DEPARTMENT OF MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1968/1

MARINE GEOPHYSICAL SURVEY NORTH WEST CONTINENTAL SHELF, 1968

PREVIEW REPORT

by

R. Whitworth and A. Turpie

Record 1968/1

MARINE GEOPHYSICAL SURVEY
NORTH WEST CONTINENTAL SHELF, 1968

PREVIEW REPORT

by

R. Whitworth and A. Turpie

CONTENTS

PLATES

APPENDICES

SUMMARY

The emphasis in oil exploration in Australia has shifted from land to offshore areas over the last few years. The Bureau of Mineral Resources has carried out two large scale reconnaissance marine geophysical surveys in the Joseph Bonaparte Gulf and Timor Sea areas in 1965 and 1967. It is proposed to continue this geophysical reconnaissance to the south over the northwest continental shelf from Ashmore reef to Barrow Island. 16 000 line miles should be covered in 3 months on mainly east-west lines 9 nautical miles apart. The boat speed will be about 10 knots. The survey will be done by Ray Geophysics (Australia) Pty Ltd under contract.

The Seismic System will consist of a 21 000 joule sparker source and a six channel streamer. A second single channel streamer will be towed for recording shallow information at high resolution: Refraction seismic recordings will be made at selected points using 2 air guns, each of 300 cubic inch capacity, as source with energy received and transmitted by sonobuoys out to about 15 miles.

Gravity will be measured on a LaCoste and Romberg meter mounted on a stabilized platform.

Total magnetic intensity will be measured by a magnetic sensor towed behind the boat.

Navigation will be by a combination of satellite Doppler, sonar Doppler and VLF systems.

The gravity, magnetic, bathymetric and navigation results will be reduced and maps will be drawn by digital computer.

Geological objectives survey programme, and system descriptions are given in some detail.

1. INTRODUCTION

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

The Bureau of Mineral Resources has now carried out two large scale marine geophysical surveys, both of them in the Joseph Bonaparte Gulf-Timor Sea area. They have been carried out by the Bureau to assist in the exploration and development of the continental shelf, and to introduce and test the feasibility of geophysical methods new to surveys in Australia.

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

As the seismic system proved successful, the source energy was increased to 21 000 joules aiming at greater depth of penetration in the 1967 survey which covered the Timor Sea area to the north of the previous survey. The Toran navigation system was replaced by a VLF system which, though of lower accuracy, was still adequate and enabled 24-hour-a-day operation to be maintained. The Askania marine gravity meter gave a slightly improved performance, a mean difference of 2.5 milligals at intersections being achieved, equivalent to a standard deviation of 4.0 milligals despite the less accurate position and consequent velocity determination. Continuous magnetic profiling was added to the program.

A satellite navigation system will be used this year to provide control points for the network of VLF determined traverses and they improve the VLF position fixes and velocity determinations. A standard deviation of 2.0 milligals for the gravity differences at intersections is the set standard. A La Coste and Romberg meter on a stabilised platform will be used. Refraction profiling will be added to the seismic work, using sonobuoys as detectors and an air-gun as energy source. The survey area will be south of the 1967 area, stretching from Ashmore Reef to Barrow Island (Plate 1). It will cover the Mesozoic-Tertiary basin believed to stretch from north of Melville Island to the Rowley Shoals area sub-parallel to the coast, and should determine the relationship between this basin and the Canning Basin.

To achieve an accuracy of 1 milligal in the gravity results, the ship's speed needs to be known to about 0.1 knot, and latitude to the order of 1 minute. The combined satellite doppler-V.L.F. system is expected to approach this accuracy. Sonar doppler will be used to provide a determination of traverse and velocity independent of VLF and thus provide a cross-check on and supplement to the velocity determination by VLF. Raydist control will be available during daylight hours over some parts of the area by arrangement with B.O.C. of Australia, Ltd. This will allow an independent assessment of the accuracy of the navigation system.

