gravity data. This figure gives near-compatibility with the seven mile square grid of stations used on BMR's helicopter gravity surveys on land. The east-west orientation was chosen because with the planned navigation system it was considered that the east-west component of the ship's velocity (critical for the gravity Eötvos correction) could be more accurately measured with this orientation. Also, east-west lines would cross all of the north-west, north-east, and north-south tectonic trends indicated for the survey area. It was planned to complete the survey in three cruises, each of about 28 days' duration. Small modifications to the line grid were planned to allow crossing of the Timor Trough, Lynedoch Bank, Goodrich Bank, Sahul Banks, Ashmore Reef, and the d'Artagnan Shoal. In addition, two lines were planned to fill-in a gap in the 1965 gravity coverage in the extreme south of Joseph Bonaparte Gulf. At least one of the possible intrusive structures in this gap (Anacapa

1966) was to be crossed. The opportunity of crossing one or more of the intrusive structures farther north (Smith, 1966; Arco Ltd and Australian Aquitaine Petroleum, 1966) on the way into or out of this gap was to be taken. The 500-fathom isobath was taken as the outer limit of the survey area in general. A working speed of 10 knots was planned.

The gravity meters (surface and underwater) were to be calibrated on the Brisbane calibration range before the survey, and drift checks were to be made at all stops en route from Brisbane to Darwin and at the beginning and end of each cruise. The voyage from Brisbane to Darwin was to be considered a shake-down cruise to ensure the successful operation of all the equipment and the familiarity of the personnel with the equipment.

Programme carried out

Before the ship left Brisbane, both the Askania sea gravity meter and a La Coste and Romberg type "W" underwater gravity meter were calibrated on the Brisbane calibration range to achieve compatibility with the Australian milligal. A shore station was established at the Evans Deakin Shipyard in Brisbane to act as an initial datum. Most of the survey equipment was installed on the "Wyrallah" in Brisbane.

The ship departed from Brisbane on 20 August 1967, and was at Cairns from the 24th to the 26th, Thursday Island from the 28th to the 30th, and arrived in Darwin on 2 September. Wharf gravity ties made at all ports of call enabled an early estimate of the drift-rate of the Askania meter to be made. All equipment was tried to some extent on this positioning voyage and many minor problems were encountered. These are briefly covered, along with later equipment troubles, in the relevant appendixes to this report.

Several days were spent in Darwin before the first attempt to commence the survey. During this period, final adjustments were made to the cross-coupling computer and ship-to-shore radio communication systems, and the shore-based magnetometer station was established.

The ship left Darwin to commence the survey on 8 September, but after a day at sea it was obvious that many problems remained unsolved; in particular v.l.f. transmissions from North West Cape were so strong that they overdrove the receivers and interfered strongly with reception of other stations; proper synchronisation of segments was lost for one period of a day on a 599Q receiver (see Appendix B). Ship-to-shore radio communication was also a major problem. Accordingly the ship returned to Darwin on 11 September.

The "Wyrallah" remained at Darwin until 23 September while modifications to the v.l.f. equipment and techniques were effected under the supervision of Mr W. Donnell of Tracor Inc., manufacturers of the equipment.

The first readings used in the data reduction were taken on 23 September, and the "Wyrallah" subsequently spent the following periods at sea.

23 September	to	24 September
28 September	to	23 October
1 November	to	29 November
4 December	to	21 December

The ship returned to Darwin at the end of each cruise.

In all, then, data recorded on 70 days at sea have been used in the reduction and presentation, representing some 13,050 nautical line miles. As planned, a double crossing of the Timor Trough was carried out, in addition to crossings over or running near to Lynedoch Bank, Goodrich Bank, the Sahul Banks and Ashmore Reef. An attempt to locate the d'Artagnan Shoal failed, and it is now believed that this shoal does not exist. The two lines in the south of Joseph Bonaparte Gulf were run and an intrusive type structure was crossed here as well as another farther north (13° 23'S, 128° 07'E), as planned.

The original plan envisaged a working speed of 10 knots, as the seismic cables (six-channel and single-channel high resolution) were designed to work at speeds as high as this. On 30 September, however, the six-channel cable was lost owing to a breakage, and the spare single-channel cable was used thereafter in the programme (see Appendix D). As this replacement cable was not designed for speeds in excess of 7½ knots, results were much poorer owing to tow noise. However, as the survey was primarily intended to provide gravity coverage, and previous seismic surveys had shown that good seismic results could not be obtained with simple equipment over a large part of the survey area, a working speed of 10 knots was continued except in areas where no previous seismic data had been obtained or where it was deemed that good data were desirable to co-ordinate the results of previous surveys.

Two experiments were also carried out during the survey. One day was spent anchored near Ashmore Reef in the west of the survey area to monitor the diurnal phase variation in the received v.l.f. signals. This was to gain an idea of the possible errors introduced by extrapolating the variations in Darwin over the whole survey area. Also, on 27 and 28 November, four buoys were placed (using radar and gyro-compass bearings) in the form of a square of side four miles. Several runs round the square were made (four clockwise, two anti-clockwise) to check out the accuracy of the Eötvos correction obtained from the sonar doppler system. The v.l.f. system was also checked during this experiment.

6. DATA REDUCTION AND PRESENTATION

Navigation

The v.l.f. phase readings taken on the ship each half hour were subject to several corrections before initial plotting. These were:

(1) An algebraic addition of time varying fluctuations (the shore monitor recorded variations) which were transmitted via the ship-to-shore radio.

(2) A datum adjustment decided on at Darwin to give a fixed starting point.

(3) A correction for relative oscillator (local time standard) drift between ship and shore.

(4) A night-time path correction consisting of 0.3% of the difference in phase between the ship's position and the shore monitor (a figure suggested by Tracor Inc.). This was to correct for the difference in the proportion of night-time path in the travel path from the transmitter to the ship and the transmitter to the shore monitor.

(5) A time difference correction to allow for the difference in local time between the ship and the shore monitor (introduced in December).

(6) On signals from Haiku and NPG, a standing wave correction. Transmission from the long and short arcs of the great circles through these transmitters and the ship were of comparable amplitude during some periods of the day, and produced a standing wave pattern in the survey area. This caused spurious cyclic phase changes, having half the wavelength of the basic signal, to be superimposed on the normal phase record. These were removed by a smoothing process described by United Geophysical Corporation (1968) and Ingham (1968).

All the corrections described are more fully described in the above reports.

The resultant phase ranges computed as above were plotted on charts showing lines of equal phase for each transmitter (see Appendix B) and the ship's latitude and longitude were read off. These fixes were used in preliminary gravity reductions on board ship.

The resultant plots were in general far too erratic to represent the ship's true course, so further smoothing and other adjustments were carried out after the survey was completed. Large-scale manual plots of the computed latitude were made against time, and smooth lines were drawn through the half-hourly points where there were no known course or speed changes. Before these lines were drawn, all independent fixes (radar and celestial), buoy positions, and water depth ties at some intersections were also plotted and used in drawing the lines. The relative weights allowed these data were allotted by subjective judgement, but infinite weight was generally assigned to celestial and radar fixes, and independent fixes on the same buoy were generally meaned. A similar procedure was adopted with longitude versus time plots. The finally adopted position of the ship each ten minutes was then read from the smoothed lines.

Because the sonar doppler system did not perform satisfactorily for a large part of the survey, it was necessary to estimate the Eötvos correction for the gravity reductions from the corrected and smoothed position data obtained as described above. This was done by measuring the slope of the longitude versus time plot to get the east-west component of the ship's velocity. Where the sonar doppler system was working satisfactorily, the fore-and-aft component, which was recorded on a chart recorder during the latter part of the survey, was used and the slope-measured estimates were used for comparison purposes.

Gravity

The gravity beam reading with the cross-coupling correction removed was available as a chart recording on the ship and preliminary reductions, using the navigation data computed on the ship, were made on the ship to provide a current record of the results. The data were again manually reduced after the survey, using the smoothed navigation data. The following corrections were made in the reduction.

Water depth correction (or Bouguer correction). This correction effectively replaces the water under the ship with rock of the required density. Its value is $dg_W = 0.01278$ (density of rock - density of water) x (depth in feet) mgals. The density of sea water is assumed to be 1.03 g/cm^3 and that of rock to be 1.90, 2.20, and 2.67 g/cm^3 to give three values of the Bouguer correction for each point. There is no free-air correction, as it is assumed that there is no change in elevation.

Eötvos correction. This correction counteracts the effect of the gravity meter's relative motion over a rotating Earth; it depends primarily on the east or west component of the ship's velocity and amounts to about 6 mgal per knot of this component. The correction is positive for an eastward component, negative for westward.

The Eötvos correction, dg_e, was obtained from the following formula

$$dg_e = \left(\frac{1}{R\phi^2}\right) (2\, V\phi\, Ve + V^2)$$

where $R\phi$ is the radius of the Earth at latitude ϕ

$V\phi$ is the speed of rotation of the Earth's surface at latitude ϕ.

V is the ship's "ground" speed.

Ve is the eastward component of V

For an east-west course, this reduces to the approximate relation

$$dg_e = 7.503 \; Ve \cos \phi \text{ mgal}$$

where V is in knots positive to the east (Glicken, 1962)

Theoretical gravity correction (latitude effect). Tables of theoretical gravity on the International Ellipsoid were supplied to the contractor. These have been calculated from the formula

$$g_{th} = 978{,}0490 \; (1 + 0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi)$$

gals, where ϕ is the latitude.

Base ties. The observed gravity for each station was made consistent with the Australian base network. Ties were made to base stations at the wharves in Darwin, for which gravity values consistent with the Australian network were established with a land gravity meter by BMR. A value of 978,318.74 milligals was adopted for station 6491.0332 at Stokes Wharf. As the tidal range at Darwin can be more than 20 feet, ship's tie readings were taken at times of mean sea level.

Station observed gravity. The gravity stations were at ten-minute time intervals along the ship's track. The observed gravity g for each station was calculated by converting the outputs of the gravity meter units to milligals using the calibration factor established in Brisbane (47.633 milligals per spindle revolution), and reducing this to the Australian datum using the base ties. Adjustments for drift and misclosures were made as described by United Geophysical Corporation (1968). Readings at line intersections were usually meaned.

Tidal corrections. A preliminary study of Earth tide corrections for the survey area over the period of the survey showed that fluctuations were less than 0.3 milligals; however, tidal corrections were made using the tables published in Geophysical Prospecting.

The Bouguer anomalies. For each station the Bouguer anomalies were calculated as follows:

$$\text{Bouguer anomaly} = g - g_{th} + dg_w + dg_e$$

Three values were obtained for each station corresponding to the three rock densities assumed. In some areas, additional corrections were made as follows:

Rough sea bottom effects. Areas of shallow and rough bathymetry affected the gravity results both directly (a shoal produces a positive anomaly, a sea valley a negative anomaly) and indirectly (strong local current variations caused quick velocity changes). Because of the difficulty of resolving these effects due to incomplete knowledge of the environment, and because of their localised nature, the procedure generally adopted was one of smoothing the gravity profiles over such areas.

Scarp corrections. When the ship approaches a steep rise in the bottom profile (steep enough to approximate a scarp or fault, e.g. the Timor Trough), the gravity meter begins to show an increase in gravity at a horizontal distance from the scarp about six times the depth of the scarp (United Geophysical Corporation, 1968). The water depth correction, however, does not come into play until the ship is directly over the scarp. Similarly an anomalous negative gravity effect is obtained on the shallow side of the scarp. It was found that these high-low doublets could be as large as 5 milligals. As the effects could not be analysed properly because of the incomplete knowledge of the bathymetry, these effects were also smoothed out.

The Bouguer anomalies computed for an assumed density of 2.20 g/cm^3 were used in the gravity presentation. The values at each 10-minute station were plotted on base maps of 1:250,000 scale along with the water depth (given as negative elevations in feet). The Bouguer anomalies were then contoured manually using strict linear interpolation. The contour interval was 5 milligals. These maps are included in the report by United Geophysical Corporation (1968). The maps in the present report show the same data in the form of Bouguer anomaly profiles along idealised traverse lines to facilitate comparison with the magnetic and seismic data.

Seismic

At this stage, only the deep monitor records have been used in obtaining the results presented. The deep monitor records had a vertical scale of 2.0 or 2.5 seconds two-way time and the range was switched to 0 to 2.5 (0-2.0), 2.5 to 5.0 (2.0-4.0), or 5.0 to 7.5 (4.0-6.0) according to the water depth. Where possible, events definitive of the basic structure were picked, along with the water bottom, and these were plotted at a scale of one inch per second (two-way time) under the same idealised traverse lines used for the gravity profiles on the plates in this report. The shallow monitor records are being studied by Dr J.J. Veevers of Macquarie University who plans eventually to reduce the data to a similar mode of presentation.

Magnetic

The total field strength data recorded on board ship were corrected for the regional field and for diurnal variations, and a datum adjustment was made.

The regional field was estimated as follows: Values on the corners of one-degree squares covering the survey area were estimated from a map of total magnetic intensity for the epoch 1965.0 compiled at the Royal Greenwich Observatory in consultation with the United States Coast and Geodetic Survey and the Dominion Observatory. These values then became the basis for computation of the regional field at each station by a digital computer interpolation programme. Values at the same longitude as the required station on the north and south sides of the square in which the station was positioned were interpolated, then a value for the stations was interpolated between these. A second value for the station was interpolated in a similar manner from points on the east and west sides of the square having the same latitude as the station. The finally adopted value of the regional field at the station was the mean of these two values.

For making the diurnal corrections, the output of the shore monitor magnetometer was used when these data were available (see Appendix E). When this station was not operating, diurnal variation values were computed from records of the horizontal and vertical components of the Earth's field recorded at BMR's Port Moresby Geophysical Observatory. It was found that a constant correction of 3341 gammas made the Port Moresby values satisfactorily comparable with the Darwin values.

The computation of the final corrected value at each station relative to the regional was done by computer at stations ten minutes of time apart. Where local magnetic anomalies had a short wavelength and were not satisfactorily represented by ten-minute sampling, the true shape of the anomalies was drawn in on the profiles assuming linear changes in regional and diurnal effects over each ten-minute segment. The final presentation, then, is as profiles with a vertical scale of 200 gammas per inch and an arbitrary but annotated datum. This mode of presentation is used both in this report and in the report by United Geophysical Corporation (1968), but the datum values are not necessarily the same on the two sets of plates.

The presentation used in the plates

Plates being drawn to accompany this report are based on the standard 1:250,000 sheets, sized one degree of latitude by 1½ degrees of longitude. The ten-minute station positions are shown. Each line has been broken into convenient linear idealised segments which have been used as datum lines for plotting the seismic, Bouguer anomaly, and magnetic anomalies derived as described above.

7. GRAVITY RESULTS

Introduction

The error in gravity measurement on this survey has been estimated (United Geophysical Corporation, 1968) from misclosures at 170 line intersections. The mean error was 2.5 milligals and the maximum misclosure was 8.7 milligals. Most of the error is probably due to poor navigation data (particularly velocity data) but lack of correction for changes in elevation due to sea level may also be significant. The tidal range at Ashmore Reef may be as large as 15 feet, which could give rise to gravity errors of ± 1 milligal.

The gravity results are presented in the form of Bouguer anomaly profiles in Plates 5 to 38, and a compilation in the form of

5-milligal contours is presented in Plate 3.

The gravity results have previously been discussed in the report by United Geophysical Corporation. In the present report the area has been subdivided into gravity provinces and units, which are shown in Plate 3 and are listed below:

(1). Ashmore Regional Gravity Gradient (new name, after Ashmore Reef)
(2). Cartier Regional Gravity Shelf (new name, after Cartier Island)
(3). Timor Regional Gravity Low (new name, after Timor)
(4). Sahul Regional Gravity High (new name, after Sahul Rise)
(5). Bonaparte Regional Gravity Depression (new name, after Bonaparte Depression)

Unit 5A North Bonaparte Gravity Shelf
Unit 5B East Bonaparte Gravity Low
Unit 5C South Bonaparte Gravity Low
Unit 5D West Bonaparte Gravity Low
Unit 5E Wickham Gravity High (Smith, 1966)

(6). West Arafura Regional Gravity Platform (new name, after Arafura Sea)
(7). Wangites Regional Gravity Ridge (Whitworth, 1968)

These provinces are now briefly discussed in order.

Ashmore Regional Gravity Gradient

Only the south-eastern portion of this gravity province has been defined by the survey. The south-eastern margin extends in a north-easterly direction from D51/6 in the south to C51/12 in the north. The feature presumably merges into a general oceanic regional gravity "high" to the west. The contours show a marked north-easterly trend in general. Several small closed "highs" are superimposed on this trend, including one over Ashmore Reef. The trend direction agrees with the general structural trend direction in the area shown by bathymetric, seismic, and aeromagnetic data, although the correlation is not simple when looked at in detail. The rapid rise in the Bouguer anomaly values to the north-west undoubtedly corresponds to crustal thinning; for example, towards the south of the province the contours maintain their strong north-east trend while crossing a strong bathymetric and seismic feature at right angles immediately south of Ashmore Reef. The province extends to the south into an area of a marine gravity survey being conducted by BMR in 1968.

Cartier Regional Gravity Shelf

This gravity province lies almost entirely on the continental shelf south-east of the Ashmore Regional Gravity Gradient. The southern boundary of this province was not defined by the survey, but the province is elongated north-east to south-west. The southern portion lies in deep water. The contours within the province show no distinct trends and two roughly circular Bouguer anomaly "highs" are included. Of these, the northern one, on the border of C51/16 and

D51/4, corresponds approximately to a seismic "high", A22, obtained on the Sahul Rise survey (Arco Ltd and Australian Aquitaine Petroleum, 1968). The southern one, on the border of D51/3 and D51/7, appears to have no seismic correlation and lies in an area of relatively thick sediments on the shelf. In the centre of C51/16 there is a Bouguer anomaly "low" which, on its north-western side, is elongated in a north-east direction. It also has an extension to the east. The area of north-east elongation corresponds to a prominent syncline about 30 miles wide (see Plate 4) and an associated bathymetric "low".

Timor Regional Gravity Low

Only portions of this large negative feature, well known from previous work (Vening Meinesz, 1948, 1954, Helfer et al., 1962) were covered. The general features (see Chapter 3) were confirmed including a minimum of about -50 milligals in Bouguer anomaly and the fact that the centre of the feature lies north of the axis of the Timor Trough.

Sahul Regional Gravity High

This is a prominent, arcuate gravity province over the continental shelf area. The trend is east-north-east in the west and nearly east in the east. It corresponds to a bathymetric feature: the Sahul Rise. Seismic results from the present survey are extremely poor over most of this region. The shallow seismic horizons (2 and 2a) mapped by Arco Ltd and Australian Aquitaine Petroleum (1968) show a relative "high" in this region, and the time contours generally exhibit trends parallel to the gravity feature. A prominent Bouguer anomaly nose, with flanking "lows", extends north near the border of C52/5 and C52/6. The shallow seismic horizons and bathymetry show no corresponding features, but there are indications of north-south-trending seismic features on the deeper horizons (4) of the above-mentioned survey.

The steep gravity gradient which marks the southern boundary of this province on C52/10 corresponds well in detail with a major fault, downthrown to the south, found on the above mentioned seismic survey. For most of its length this fault is along the Malita Shelf Valley.

Gravity undulations within the province do not correlate well with the seismic features, which are complex and change drastically with depth. The tendency to north-south features in the area of C52/7 and C52/8, however, corresponds to indications of north-south folding superimposed on a strong northerly regional dip shown by the seismic results on the present survey (Plate 4).

Bonaparte Regional Gravity Depression

This large province has been suvdivided in 5 units which will be discussed in turn.