The survey is expected to commence in mid-September, and will consist of three cruises of 25 days duration, using Broome as base. At least 16,000 miles are expected to be covered, moving in a general north to south direction. The proposed program is shown in Plate 2. Ray Geophysical Division of the Mandrel Corporation will carry out the survey under contract to the B.M.R.

The geology of the area, previous geophysical surveys and the main objectives of this survey are given in the following pages. Details of organisation, equipment and method of data reduction for the survey are laid out in the appendices.

2. GEOLOGY

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

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

A significant feature of the whole of northwest Australia is the dominance of two tectonic trends. The Halls Creek mobile belt, the west coast of the Kimberley Block and the inferred offshore basin and outer structural ridge all trend northeast, as does faulting within the Kimberley Block and the eastern margin of the Bonaparte Gulf basin. The second major trend is exhibited by the northeast coast of the Kimberleys, the King mobile belt, Fitzroy Trough, and the Pilbara Block. This trend is northwest in the north, but gradually swings to a more westerly trend southwards. Features of a similar trend can be traced across the continental shelf for a considerable distance (Woodside 1964, B.O.C. 1967).

Five geological provinces bound the survey area on the landward side, but the extent to which they encroach upon the shelf is uncertain (Plate 3). Descriptions of the surrounding geological provinces and the inferred geology of the shelf are given below. Although not always specifically mentioned Condon (1964, 1967) Fairbridge (1953a) G.S.A. (1962), McWhae (1958), Reynolds (1963), Veevers (1967), Veevers & Wells (1961) and many B.O.C. subsidy reports have been heavily drawn upon.

Kimberley Block

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

The Upper Proterozoic sediments were unconformably deposited upon the Halls Creek Metamorphics of presumably Lower Proterozoic age when the area sank to become a nuclear basin. About 8 000 feet of an arenite-volcanic sequence (King Leopold Formation, Mornington Volcanics and Warton Beds) were laid down in lower Upper Proterozoic times, followed by tillites (Walsh Tillite), dolomites, siltstones and arenites (Mount House Beds) in the upper Upper Proterozoic. The volcanics and tillites are found only in the west. At the end of the pre-Cambrian, the region was raised and deeply dissected. Possibly Antrim Plateau Volcanics were extruded over some of the block, but only two small areas remain in the north-east.

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

King Leopold Complex

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

The oldest rocks exposed are Lower Proterozoic geosynclinal rocks of predominantly greywacke type, with some carbonates and volcanics, in a highly metamorphosed state, called the Halls Creek Metamorphics. The total thickness of strata is unknown. The rocks have been intruded by dolerite and gabbro, followed by the large scale granitic intrusion of the Lamboo Complex and granitization. Intrusion does not affect the overlying King Leopold Formation of Upper Proterozoic age. Considering the degree of folding and metamorphism, the metamorphics and granites are placed in the Lower Proterozoic. Isolated inliers of probably Upper Proterozoic rocks have been found in fault zones.

The axes of folding and major faults run parallel to the length of the mobile belt.

Canning Basin

The Canning Basin has a land area of 150 000 square miles, and may extend a considerable distance to seaward over the Rowley Shelf. It can be split into three major areas - (a) Fitzroy Trough, (b) Broome Platform and (c) Kidson Basin. Aeromagnetic and gravity surveys have shown several sub-basins within the platform area, much of which is imperfectly known.

The basement appears to be predominantly Lower Proterozoic metamorphic and igneous rocks, except in the northeast where sediments of Upper Proterozoic age occur. About 3 000 feet of Upper Cambrian to Ordovician marine limestone, dolomite, shale and sandstone occur over much of the basin, locally thickening to over 6 000 feet in sub-basins in the south-west. Devonian marine organic reefs and associated sediments interfinger with conglomerate, sandstone, calcilutite and limestone breccia to form deposits up to 3 000 feet thick within the Fitzroy Trough, followed by 6 000 feet of Carboniferous marine calcarenite, sandstone and siltstone. Devonian and Carboniferous deposits were thought to be absent elsewhere until recently. Drilling has recently found a claystone-salt sequence followed by red sandstones and anhydritic limestone in the south (WAPET 1966d), thickening to over 4 000 feet towards the Kidson Basin (WAPET 1966c). The deposits are tentatively interpreted as Silurian to Middle Devonian. Peneplanation could have removed Devonian deposits from elsewhere in the south before the widespread deposition of Permian tillites, marine greywacke, conglomerate limestone and shale, and freshwater sandstone. 3 000 feet of these sediments are found in the south, thickening northwards to 14 000 feet in the Fitzroy Trough. Triassic mudstone and sandstone 1 000 feet thick followed by 2 500 feet of Jurassic-Cretaceous conglomerate, sandstone, siltstone and shale were than laid down over most of the Canning Basin. Cainozoic deposits are mainly superficial.