North Bonaparte Gravity Shelf. This unit merges with the Cartier Regional Gravity Shelf to the west. It corresponds, in area, to the Bonaparte Depression and the deepest part of the offshore basin (see Chapter 3), but the many small features within its area have no obvious correlation with structure. The reason why the Bouguer anomaly values are high relative to the flanking East and West Bonaparte Gravity Lows when the sedimentary section is thicker may only be conjectured, the most likely explanation being a genetic relation to the Wickham Gravity High to the south-east.

Wickham Gravity High. This unit was defined in 1965 and has been previously described (Smith, 1966; Geophysical Associates, 1966) and interpreted as arising from an intrabasement feature. Its southern plunge was noted on an underwater gravity traverse in 1959 (Williams & Waterlander, 1959). As mentioned earlier (Chapter 3)it is now postulated to arise from a body of relatively dense material, perhaps limestone or volcanic derived material, within the sedimentary section.

The West Bonaparte Gravity Low, the South Bonaparte Gravity Low, and the East Bonaparte Gravity Low. These form a prominent V-shaped series of gravity units flanking the Wickham Gravity High and the North Bonaparte Gravity Shelf. Trends in these units closely follow the seismic, aeromagnetic, and bathymetric trends. The outer margins mark the steep flanks of the Bonaparte Gulf Basin offshore. The South Bonaparte Gravity Low is separated from the West and East Bonaparte Gravity Lows by a possibly continuous east-south-east trending Bouguer anomaly ridge on the MEDUSA BANKS and PORT KEATS 1:250,000 sheet areas. The West Bonaparte Gravity Low is slightly arcuate and concave south but trends mainly east-south-east. The South Bonaparte Gravity Low is roughly triangular and outlines the southern extremities of the Bonaparte Gulf Basin. The East Bonaparte Gravity Low is also slightly arcuate, concave west, but trends mainly north-south.

The anomalous aspect of this province is the reversal of correlation between the rising Bouguer anomalies and thickening sediments across the Wickham Gravity High and the North Bonaparte Gravity Shelf.

West Arafura Regional Gravity Platform

This province lies completely on the continental shelf to the north of Melville Island and Cobourg Peninsula. Its east-west-trending southern margin is marked by a steep gravity gradient, increasing northwards. The seismic results show that Mesozoic-Tertiary section thickens to the north. The smaller gravity features within the province, however, show no obvious correlation with seismic results, which were poor in this region.

Wangites Regional Gravity Ridge

The northern boundary of this province, described by Whitworth (1968), has been added.

Discussion

A specific objective of the survey was to investigate the gravity expression associated with known seismic "highs" such as

Ashmore Reef and Sahul Bank. Because of the previously mentioned problems of bathymetric effects and local current variations, no definite conclusions can be drawn here although it seems likely that the Ashmore Reef structure has an associated positive Bouguer anomaly feature.

Another specific objective was to investigate the gravity expression over the suspected intrusions in the Joseph Bonaparte Gulf. This was to some extent thwarted by short runs between speed changes in areas of interest, but certain conclusions may be drawn. Line 75 from 0840 to 0900 crossed what had previously been mapped as a possible intrusion. Seismic results from the present gravity deviation (not more than 2 milligals) was obtained over the structure, and a possible positive magnetic anomaly of 3 gammas was found. Farther to the north-west, an intrusive type structure was crossed three times on line 77 (0305 to 0325, 0440 to 0500, and 0610 to 0615). On the first crossing, a positive gravity anomaly of about 2 milligals was recorded immediately over the seismic structure, but the later crossings showed little or no effect; a roughness of the sea bottom, typical of the area, was obtained on the echo-sounder on all three crossings. It seems unlikely, then, that the features are basic igneous intrusives. It could be expected that salt diapirs would have a more pronounced gravity effect. The possibilities remaining include mud diapirs and acid igneous intrusives.

INSERT A

8. SEISMIC RESULTS

The seismic horizons picked are plotted in profile form in Plates 5 to 38. Where possible, definitive events have been picked. Because of the preliminary nature of this report no attempt has been made to correlate events from line to line. Only the ship's monitor records from the deep cable have been picked, results from the shallow, high-resolution cable being used as interpretation aids.

The results are generally poor on the continental shelf because of the loss of the 6-channel cable and the high working speeds. This applies particularly to the Sahul Rise, Londonderry Rise, and Van Diemen Rise areas, but other seismic surveys (see Chapter 3) have been carried out over much of these areas. On the continental shelf area (less than 100 fathoms) it seems that the quality of results obtained with the high-resolution cable may be better than those from the single-channel Chesapeake cable if suitable filtering and time scalers are used. The 6-channel cable was used only for lines 92, 6, and the western half of line 7 before its loss. Results from this cable were generally excellent and far superior to those from either of the other cables. Water bottom multiples, lack of penetration of energy through the bottom, and tow noise were the main problems on the shelf area.

Results from deeper water areas, particularly on the continental slope, were generally good down to water depths of about 500 fathoms. One problem was that the datum on the facsimile recorders used could only be changed in full scale steps (2 or 2.5 seconds) so that many data have been lost on the monitor records.

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survey, however, were poor and showed only a shallow anticline. No significant

These data were recorded on magnetic tape, however, so are available for future playing back.

Results from areas of water depth greater than 500 fathoms are poorer because the seismic system had insufficient energy. This applies to only a few areas (Timor Trough and the extreme west of some lines).

In interpreting the profiles extreme caution should be taken to ensure that apparent reversals are not the result of course changes, which were sometimes large. In some areas spurious folding has been produced by variations in the ships course when it has been sailing more or less along the strike. Water depth corrections have not been made.

The main structural features found from the seismic results of this survey are summarised in Plate 4. Where usable results were obtained on the continental shelf, they generally agree well with results of previous work. Areas are marked in Plate 4 as being of complex tectonics where the features are too local to be able to infer their trend with any certainty. Their investigation requires more detailed surveys.

The continental slope results show that faulting is the principal tectonic phenomenon, at least near the surface. This also applies to the southern flank of the Timor Trough. Erosional factors, probably due to strong ocean bottom currents, have resulted in the continental slope being an erosional surface, and most of the faults have no surface expression. Despite the erosion, the deepest part of the Timor Trough is filled with recent sediments only in a flat-floored valley five miles wide. Most of the eroded material would appear to have been transported elsewhere. The escarpment which forms the northern flank of the Timor Trough is too steep to record sub-bottom results and is recorded only as diffraction in some places. About 20 miles south of the Timor coast, there is a parallel bathymetric ridge which may imply buckling on the northern flank of the Trough.

The edge of the continental shelf to the west and south of Ashmore Reef is marked by a steep bathymetric escarpment which certainly on lines 27 and 28 is a major fault. It is illustrated by the manner in which seismic refraction horizons terminate at the escarpment face. To the south of Ashmore Reef this scarp trends east-south-east, perpendicular to the general trend and to the gravity trend in this area. An anticlinal feature running into this scarp from the south is on the trend of the Ashmore Reef Anticline and bears some resemblance to it. There are many unconformities in the section over this anticline and it appears to be formed by draping of younger beds over a more extreme deeper structure. Immediately west of this anticline on lines 28, 29, and 30, a deep buried scarp can be seen, downthrown to the west. Immediately west of this scarp the deep beds dip steeply west indicating that the scarp was once exposed and the beds are later fill. At the extreme west of lines 31 and 32, evidence of several intrusive type structures was found. Two of these have pierced the sediments to the surface and the one on line 32 has a positive magnetic expression of about 15 gammas.

Trending north-easterly from D51/3 to C41/12 (Plate 4) is a 30-mile-wide syncline with a parallel anticline north-west of it. These folds have associated bathymetric and gravity expressions (Plate 3). Both features plunge to the north-east. The syncline is about 30 miles wide with thickening of all beds towards its axis. On its north-western flank, anomalous dips in intermediate beds have produced reversals (see the Plate showing sheet area C51/16) which appear as cross bedding. Both these folds trend en echelon to the continental margin, being on the shelf at the south-west end and extending onto the slope at their north-east end. The south-west end of the syncline was discovered by Arco Ltd and Australian Aquitaine Petroleum (1968) and has been labelled S13 by them.

The two major synclines in the Bonaparte Depression area correspond to the deepest part of the offshore Bonaparte Gulf Basin and agree with S5 and S10 of Arco Ltd and Australian Aquitaine Petroleum. The shorter, more eastern syncline shown in Plate 4 is a deeper feature than the other and does not appear on shallow beds. The limits of the features as shown in Plate 4 are the survey boundary to the south and a poor-reflection area to the north. The features are presumably much more extensive in fact. The regional dip is always nearly at right angles to the gross coastline along the east margin of Joseph Bonaparte Gulf up to Bathurst Island then along to Melville Island and Cobourg Peninsula. The section thickens away from the coast towards the sea here. North of Melville Island, from nine degrees south to ten degrees south there are indications of north-south-trending folds superimposed on a north regional dip. The gravity contours also show north-south trends here. These may represent a continuation of the Precambrian trend exhited by the Halls Creek Mobile Zone and trends near Darwin.

There is a distinct anticlinal reversal on line 81 in Dundas Strait which was discovered on this survey. Because of the shallow water and proximity to Darwin this feature should be further investigated.

A specific objective of the survey was to investigate seismic expression over Goodrich Bank. Two crossings of this feature were made (see the Plate showing sheet area C52/11) which showed a positive "high" although no allowance for water correction has been made. Critical closure for this would be north-south, however, and no crossings were made in that direction.

In view of the generally poor results on the shelf it will not, in general, be possible to use them to co-ordinate and integrate previous seismic work.

9. MAGNETIC RESULTS

The magnetic results are presented in the form of profiles in Plates 5 to 38. No interpretation has, as yet, been done on the data.