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

Pilbara Block

Three distinct pre-Cambrian systems may be defined within the Pilbara Block, an extensive area of sediments, metamorphic and igneous rocks lying on the southern edge of the Canning Basin. The oldest Warrawoona System consists predominantly of basaltic and andesitic lavas with associated conglomerates, sandstone, shale and some limestones. All are highly metamorphosed and folded into long, narrow belts either trending north-northwest or forming peripheral belts around granitic nuclei. The system is mainly preserved within a zone of massive granitic intrusions.

A thick assemblage of sediments forms the Mosquito Creek System. The volcanic component is subsidiary, unlike the Warrawoona System, which it overlies. This system is folded along axes different to the previous system and is considerably less metamorphosed. Similarity of lithology and degree of metamorphism has been used by some workers to correlate the Mosquito Creek System with lower Lower Proterozoic rocks elsewhere.

Unmetamorphosed conglomerate, sandstone which is often glauconitic, thin dolomitic limestones and pyritic shales, and volcanic rocks form the uppermost Nullagine System. The sediments are 1,000 to 3,000 feet thick and are typically flat-lying or gently folded along east-southeast axes. It is suggested that they are the equivalent of similar deposits of Upper Proterozoic age on the Kimberley Block.

Carnarvon Basin

The Carnarvon Basin is an epicontinental feature of Proterozoic to Tertiary age, with a landward area exceeding 50,000 square miles. Several sub-basins occur within the main basin, separated by basement ridges.

Proterozoic to Palaeozoic sandstones up to 8,000 feet thick are found in the southern part of the basin, and may be overlain by Silurian limestones. Marine sandstone, limestone, shale and conglomerate of Middle Devonian to Lower Carboniferous age overlie the Lower Palaeozoic sediments. There are more than 7,000 feet of these apparently conformable deposits. An unconformable sequence of glacial deposits about 4,500 feet thick was laid down, and was succeeded by about 1,000 feet of limestone, sandstone and greywacke, followed by 4,000 feet of alternating carbonaceous shales and sub-greywacke, and finally by 2,500 feet of sandstone with some siltstone, during the Permian. Relatively thin marine Cretaceous sediments are the major Mesozoic deposits except in the North West Cape area where a thick sequence of Jurassic clastics was deposited.

Barrow Island and surrounding areas are in the Onslow sub-basin, which is separated from the main Carnarvon Basin by the Yanrey and Chinty basement ridges (Spence 1961). Recent regional geological studies, drilling and intensive marine surveys (WAPET 1964, 1965, 1966b) have shown that the northwest part of the Carnarvon Basin is primarily a Mesozoic province with a separate history to the predominantly Palaeozoic provinces to the south, and has an affinity with the series of off-shore Mesozoic-Tertiary depressions extending along the coast to the Sahul Shelf and beyond. The geological section typically contains 100 to 1,000 feet of Tertiary calcarenite, 2,000 to 5,000 feet of Mesozoic siltstone with minor calcilutite and limestone, and upwards of 5,000 feet of Jurassic sandstone and siltstone (WAPET 1967a, 1967b).

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

The Shelf Area

As mentioned in the introduction to the geology, interpretation of the offshore geology is primarily based upon a correlation of bathymetric features, seismic and aeromagnetic surveys and similarity with continental features. Some stratigraphic evidence is available from the Barrow Island No. 1 and Ashmore Reef No. 1 wells, and Legendre No. 1 well which is now being drilled, but this is sparse control for an area that stretches almost 1000 miles.