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APPENDIX A

ORGANISATION OF THE SURVEY

The Bureau of Mineral Resources let a contract to United Geophysical Corporation of Brisbane for the execution of the marine gravity, seismic, and magnetic survey described in this report. United was responsible for: the overall management of the survey; the supply of all personnel (except for three surveyors from the Department of the Interior, who worked in with United on the navigation) and equipment (except the seismic equipment and the shore-based magnetometer) necessary to carry out the survey; the operation of the equipment; and the reduction of the data and presentation of results, including progress reports and a final report on the gravity survey.

The sparker equipment and seismic streamer cables and recorders were provided by BMR; United was responsible for their installation on the ship and their operation.

The personnel provided by United Geophysical Corporation for the survey are listed in a separate report (United Geophysical Corporation, 1968). In addition to their personnel, three surveyors of the Department of the Interior (V. Ingham, D. Chudleigh and T. Harvey) were attached to the operation. Two were on board at most times. These officers, in addition to being integrated into the routine navigation operations, performed many non-routine tasks including the taking of independent (non-v.l.f.) fixes, and V. Ingham has prepared a detailed report on the navigation aspects of the survey (Ingham, 1968).

A brief list of the instrumentation used on the survey follows.

(1) Gravity

1 Askania Seagravimeter Gss-2 after Graf, Type C.
1 Anshutz Gyrotable
1 Analogue cross-coupling computer (manufactured by United Geophysical Corp.)

(2) Seismic

1 21,000-joule Spark-Array and towing cable. with E.G. & G. power supplies, capacitors, and trigger units
1 Chesapeake 6-channel hydrophone streamer
1 Geotech SUBot single-channel high-resolution hydrophone streamer
1 Chesapeake single-channel hydrophone streamer (Model 12)
1 S.I.E. MU-500 six-channel seismic amplifier
1 Ampex 14-channel magnetic tape recorder
2 E.G. & G. model 254 facsimile recorders
1 Timing unit, BMR Model

(3) Magnetic

1 Varian model V4970 towed proton-precession magnetomer (ship)
1 BMR model MNZ-1 proton-precession magnetomer (shore monitor)

(4) Navigation

(a) v.l.f. system
4 Tracor model 599Q Omega tracking receivers (2 for shore monitor)
2 Model 304B Rubidium Standards
1 Sultzer Model 401M clock with HP5322L electronic counter

(b) Sonar Doppler system

1 Modified JN-410 sonar doppler system manufactured by General Applied Science Laboratories

(5) Auxiliary

2 Recording fathometers, Kelvin Hughes model MS37
1 Sperry Mark 14 Model 2 gyro compass
1 Kelvin Hughes Type 17 radar
2 Collins 32RS-1 SSB crystal controlled transceivers
1 Collins 51-S1 communications receiver
about 100 Radar reflector buoys with anchors, expendable.

The characteristics of the ship used for the survey are listed below.

Name: M.V. "Wyrallah"

Type: Motor, cargo ship, North Sea trawler type

Length: 215'

Beam: 36'6"

Draft: 13' (loaded)

Tonnage: 1050 gross, 535 net

Engine: Burmeister and Wain 6-cylinder direct reversing 130 hp

Crew: 14-16 men

Accommodation: 15-18 men plus 2 house trailers giving accommodation for an extra 16 men

Speed: 11 knots

The ship was of a shape and size which made it suitable for marine gravity work involving long traverses as carried out on this survey. Although periods of heavy seas and swell were rare, especially during the survey proper, she showed herself able to hold stability and steady course better than would be expected from most survey ships. Additional water and fuel tanks were installed in the holds to provide ballast and extend the operating range. Thus, the fuel capacity was 73,500 gallons and the fresh water capacity 74,000 gallons. The ship's refrigerated cargo area of 750 square feet was air-conditioned and used as instrument, navigation, and computing rooms. Four diesel generators were mounted on the foredeck to provide A.C. power for instrumentation, the spark-array system, and for air-conditioning. These included two 44-kVA and one 60-kVA Lister-Dunlite 3-phase 440/220-volt, 50/60-Hz generators and one 15-kVA Köhler single-phase 220/110-volt 60-Hz generator. The spark-array power supplies, capacitor banks, and trigger units were mounted in the after hold. Sea-chests were placed in the hull for the sonar doppler and echo-sounder transducers. A hoist for the underwater gravity meter was built on the starboard side of the foredeck. Reels for the 6-channel cable, the high resolution cable, and the magnetometer sensor were mounted on the after deck. Booms were constructed to allow sufficient separation of all the towed cables.

APPENDIX B

NAVIGATION SYSTEM AND PERFORMANCE

The navigation methods, instruments, and their performance have been discussed by Ingham (1968) and United Geophysical Corporation (1968) and only a brief summary is given below.

To fully utilise the recent improvements in sea gravity meters, navigation control should be such that errors due to inaccuracies in position and velocity are of the order of one milligal. In the area of the present survey, this implied knowing the ship's position to within about a minute for the latitude correction, and its velocity to about 0.1 knots for the Eötvos correction. The navigation control can be considered as having three main aspects:

1. Geographic position.
2. Ship's speed and azimuth.
3. The relative position of lines.

It will be convenient to discuss the navigation system for this project under these headings.

Geographic position

The ship's primary navigation system was a v.l.f. radio relative navigation system, as described by Stanborough (1965).

Frequency-stabilised transmissions in the range 10 to 30 kHz are propogated in a duct between the Earth's surface and the ionospheric D layer and are affected by diurnal variations to a lesser degree than higher frequencies. The transmissions suffer relatively little attenuation and have world-wide range. Navigation using these transmissions is effected by commencing from a known point and finding new positions relative to this point by measuring the phase changes of two (or more) transmissions; that is, by measuring the component of movement of the ship towards or away from each of the two transmitting stations. These measurements were made with v.l.f. tracking receivers which make phase comparisons of the received signals with a "local" standard oscillator. Phase differences in microseconds or centicycles were output to graphic records. Geographic changes in the ship's location were then plotted on charts which were prepared in advance to show isolines of transmission time from the stations being used.

Although the diurnal phase variations are small and other variations are usually smaller, the variations must be accounted for. A fixed monitor station on shore was manned to measure these variations continuously.

There are many stations which transmit in the v.l.f., range but most of these are weak, do not broadcast continuously, or are not sufficiently frequency-stable. Suitable stations which can be picked up in Australia more or less continuously are:

6BR Rugby, England, 16.0 kHz
NPG Jim Creek, USA 18.6 kHz
NWC North West Cape, Aust., 15.5 kHz, 19.8 kHz, and 22.3 kHz
NPM Hawaii, 23.4 kHz
OMEGA (Haiku) Hawaii, 10.2 and 13.6 kHz
OMEGA (Aldra) Norway, 10.2 and 13.6 kHz

The last two stations listed are two of an intended world-wide network of eight transmitters broadcasting on the same frequencies on a time-sharing basis and called the OMEGA system (Pierce, 1965). This system has been specially designed for marine navigation, and the station sites have been appropriately chosen. The stations will all be mutually synchronised and will provide lane identification facilities. For the present survey, however, the stations were used only in their capacity of transmitters of a stable frequency. It was intended to track with four stations (including the two OMEGA stations), thus providing a good deal of redundancy for accuracy checks. The same stations were to be monitored on shore.

Of great importance for v.l.f. navigation is the local time source of the ship. One nautical mile is represented by a phase change of 6.18 microseconds so that it is obviously desirable that the local time source should be accurate to within at least a couple of microseconds, after allowance for drift has been made.

The local time source was based on a rubidium frequency standard. Rubidium standards typically show drift rates of a few microseconds per day but in a manner which can probably be approximated (to within a microsecond or so) to linear drift. Checks of the local time source on the ship were made by fixing from topographic co-ordinates whenever possible, and a relative drift rate between the ship and shore averaging 6.6 microseconds per day was established. An allowance for diurnal drift and drift of the shore monitor's time source then allowed the drift of the ship's source to be calculated. The shore monitor's time source drift was estimated by v.l.f. phase checks, any long term changes in phase drift at <u>the same time each day</u> being attributed to drift of the frequency standard rather than to diurnal drift.

The drift rate of the monitor's time source is, then, not so important provided that it is sufficiently stable. An ordinary crystal frequency standard would probably be sufficient for the monitor, but a rubidium standard was used with a crystal standard on standby. The rubidium standard was thus available as a spare in case the ship's standard became unserviceable; the crystal standard would then be available for the monitor.

A v.l.f. tracking receiver makes a phase comparison between a received v.l.f. signal and the local standard oscillator. The v.l.f. signal and the oscillator signal are synthesised to one frequency for this purpose. The phase difference was plotted out continuously on a chart recorder. Two types of v.l.f. tracking receivers were used for this survey: Tracor models 599Q and 599G. The Tracor model 599Q receiver is capable of handling and plotting measurements from up to eight OMEGO stations continuously. This can be done because the OMEGA transmitters broadcast on a time-sharing basis and on the same frequencies. The 599Q receiver, then, has a synchronised commutator unit which acts as a gate so that measurements are made sequentially on all channels. The 599Q can also be used for tracking from an ordinary v.l.f. station, but in this capacity can track only one station. The Tracor model 599G receiver handles one v.l.f. station. The system used for this survey included two 599Q receivers and one 599G receiver, both for the ship and for the monitor. One 599Q receiver tracked from the two OMEGA stations. The second 599Q was used for an ordinary v.l.f. station and was available as a reserve OMEGA receiver in case of the failure of the first receiver. The 599G normally tracked a fourth station.

A complete list of the equipment to be used for the v.l.f. tracking has been given in Appendix A.

For plotting the v.l.f. phase changes on navigation charts, a special set of charts was prepared by the supplier of the equipment. A UNIVAC 1108 programme was used for computing the latitude and longitude values of the v.l.f. isophase contours. In the programme, corrections were made for the ellipticity of the Earth. The values were then plotted manually onto the charts in the form of isolines of phase.