The outer edge of the shelf is bounded by a series of shoals, exposed at Rowley Shoals, Scott Reef, Ashmore Reef and Sahul Banks. Offsets occur in the ridge south of Ashmore Reef and north east of Sahul Banks, which may possibly be caused by faulting. The ridge may not be continuous further to the northeast of Sahul Banks. In the south the ridge corresponds to the anticlinal trend of the Rough Range - Barrow Island structure. Further north, the aeromagnetic survey by Woodside (1964) indicated a basement high under the ridge at least as far as the Ashmore Reef area. Van Andel and Veevers (1965) believe the ridge to have been exposed for much of the Tertiary.

However, the Ashmore Reef Well indicates that a thickness of sediments in excess of 11,000 feet was laid down fairly continuously throughout the Mesozoic and Cainozoic. Considerable similarity of the sequence with that found in Timor is evident (B.O.C. pers. comm), suggesting that the Sahul Banks were part of the Timorian depositional area rather than on the stable foreland beyond the geosyncline during most of the Tertiary. Intra-section volcanics of Jurassic age are the probable cause of the interpreted magnetic basement "high". The magnetic defined basement ridge under Rowley Shoals and Scott Reef may have a similar origin. Where the transition from anticlinal ridge to sedimentary thick occurs is uncertain.

The depression on the shelf inshore of the shoals has been interpreted as a sedimentary basin by Fairbridge (1953) Boutakoff (1963) and Veevers (1967). Surveys by Woodside (1964) and BOC (1965, 1966, 1967, 1968b) confirm the existence of a considerable development of sediments in this zone. The basin is inferred to be a Mesozoic to Tertiary feature though there is no evidence to indicate the age of the deeper section. Its southern extremity appears to be the Onslow embayment, a feature usually placed in the Carnarvon Basin. The northern end of the basin is north of COBURG PENINSULA, though a Palaeozoic basin appears to continue further to the east (Shell Development 1966a, 1966b).

Veevers (1967) postulates that the basin is coextensive onshore with the Canning and Bonaparte Gulf Basins. It would seem simpler, however, to consider the Canning Basin and offshore basins as separate, as one is predominantly Palaeozoic with fairly uniform flat-lying Mesozoic deposits with north-westerly trend, while the other shows a considerable thickening in the Mesozoic-Tertiary section along a north-easterly axis. Onshore features of the Canning Basin have been shown to continue offshore for some distance (WAPET 1966a) but presumably dip beneath the offshore basin.

A series of bathymetric rises can be followed across the shelf with trends similar to pre-Cambrian features on land (Van Andel et al., 1961). Geophysical evidence (Woodside 1964, BOC. 1967) also suggests that the major pre-Cambrian tectonic features still exert a considerable influence in Mesozoic times viz. the offshore extension of the King Leopold mobile belt has only a thin sedimentary section draped over it, and WNW trending arches and the trend of faulting of the Pilbara Block have caused structural closures in the Rankin Bank area.

The relationship between the offshore basin and Proterozoic Kimberley Block is ill-defined. There appears to be a basement ridge trending northeast under the northwest edge of the block (Whitworth 1968, in prep). Whether Proterozoic sediments occur to the west of the ridge is unknown. Similarly the boundary between the Pilbara Block and the shelf sediments is almost unknown.

3. PREVIOUS GEOPHYSICS

Some surveys have been carried out by B.O.C. and WAPET within the survey area. However most surveys have been confined to the onshore Canning Basin and areas around Onslow and Barrow Island. The offshore surveys by B.O.C. started as reconnaissance surveys in the shoal and reef areas and have gradually concentrated around Rankin Bank and Ashmore Reef, culminating in the drilling of Ashmore Reef No. 1 well followed by Legendre No. 1 well which is now in the process of being drilled.