The v.l.f. receiving equipment performed well for most of the survey; most of the problems experienced with v.l.f. navigation resulted from the geographic position of the survey area rather than from equipment malfunction. However, a considerable amount of operator experience was necessary with the gain and blanking controls of the equipment to ensure optimum performance. A Tracor engineer, Mr W. Donnell, assisted in training of personnel in this respect. Modifications made to the equipment included the provision of notch and high-cut filters on receivers used for stations other than NWC. This was because the proximity of NWC and its extremely high transmitting power caused erratic phase distortion within the receivers used for the other stations recorded. The filters were thus designed to attenuate the three NWC frequencies for the other receivers. NWC did not broadcast for 8 minutes each hour and for about 6 hours once a week, and also changed frequency once a week.

Ship's speed and azimuth

The ship's secondary navigation system was a sonar doppler navigation system. The principal use of this system was for obtaining the ship's speed and course made good relative to the Earth. The principle of the system is that the doppler shift in frequency of an ultrasonic beam transmitted from a moving ship, reflected from the ocean bottom and received back at the ship, can be converted to a component of the ship's motion in the direction of the beam. Problems arise from the pitch, roll, and heave of the ship and additional, unwanted motions of the ship with respect to the bottom. To cancel their effect, the system employs pairs of beams: one pair angled fore and aft, and another port and starboard. If the ship's motion is forward, the doppler shift of the forward beam will be positive and that of the aft beam will be negative. The difference will be essentially independent of any component due to pitch. In a similar way the port and starboard beams cancel out roll.

The system used was a modified Janus JN-410 manufactured by General Applied Science Laboratories. Each beam of the system was angled at 30 degrees to the vertical and was approximately three degrees wide. Two four-element transducer arrays are used for transmitting and receiving the four beams. The forward and sideways speed components were measured separately. The ship's true speed and drift angle are then automatically computed from the two components. The speed is automatically integrated over time to provide a reading of true distance travelled. The computing unit of the system also allows for changes in the sound velocity due to water temperature changes; a thermistor mounted in the transducer unit measures the near-surface temperature.

This system was designed to operate in water depths as great as 50 fathoms, below which it was supposed to operate from back-scatter from particles and temperature gradients in the water, so giving ship's speed relative to the water mass above about 50 fathoms. A large proportion of the survey area was in water less then 50 fathoms deep.

The system measured speeds up to 20 (optional) knots with an accuracy of one per cent, and so should have satisfied the requirements of the gravity work. The distance travelled is measured with an accuracy of one per cent.

In practice it was found on the voyage from Brisbane to Darwin that the system began to lose bottom, when pitching and rolling in water depths of about 25 fathoms, and did not operate off back-scatter in deeper water. Despite much investigation of the system, this could not be improved significantly, so the system was modified. This was done during the survey by the addition of two phase-lock tracking filters (Interstate Electronics Corporation Model PL107), one for the fore-and-aft output and one for the port-starboard output. These significantly improved the ability of the receiving section to hold signal but because of the inability of the port-starboard filter to assess polarity, an unambiguous total velocity vector could not be computed. Hence, continuous recording of the fore-aft component was attempted from November. In general then the system did not perform to specifications standards and for more than half the survey the results could not be directly used.

Relative position of lines

For the purpose of making gravity loops and assessing accuracy of the v.l.f. results, a number of tie-lines were run across the primary traverses. It is obvious that these should cross at well known positions, and for this purpose 89 buoys were used. The buoys were dropped and anchored at planned points on the initial grid. They were equipped with radar reflectors so that their position could be established relative to a succeeding traverse. This also provided an additional way of checking the drift rate of the ship's rubidium frequency standard.

The buoys were of simple, inexpensive construction and were made up on the ship as required. Each buoy consisted basically of a polyurethane foam float moulded in a cardboard box with an axial aluminium rod on top of which (about 14 feet above the water) was mounted a radar corner reflector, and on the bottom a counter-weight. A nylon mooring line was anchored with a concrete block and a small boat's anchor. The design details were modified during the survey when it was found that the axial rods tended to break where drilled for reinforcing wires on early models. Of the 89 launchings, 42 were resighted, some after several weeks. The buoys could be sighted on radar up to about five miles away.

The system as a whole

The poor performance of the sonar doppler system placed greater demands on the v.l.f. information, as was mentioned in the report. Early in the survey, when it became obvious that the v.l.f. system was not as reliable as had been hoped, celestial fixes were begun on a routine basis at dawn, noon, and dusk, to provide a rigid framework on which to base the v.l.f. results. The Department of the Interior personnel on board, who were equipped with two sextants, did the celestial fixes. As many other independent fixes as possible were used in this way; for example, land sightings and radar ranges. Unfortunately these were few, as most of the lines were far from land.

Owing to an error in page numbering,
the report continues on page 66

APPENDIX C

GRAVITY INSTRUMENTS AND PERFORMANCE

The surface gravity meter used on the survey was Askania Seagravimeter Gss-2, type C, serial no. 27 and it was mounted on an Anschutz gyro-stabilised platform.

The meter was as described by Schulze (1962); that is, it featured strong magnetic damping and automatic servo-controlled nulling of the beam. Basically, the meter consists of a horizontal beam with one end pivoted by torsion springs and the other end suspended on a tension spring. The beam is mechanically constrained to move only in the vertical plane. It moves through a very strong magnetic field which provides a high degree of damping for all short-period motions of the beam. Any deflection of the beam sets an automatic servo-control system into operation which restores the beam to its null position and gives an output signal corresponding to the change in vertical acceleration which produced the deflection. The very high reduction gearing in this automatic system causes it to have slow response, further attenuating high-frequency output caused by the vertical component of the sea motion. Because of the reduction in beam motion, off-levelling effects (caused by the response time of the stabilised platform servo system) and cross-coupling effects (caused by horizontal accelerations in the beam direction when the beam is temporarily deflected by a change in vertical acceleration) are reduced.

The gyrotable, on which the meter was mounted, is a stabilisation device built for use at sea in maintaining the meter level independent of the movements of the ship. It has been described by Karnick (1964) and also, briefly, by Hayes et al. (1964), who measured its effectiveness with simulated ship's motions. The platform is attached to a fixed base by a universal joint. A vertical gyro serves as the orientation reference. Deflections of the platform from horizontal are picked up electrically, are amplified, and drive servo-motors (two at right angles) which act to return the platform to horizontal. Erection of the gyro can be effected in one of two ways: by using electrical erection, which is generally considered to be the better method; or by using an oil erection system, which is not so well suited to rough sea conditions. The erection systems sense drifts of the spinning axis from the apparent vertical, and through a torque motor, restore its alignment.

The apparent vertical is the vector sum of gravity and the instantaneous accelerations caused by the motion of the ship. Horizontal components are time-averaged out. On this survey, the electrically erected gyro was used, with an oil erected gyro available as a spare.

The effect of cross-coupling errors on a stable platform meter has been discussed theoretically by Harrison (1960) and investigated in practice by Wall et al. (1966). An analogue computer to continuously calculate the magnitude of the correction has been built by the Lamont Geological Observatory (Talwani et al., 1966). United Geophysical Corporation built an analogue computer, based on the Lamont design, for use on this survey. It used the outputs of two Donner horizontal accelerometers mounted on the gyrotable to calculate the horizontal acceleration acting on the beam. The output of the beam was filtered. From the instantaneous beam deflection and the instantaneous component of horizontal acceleration acting on the deflected beam, the cross-coupling correction was computed.

The platform-mounted gravity meter was mounted as near the point of least motion of the ship as practicable, to reduce apparent ship's motions. It was mounted with the beam in a fore-and-aft orientation. The total gravity system had a time constant of about 300 seconds.

The recordings from the gravity system were all made on analogue chart recorders and the variables recorded are listed in another report (United Geophysical Corporation, 1968) in which the whole system is more fully discussed.

The system performed very well throughout the survey. The only trouble experienced was with the Donner accelerometers, two of which were found to be faulty on the cruise from Brisbane to Darwin. These were replaced with two accelerometers manufactured by the Palomar Scientific Corporation (Douglas part 7869913-501) and no further trouble was experienced.

It was intended to use an underwater gravity meter to check the drift and general performance of the Askania system each two or three days where water depth was less than 450 feet. The underwater meter originally supplied by the contractors (a La Coste and Romberg model W, serial number 3) was calibrated on the Brisbane range before the "Wyrallah" departed that port. As this meter had an insufficient range without resetting (150 milligals) it was replaced in Darwin before the survey commenced with a La Coste and Romberg model H-G world-wide range meter. After the first two marine readings it became obvious that this meter was not performing satisfactorily so that later observations (20 more) were made only when the ship was stopped for some other purpose. A run over a gravity range near Darwin showed that the meter had an extremely high drift rate (0.1 milligals/hours) and a faulty thermostat was found by the manufacturer after the survey. As the drift and general performance of the Askania system were good, no underwater readings have been used in the gravity reductions.

APPENDIX D

SEISMIC EQUIPMENT AND PERFORMANCE

Introduction

The early methods of continuous seismic profiling at sea evolved from standard depth sounding equipment and techniques. Under favourable conditions, it had been found that the sound pulses used had effectively penetrated a considerable thickness of unconsolidated sediments. The transducers used in depth sounders are generally of low power and use frequencies in the 10 to 15 kHz range. Subsequent developments increased the power of the source and decreased the frequency. There has also been considerable improvement in the receiving equipment used.

One of the earliest developments was the "sparker" system, which produced a simulated explosion in the form of a high-voltage spark fired under water. Penetrations of the order of 1000 feet have been recorded with high-power "sparker" units. A number of other repetitive sources have been developed, such as the air gun. The air gun produces a low-frequency pulse by releasing compressed air confined in a towed chamber. The chamber is submerged in the water. Other similar repetitive sources are the gas gun, the gas hammer ("Dynoseis"), the gas tube ("Gasop"), the vibrator ("Vibroseis"), the caged charge ("Flexotir") and the exploding wire ("Wassp").

Dr H.E. Edgerton has developed a spark system which uses an array of spark gaps to increase the power and low-frequency content of the pulse. This was the system used on this survey and the equipment was manufactured by Edgerton, Germeshausen, and Grier, Inc. (E.G.G.).