Aeromagnetic Surveys

A reconnaissance survey by Woodside (Lakes Entrance) Oil Co. Ltd out of Derby, Wyndham and Darwin covered the fringing reefs of the continental shelf (Woodside 1964). Navigation was by dead reckoning and photo identification of the exposed reef areas, which proved adequate for such isolated reconnaissance lines. The results suggested that the Fitzroy Trough terminated a few miles offshore. However, the data has been alternatively interpreted by B.O.C. (pers. comm.) as indicating the presence of volcanic plugs rather than shallow basement with the trough continuing to sea. The King Leopold mobile belt extends out over the shelf with a more easterly trend at a depth of 2,000 to 5,000 feet. Inshore of the line of shoals the sedimentary section is about 25,000 feet deep, but shallows to about 10,000 feet under the Rowley Shoals, 15,000 feet under Scott Reef and 5,000 to 7,000 feet under Ashmore Reef and Cartier Island. At Ashmore Reef this magnetic depth estimate correlates with intra-section volcanic beds found in the well at 7,200 feet. Magnetic basement is deeper than 11,000 feet under the reef. Browse Island, Adele Island and Churchill reef appear to be in the deep section of the basin. Intermediate magnetic horizons possibly also exist at Rowley Shoals, Adele Island and Scott Reef as at Ashmore Reef. The general indication is that a trough perhaps 30,000 feet deep parallels the coast about 100 miles offshore and is bounded by an outer ridge about 15,000 feet deep that seems to support the reefs. The ridge may not be continuous.

West Australian Petroleum Pty. Ltd. carried out an offshore aeromagnetic survey where the Canning Basin extends offshore. (WAPET 1966). Lines were flown parallel to the coast in bands so that anomalies suitable for depth determinations were adequately defined. The Napier Platform was found to extend across PENDER and YAMPI with an easterly strike at a depth less than 5,000 feet. The Fitzroy depression is about 12,000 feet deep and may shallow offshore (see above). The Broome Swell and La Grange Platform appear to extend for some distance across the shelf. However, the Platform is thought to be deep and cut by a basement swell near Cape Bossut into two basins which may contain significant thicknesses of Mesozoic rocks. The Samphire Depression is fault bounded and does not appear to extend offshore. The survey did not extend far enough out to sea to determine the relationship between the Canning and offshore basins.

Two surveys have been conducted over the northern end of the Carnarvon Basin. A combined aeromagnetic and radiometric survey by the BMR in 1959 (Spence 1961) showed a shallow basement ridge existed along the eastern shore of Exmouth Gulf called the Yanrey Ridge. A deep embayment lies between this ridge and the onshore Chinty Ridge to the east. A survey by WAPET (1968) showed that northeast of Barrow Island the basement is shallow until 30 miles offshore, then deepens to perhaps 10 000 feet. South of the island, depths of over 25 000 feet occur in the west, shallowing to around 5 000 feet over the Yanrey Ridge before deepening again to 20 000 feet in the Onslow embayment east of the ridge. Some of the non-magnetic sediments in the embayment may be pre-Cambrian in age. At the coast, the basement depth is around 5 000 feet.

Gravity Measurements

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

The 1967 marine survey borders the area to the north (Jones, 1968 in prep, UNITED 1968, in press). A series of BA highs and lows run essentially parallel to the main inferred structures in the Ashmore Reef area. The Reef area coincides with a local gravity high despite the considerable thickness of Mesozoic-Tertiary sediments, suggesting that it may still form a ridge relative to the offshore basin. The basin correlates very roughly with a fairly extensive BA depression, but is greatly disturbed by several BA maxima along its axis. A similar feature occurs within the Joseph Bonaparte Gulf Basin (Smith, 1966) which has been interpreted as a horizontal density variation within the basement. However, analysis suggests the cause of the feature is fairly shallow, possibly within the sedimentary section (Flavelle, pers. comm.). Dense Tertiary limestone or thick beds derived from volcanic source material might be a possible cause of these gravity highs within the basin.