Three hydrophone streamers were initially available for the survey; a six-channel streamer developed by Chesapeake Instrument Corporation, a single-channel, high-resolution cable built by Geotech, and a single-channel unit with medium frequency response, which was to be used as a spare for either of the first two units in the event of their failure.

The hydrophone streamers were designed and built by Chesapeake Instrument Corporation and Geotech and consist of multiple hydrophone arrays with low noise characteristics.

Discharge system

The three basic components of the sound source system are the power supply, the capacitor bank, and the transducer or spark-system. The power supplies, which operated from a 220-volt, 50-Hz, a.c. supply at an average 200 watts under operation, provided high-voltage d.c. at 3500 to 4000 volts to the capacitor banks. The triggered capacitor banks took the high-voltage d.c. from the power supply, or from the 2000 watt-second capacitor banks, and supplied the stored electrical energy to the spark system. The standard trigger capacitor bank contained 10 energy storage capacitors connected in parallel to give a total bank capacity of 160 microfarads. The 2000 watt-second capacitor banks had 320-microfarad modules which were used to provide additional energy storage for the higher power systems. A high-voltage trigger impulse which was keyed from the timing unit, caused a spark gap in the capacitor bank to become conductive, allowing the capacitors to discharge into the transducer.

Theoretically, the maximum firing rate is limited by the ratio of the total stored energy to the power supplied. In actual practice, line losses and voltage fluctuations may reduce this considerably. The formula recommended by the manufacturer is:

$$\text{Minimum Firing Interval} = \frac{\text{Total Energy Stored}}{\text{Power Supplied}} \times 1.6$$

There were nine power supplies, nine 2000-watt-second capacitor banks, and four 1000-watt-second triggered capacitor banks (one spare) used in the survey, making the total energy of the system 21,000 watt-seconds. These were assembled as three separate units operating into three separate "Spark-Arrays" assembled in a single 9-electrode array. Thus the minimum firing interval should be:

$$\frac{3 \times (2000 + 1000)}{3 \times 1000} \times 1.6 = 3.7 \text{ seconds}$$

or a firing rate of about once every four seconds.

Spark-array transducer

The "Spark-array" produces an acoustic pulse by creating a high-voltage spark under water. By using a high-capacitance, lower-voltage (3600 volts) discharges system, and an array of three spark electrodes per unit, lower frequencies and more energy output are obtained. Each unit is rated at 7500 watt-seconds energy capacity, and three of them were strapped together and used with the 21,000-watt-second capacitor bank available. The sparker unit was towed about 50 feet astern of the ship from a boom on the port side.

Six-channel hydrophone streamer

The main hydrophone streamer to be used for this survey was a six-channel neutrally buoyant cable built by the Chesapeake Instrument Company, with acceleration cancelling hydrophones encased in an oil-filled flexible housing. Chesapeake PC-100 hydrophones were used. The six channels were separated by five 440-foot, $1\frac{1}{4}$ inch diameter neutrally buoyant interconnecting spacer sections. The active length of each channel was 160 feet giving a 600 foot centre-to-centre spacing for the active sections. The 160-foot active length sections were 3 inches in diameter and were encased in nylon reinforced neoprene hose which carried the towing strain and had a rated tensional breaking strength of at least 10,000 pounds. The compressibility of the hose material matched that of sea water so that acoustic matching was achieved. Of the 160 feet available, active lengths of 40, 80, 120, or 160 feet could be selected by relay switching from the ship. In each 40-foot section there were 16 hydrophones at 2.35-foot spacing. Three depth sensors, with range to 100 feet, were mounted at channels 1 and 6 and at mid-cable. Their output was on three meters mounted on the ship. The depth of the streamer up to 35 feet was controlled by the amount of tow cable out. There was normally 800 to 1000 feet of neutrally buoyant leader cable ahead of the first active section. The hydrophones were parallel connected and gave a sensitivity for an active channel of -66 dB relative to one volt per microbar, independent of channel length. The frequency passband of each channel was 20 to 5000 Hz. An impedance-matched preamplifier was provided in each channel. Manufacturer's specifications stated that the towing noise at speeds as high as 10 knots was less than the ambient ocean noise at frequencies down to less than 50 Hz so that it was planned to operate at 10 knots on this survey. The oil used to fill the active sections was a blend of "Lubricin" and "Isopar".

Single-channel high-resolution streamer

This streamer was intended for shallow penetration and high resolution. It was a Subot Hydrostreamer manufactured by the Geotech Division of Teledyne Industries. It had one 40-foot active length section which contained Geospace MP-7 crystal element hydrophones spaced 1.5 feet apart connected to a preamplifier. In addition, a separate set of six hydrophones 1.5 feet apart in the centre of the active section was connected to another preamplifier. The 10- or 40-foot active sections could be selected by switching on the ship. The active section was encased in a $1\frac{1}{4}$ inch diameter oil-filled P.V.C. tube. The depth of the active section was monitored and controlled from 0 to 35 feet with a pneumatic control system on the ship (Geotech Model 25643). The system had a frequency response of 35-2500 Hz. The tow cable was 600 feet long. The system was designed for towing speeds of 3 to 10 knots.

Spare single-channel streamer

This streamer was similar to the one used for BMR's 1965 survey (Smith, 1966). It was the "Towflex" model 12 manufactured by the Chesapeake Instrument Corporation. Its single active length section was 150 feet long and contained six Chesapeake PC-100 pressure-compensated, acceleration-cancelling hydrophones spaced at 30-foot intervals in a 3-inch diameter, oil-filled hose. The hydrophones were arranged to provide bottom directivity in the region of 75 Hz. An impendance-matched preamplifier was mounted in the active section. The active section was neutrally buoyant and was towed by 300 feet of neutrally buoyant stabilising cable and 800 feet of 2000-pound breaking strength tow cable. In the 1965 survey a similar cable gave good results at ship's speeds of about 7.5 knots, but increases in this speed resulted in serious noise increase (Smith, 1966).

Recording

The output from the 6-channel streamer was fed into an S.I.E. model MU500 six-channel seismic amplifier unit, comprising six TGA-1 amplifiers and three dual DHC-1 and DLC-1 filter units, and thence to six channels of an Ampex Model FR 1300 14-channel tape recorder which were recorded in F.M. mode. The tape was one inch wide and came in 3600-foot reels. Tape speeds available were 60, 30, 15, $17\frac{1}{2}$, $3\frac{3}{4}$, $1\frac{7}{8}$ and $\frac{15}{16}$ inches per second; 15/16 i.p.s. was used for this survey. The output from one selected channel was recorded on an E.G. & G. model 254 facsimile recorder. This recorder recorded in a variable-density form on an electro-chemical sensitive paper. The recording head was a helical wire mounted on a revolving drum and a steel blade electrode. As the helix wire electrode revolved, its contact point with the steel blade electrode swept across the paper. The sweep time from start to finish on the paper was 2.0 or 2.5 seconds.

The purpose of recording six channels was to enable C.D.P. stacking of the data to be done at a later stage over features of particular interest (ultimately BMR plans to have the present system integrated into an on-board C.D.P. processing system). For this purpose it was desirable to have the sparker firing at equal distance (relative to the bottom) intervals rather than at equal time intervals. Accordingly, the model 254 recorder was modified to a start-stop mode of operation by the use of a stepping motor. Each recording sweep was initiated by a pulse from the timing unit, which was obtained by dividing circuits from an output of 120 pulses per foot of distance covered over the bottom given by the sonar doppler system (see Appendix B). This triggering pulse, which also triggered the sparker transducer, could be obtained at intervals of 50, 60, 75, 100, or 150 feet, but 75 feet was chosen for this survey. The timing unit also provided the drive frequencies for the helix and the paper advance drive and gave event marks each ten minutes. This timing unit, made by BMR, also gave hour and day event marks which, marked the v.l.f. records and the magnetometer record. The output of the single-channel high-resolution streamer was recorded on another channel of the Ampex tape recorder (the seven remaining channels were used for event marks, a reference frequency, and spares). It was displayed on a second E.G. & G. model 254 facsimile recorder, also modified with the start/stop system with a start-to-finish sweep time of 0.8 seconds.

Performance of the equipment

Spark-array transducer. Two complete units were available for the survey, one to act as a spare. Trouble was experienced in that the arrays blew out parts of the stainless steel framework and wiring on occasions. At speeds of 8 to 10 knots the array tended to tow too shallow (less than ten feet) but despite a considerable amount of experimentation with weighting and an attempt to attach a paravane, this problem was not satisfactorily solved.

Six-channel hydrophone streamer. A considerable amount of trouble was experienced on trials prior to commencement of the survey proper with water leakage into connecting sections at the ends of the active sections. These caused the power supply line to short out. Immediately before the first successful cruise, all air-filled compartments in the cable were pressure packed with silicone grease to prevent further leakages.

Apart from leakages, the cable performed satisfactorily until 30 September when it broke while being reeled in at about 9° 20' south, 130° 45' east in about 500 fathoms of water. The break occurred in the first section of the spacer cable at its junction with the armoured tow cable. Despite 36 hours of grappling and visual searching and a three-hour search by aircraft the cable was not re-sighted.

Single-channel high-resolution streamer. This cable performed very well throughout the survey. Occasional vertical snaking, which was obvious from the record, was stopped by adjustment of the two depth.

Spare single-channel streamer. This cable was used occasionally before the main programme, when leaks were experienced in the six-channel streamer. After the loss of the six-channel cable it took over the role of recording deep information, and so performed in this capacity for most of the survey. As this cable was not designed for use at speeds exceeding 7½ knots without considerable tow noise, good results could not be expected at the planned operating speed of 10 knots. However, most of the shelf area of the survey had previously been covered by more powerful seismic surveys and as gravity coverage was the prime objective of the survey it was decided to continue working at 10 knots except where no previous seismic data were available or where tie data were necessary to integrate previous results. In these other areas, a speed of 8 to 8½ knots was selected.