Most of the landward part of the area has been covered by at least reconnaissance gravity surveys (e.g. Flavelle and Goodspeed 1962, WAPET 1966e, Flavelle 1968 in prep, Whitworth 1968 in prep). Over the Kimberley Block the BA features are undulating with low relief. A general rise in BA value along the northwest coast suggests that the Lower Proterozoic rocks form a buried swell under the islands. In the Fitzroy Trough area, the Bouguer anomalies features are intense, completely at variance with the known generally thick sedimentary section. Intrusions within the trough and density variations within the underlying King Leopold mobile belt appear to be the major contributing factors to these features.

In the platform areas of the Canning Basin the Bouguer anomaly features are less intense but still show a marked northwesterly strike that is not in evidence in the surface geology. The positive ridge extending inland from MANDORA to TABLETOP and possibly as far as BENTLEY may be caused by a sub-basin Lower Proterozoic mobile belt that marks the edge of the ancient West Australian Shield. This feature could well be found offshore.

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

Seismic Surveys

A considerable number of land surveys have been carried out by the BMR and WAPET in the Canning and Carnarvon Basins (e.g. Smith 1955, 1962, Vale et al., 1953, WAPET 1966f, 1967c, 1967d) mainly over local structures. Several wells have been drilled, primarily for stratigraphic purpose (e.g. WAPET 1959a, 1959b, 1960a, 1960b, 1966d). The regional implications are summarized in Plate 2.

Much of the survey area has been covered by reconnaissance marine seismic surveys. Detailed work has been carried out over anticlinal structures at Barrow Island, Rankin Bank and Ashmore Reef. In 1964, Burmah Oil Company carried out reconnaissance surveys from Rankin Bank to Cootamundra Shoals (BOC 1965). Lines were shot over the known reef and shoal areas in an attempt to elucidate the underlying structures. Considerable folding and faulting occur in the Rankin Bank area. The most prominent feature defined was an anticlinal structure running parallel to the coast. A general increase in sediment thickness to the northwest was detected. Basement could not be detected as sea bed multiples made interpretation difficult. Between Rowley Shoals and Samphire Marsh, the reflection quality was good and showed an almost featureless northwest dipping section with an indication of an unconformity at about 2 500 feet near the coast. There was no evidence of any major structural feature or of the nature of the base of the shoals. To the north, the regional picture was of gentle dips and little folding and faulting. A possible basement high occured near Ashmore Reef while to the southeast the basement dipped northwest, otherwise the limits of the basin remained undefined.

The Montebello-Mermaid Shoal marine survey (BOC 1966) defined three parallel Permian and pre-Permian anticlinal trends with probable local closures around the Rankin Bank. Southwest of Rowley Shoals a locally thick sedimentary section was indicated. From the shoals to Adele Island the onshore tectonic trends continued seawards for about 100 miles. Between Adele Island and the Sahul Shelf, the northeast trending basin appears to be associated with a more or less continuous basement ridge on its northern flank, over which the sedimentary beds lie unconformably. Ocean bottom multiples still proved troublesome and two-fold stacking seemed insufficient. Three-fold stacking was recommended with six-fold CDP in difficult areas.

The following year a more detailed study was made of selected areas in the Rankin-Troubadour survey (BOC 1967). Around Troubadour Banks which is north of the survey area, two main reflectors were detected whose geological significance is uncertain. Horizon A has a velocity of about 12 000 ft/sec but is not definitely associated with a refractor. The lower horizon B represents the most prominent reflector in the deeper section and has a velocity of about 15 000 ft/sec. It shows gentle unconformity with the overlying strata. In the Sahul Banks - Ashmore Reef area three levels were mapped (not necessarily related with other areas). Horizon A correlates with the base of the Oligocene. Horizon B is probably the base of the ? Upper Cretaceous and C is a deeper phantom horizon. Horizon B is just above an unconformity. A 16 000 ft/sec refractor is believed to be just below the unconformity. B approaches horizon A towards Ashmore Reef. A large northwest trending anticline forms the northwest limit of the Bonaparte Gulf Basin. More than 15 000 feet of sediments occurs within the basin. Ashmore Reef seems to be caused by deep structure rather than a large coral reef. No evidence of high velocities across the reef was detected, and a sea floor velocity of 6 500 - 7 000 ft/sec is common. Four horizons were mapped around the Rankin Banks. Data quality was better than in 1965, and the horizons were shown to be unconformable. Two anticlinal zones were delineated in the upper horizons. A deep syncline with superimposed anticline was detected between outer ridge and coast at the deepest Horizon D level. A series of local closures occur on the ridge, caused by a north westerly cross-trend of folding and faulting that could be a residual effect of the Canning Basin strike. A 15 000 ft/sec refractor occurs just above Horizon C.

The 1967 Ashmore Reef survey (BOC 1968a) showed the northerly trending anticlinal structure over the reef to be asymmetric at the B horizon, culminating about 6 miles north of East Island. North Westerly closure is enhanced by faulting. At the A horizon, the crest is less intense, extending southeastwards from the B horizon apex. Significant faulting at the shallow level is restricted to the northeast of the structure. The results indicate that Ashmore Reef is the southerly culmination of an anticlinal trend extending to the northeast. The structure is flanked to the south and east by a strong trough in which there is substantial thickening in the A-B interval.

The Scott-Cartier survey (BOC 1968b) confirmed the existence of a broad, faulted anticlinal fold along the regional trend at Sahul Banks. A dome appears to culminate under Woodbine Banks while Cartier Island seems to be a high area on a broad, low relief fold. Some time anomalies in this area correlate with the bathymetry, suggesting the presence of high velocity reefs. Refracted first breaks give a velocity of around 7 500 ft/sec. A velocity of about 9 500 ft/sec for the suspected reefs would account for the time anomalies. Only in the Scott Reef area were high near-surface velocities detected. Within the lagoon, a velocity of 16 500 ft/sec was found at Horizon I level. Near surface velocities were about 9 000 ft/sec, while some velocities of 14 000 ft/sec were measured. As a result, some of the presumed structural closure may be partly fictitious despite corrections for high velocity overburden beneath the lagoon. Refraction shots within and outside the lagoon indicating essentially the same depth for the deepest refractors of 16 500 and 17 000 ft/sec respectively support this belief. The Rankin Bank anticlinal trend continues to the northeast. Faulting parallel to the trend is inferred. The high relief of two elongate domal structures in the southern part of the area is reminiscent of diapiric movements. The upper horizons appear to wedge out in the southeast against the continental slope.

Surveys by Arco (1966) and Arco-Aquitaine (1967) in the Timor Sea and Sahul Banks area confirm the general interpretation provided by the BOC surveys. The existence of a deep triangular basin predicted by an aeromagnetic survey (Australian Aquitaine 1966) was confirmed.

A high trend appears to limit the basin along the edge of the continental shelf. In the north, outcrops or buried reefs distorted the horizons. The general sea bed velocity was about 6 000 ft/sec, rising to 8 000 ft/sec over reefs. Some apparent diapiric structures were mapped. In the deep section, the horizons appear conformable. Thinning of horizons occurs in the updip areas, and some beds are present only in the centre of the basin.

In the southwest, WAPET has carried out seismic surveys over Barrow Island and the shelf (WAPET 1964, 1966b). Barrow Island is a gentle anticline in Tertiary limestones similar to those exposed on North West Cape. On shore, shallow basement is indicated, deepening westwards to perhaps 20 000 feet under the island (Spence 1961). A 12 500 ft/sec refractor, probably from the basal Cretaceous unconformity, shows about 1 000 ft of northeasterly dip with an east-plunging anticlinal nose in the centre of the island. The absence of a recorded higher velocity was interpreted as indicating very thick Jurassic sediments (WAPET, 1964).