This cable performed well, except for tow noise, throughout the survey except for a breakage in the tow cable on 10 December, probably due to snagging. The cable was relocated floating after a few hours' search, and repairs were effected.

General. Because of the poor performance of the sonar doppler system (see Appendix B) seismic triggering from this source as planned was not generally possible. Hence, constant-time-interval triggering was initiated from the timing unit, the interval being manually changed in steps of 0.1 seconds by the operators, whenever the ship's speed changed sufficiently, in order to obtain a shot about every 75 feet of distance covered over the bottom.

APPENDIX E

MAGNETIC EQUIPMENT AND PERFORMANCE

A continuous profile of the Earth's total magnetic field intensity was recorded using a model V4970 proton precession magnetometer manufactured by Varian Associates. The sensing head is in a water-tight unit which was towed about 750 feet astern. The magnetometer uses phase-lock circuitry to multiply the proton precession frequency received from the sensor, and a direct gamma readout was presented on a five-digit electronic counter and an analogue strip chart recorder. The magnetic data are accurate to ± 1 gamma (± 1 count) and the range of the magnetometer tuning is 20,000 to 100,000 gammas. The analogue recorder used a 5-inch chart, and a scale of 100 gammas was used (20 gammas per inch). The complete magnetometer consisted of:

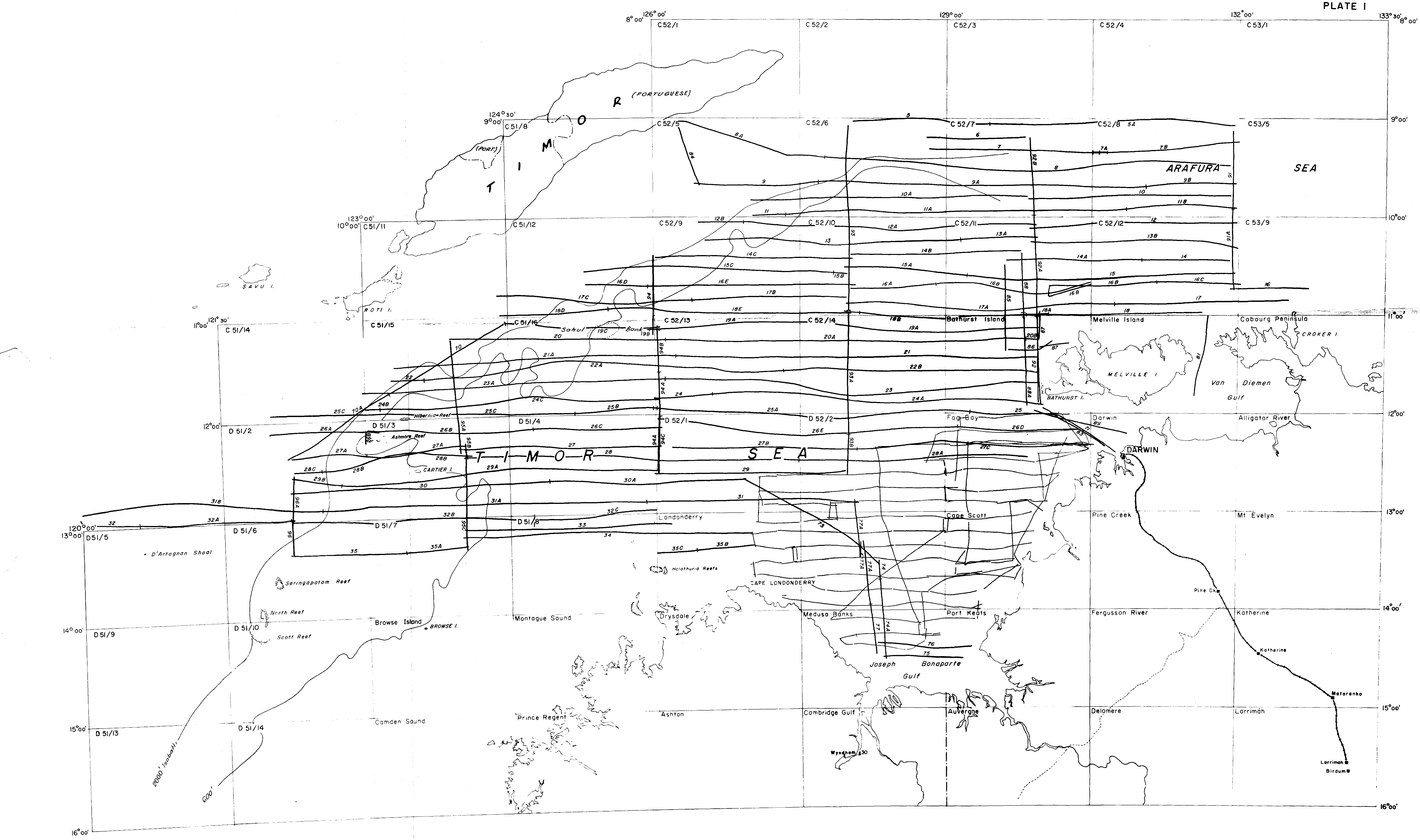
1. Proton sensor with towing cable.
2. Phase lock detector/amplifier module.
3. Counter and digital/analogue converter.
4. Analogue strip-chart recorder.
5. Power supply.

As the record obtained on the ship contained the effects of diurnal variations and other fluctuations of the Earth's field, a monitor station was established in the Darwin area and operated by the contractor. The magnetometer used at the monitor station, a type MNZ-1 designed and manufactured by BMR, was provided by BMR on loan to United. This magnetometer was a continuous-recording type with a readout in inverse gammas. The reading had an accuracy equivalent to one gamma.

Performance of equipment

The ship's magnetometer performed very well throughout the survey and it was found that the sparker system did not interfere with its operation. On two occasions the towed sensor hit the bottom in shallow water and it thus appeared to be towing at a depth of about 40 feet. It subsequently became the contractor's practice to pull in the sensor when known shaol areas were being approached; thus, data are not available for such areas.

The magnetometer used at the shore station was inoperative for several periods of up to 15 days at a time, owing to problems with the clockwork chart drive mechanism, battery problems, and pen problems, among others; as mentioned in Chapter 6, total field strength during these periods was computed from values of the vertical and horizontal components recorded at BMR's Port Moresby Geophysical Observatory. The computing was carried out by BMR for the contractors.



LEGEND

1965 BMR Marine Lines

1967 BMR Marine Lines with numbers

SCALE 40 0 40 80 120 MILES

LOCALITY MAP

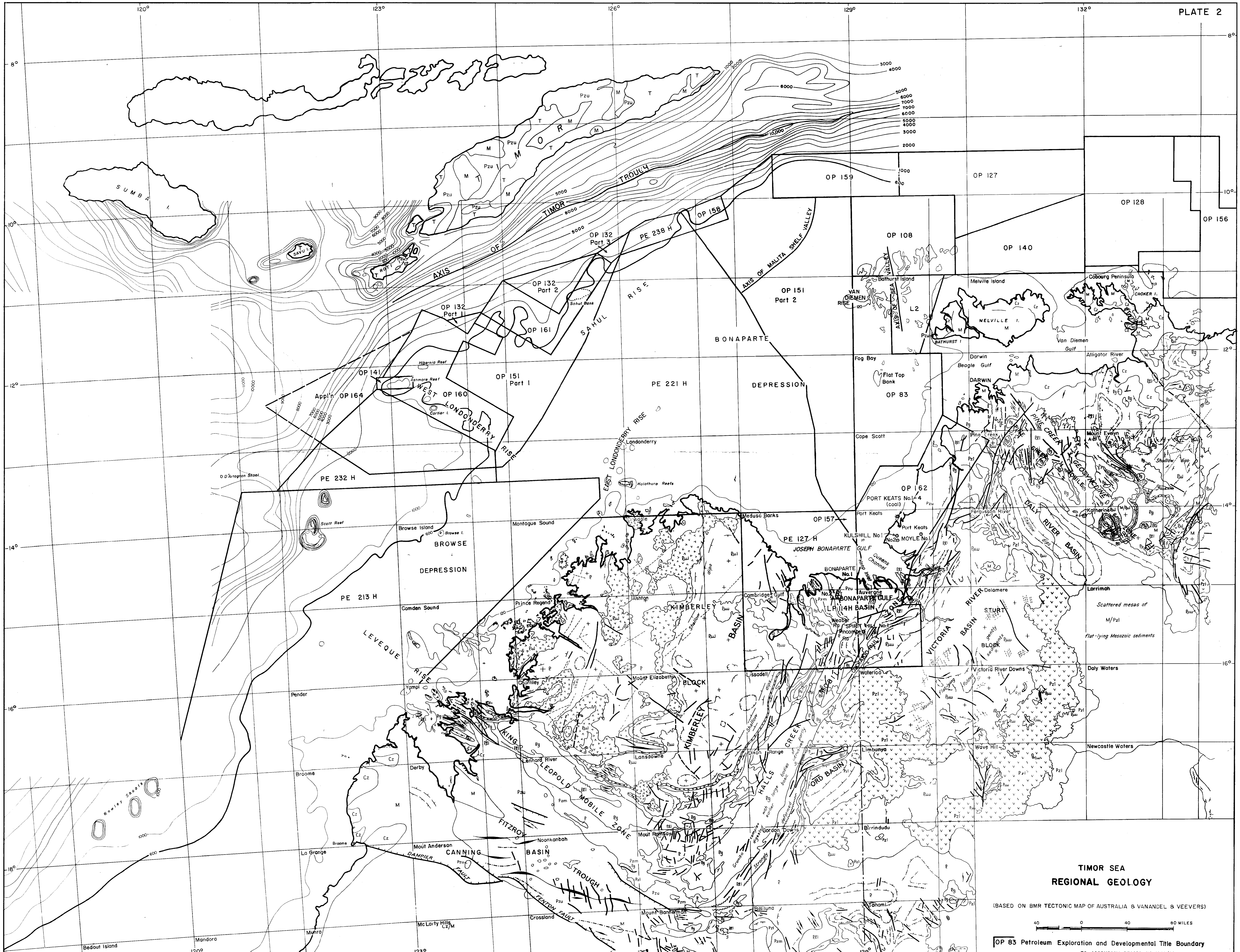
TIMOR SEA AREA

COMBINED MARINE GRAVITY, SPARKER SEISMIC AND MAGNETIC SURVEY, 1967

TO ACCOMPANY RECORD NO. 1969/40

C52/B8-18

PLATE 2



TIMOR SEA
REGIONAL GEOLOGY

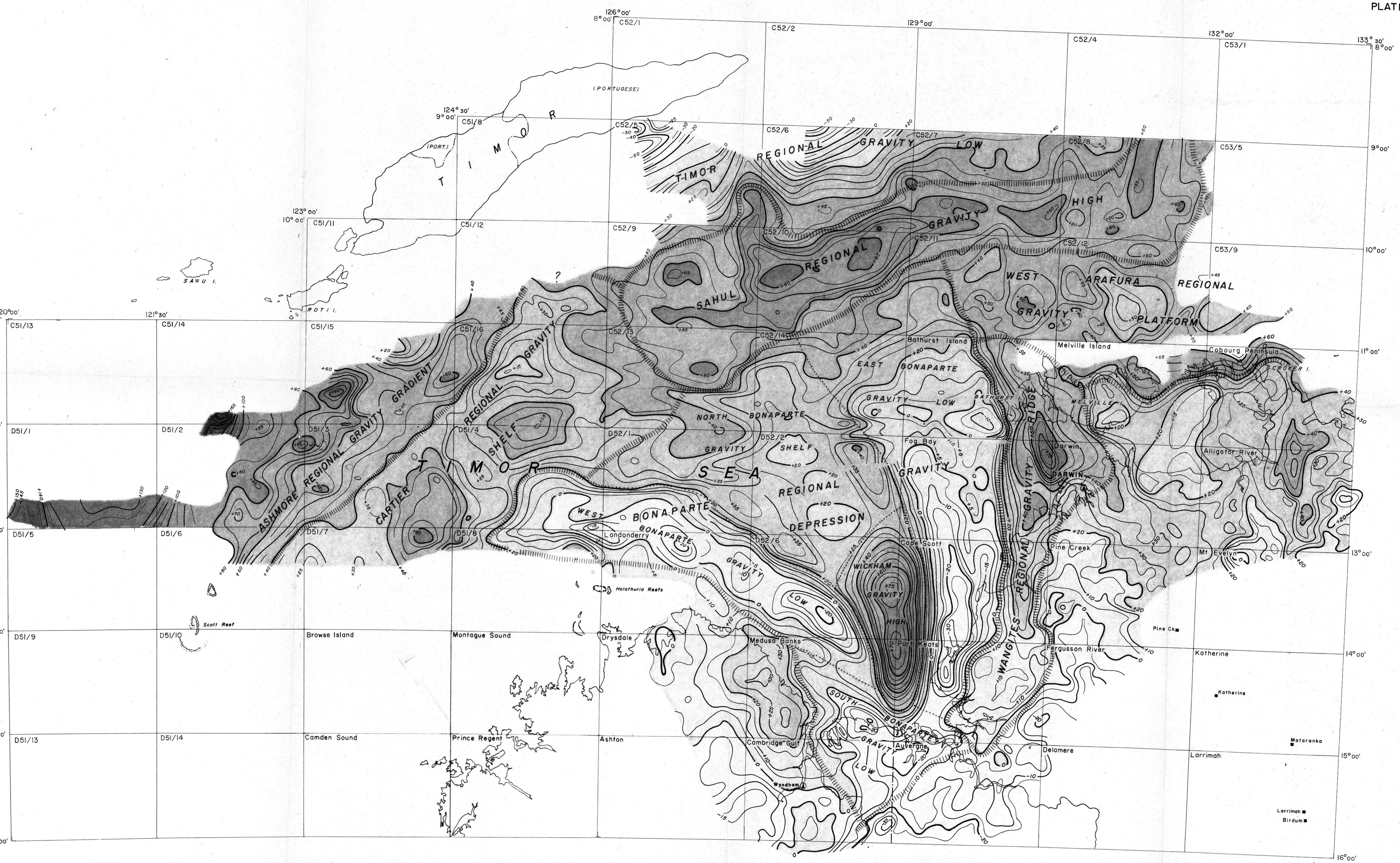
(BASED ON BMR TECTONIC MAP OF AUSTRALIA & VANANDEL & VEEVERS)

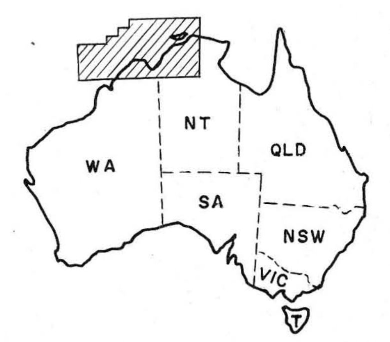
40 0 40 80 MILES

OP 83 Petroleum Exploration and Developmental Title Boundary

TO ACCOMPANY RECORD NO. 1969/40

D51/B3-19





LEGEND

Ashton — 1:250,000 map area

Cambridge pendulum station

Isogal primary station

Isogal secondary station

Isogals, values in milligals

Gravity Province boundary

Unit boundary

Gravity 'High'

Gravity 'Low'

TIMOR SEA AREA

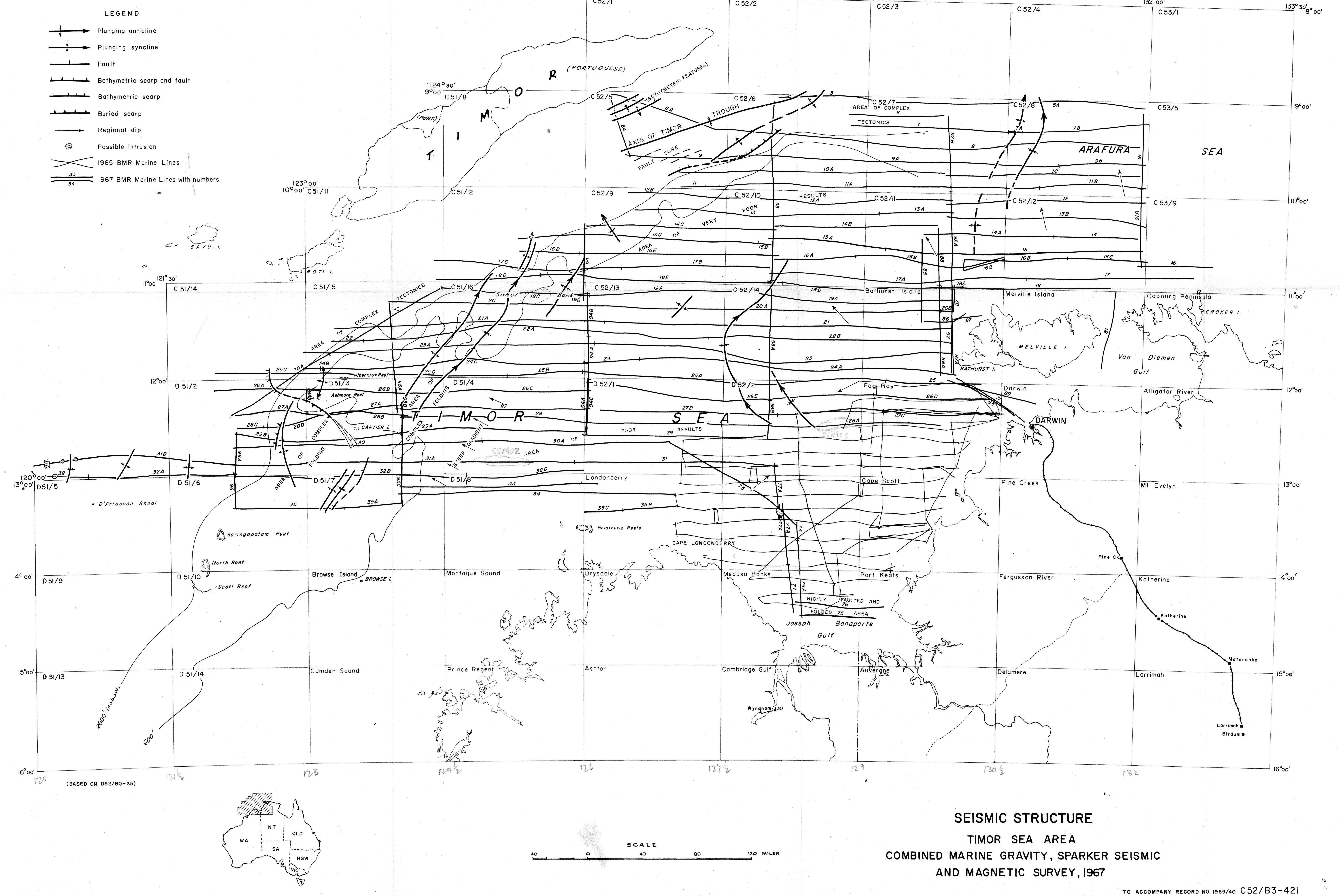
BOUGUER ANOMALIES AND GRAVITY FEATURES

SCALE

40 30 20 10 0 40 80 120 MILES

TO ACCOMPANY RECORD NO. 1969/40

WA/B2-2-1



SEISMIC STRUCTURE

TIMOR SEA AREA

COMBINED MARINE GRAVITY, SPARKER SEISMIC AND MAGNETIC SURVEY, 1967

TO ACCOMPANY RECORD NO. 1969/40 C52/B3-421

C51-16

SAMPLE SHOWING HOW THE RESULTS OF THE TIMOR SEA 1967 SURVEY WILL BE PRESENTED

1:250,000

PLATE 5

TO ACCOMPANY RECORD NO. 1968/40

C51/B8-18 (MARINE)