The Barrow Island wells confirmed the thick Mesozoic indicated by the refraction survey (e.g. WAPET 1965). East of the island a major north-south fault down-to-the-west cuts out the Jurassic section and the Cretaceous overlies highly faulted Palaeozoic rocks. Further to the east, another large fault cuts out the Palaeozoic section and the Cretaceous directly overlies pre-Cambrian rocks. The majority of seismic reflection structures appear to be controlled by faulting. Some structures are around or near islands suggesting that they may be anticlinal at depth. Structures at the Lower Cretaceous level appear to be found along old down-to-the-west faults, allowing the formation to fold or slump into the down thrown area (WAPET 1966b).

4. OBJECTIVES

The major objective of the survey is the continued reconnaissance of the continental shelf of Australia. Since 1965, the number of geophysical methods used has increased considerably as has the sophistication of the equipment used. Continuous gravity, seismic reflection and magnetic profiling will be carried out. Seismic refraction profiles will be run once every few days.

The results of these differing methods are of little value without knowing the ship's position with reasonable accuracy at all times. For the gravity work, the ship's velocity must also be determined. The cost and accuracy of navigation systems can vary by several orders of magnitude. High accuracy is rarely attained without high cost. The system adopted is the result of a compromise between cost and effort involved, area covered, accuracy relative to station interval and several other imponderable factors. More time and effort is put into the navigation data collection and reduction than any other system, with perhaps half the total effort on the survey going into finding the ship's position and velocity.

Particular stress is accordingly placed upon the maintenance of quality control on all data collection systems. The highest possible data accuracy consistent with the aims of the survey should be aimed for, rather than rapid reduction of data of a lower quality. The objectives of the survey can be conveniently divided into two categories: geophysical and geological.

Geophysical objectives

1) To continue to assess the performance and reliability of the VLF navigation system (Ingham 1968). Satellite fixes and line intersections will allow an accurate assessment of the overall accuracy to be made. Independent fixes at two hourly intervals will allow a check of the reliability of the diurnal correction obtained at the monitor station.

2) To assess the performance and reliability of the sonar doppler equipment. The pulsed system to be used this year should operate off bottom at greater depths and generally function better in the transverse mode than the continuous wave system used in 1967. A cross-check between Eotvos Corrections obtained by the VLF and sonar doppler should determine whether ocean currents are significantly affecting the Sonar-doppler results.

3) To determine the overall accuracy of the gravity data. Line intersection values will be used for this purpose. The accuracy of the position and velocity determinations will probably influence the final accuracy more than the uncertainty in the drift of the La Coste and Romberg marine gravity meter.

4) To continue the assessment of seismic data quality obtained with the Chesapeake cable at speeds up to 10 knots. CDP stacking of the six channel output will be made at a later data for areas where reflection quality is poor.

5) To tie into previous seismic surveys in the area to allow coordination of the results.

6) To carry out continuous refraction profiles in suitable areas to try to obtain the velocities to the main reflectors. This should allow more reliable correlation of reflecting horizons within the basin and possibly with known onshore horizons.

Geological objectives

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

2) To determine the continuity of the King Leopold mobile belt and Pilbara Block across the shelf.

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

4) To determine if the Onslow embayment is a feature continuous with the offshore basin.

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

6) To see if the volcanic intrusives thought to exist in the seaward extension of the Fitzroy Trough can be detected by seismic and gravity methods.

7) To run several traverses across the edge of the continental shelf to try to determine its nature and structural significance and the area of transition from continental to oceanic type crust.

5. PROGRAM

In general, the program will consist of a series of east-west traverses ten miles apart, with northeast-southwest tie lines approximately 100 miles apart. The resultant network will be used to control the gravity data, and will also provide extra control of the VLF navigation. Cross checks through the magnetic data and water depth should result in fairly accurate determination of the intersection points even where marker buoys are not available.

Data to aid in assessing the gravity meter calibration and drift will be collected by calling at Brisbane, Mackay, Townsville, Cairns, and Darwin on route to Broome. The ship is expected to leave Brisbane in early September, and the trip around the coast will be used as a shake-down cruise to ensure that all systems are operating satisfactorily, and that contract personnel are familar with the equipment and its operation.

The survey should commence in mid-September, almost immediately after arrival of the ship in Broome. Survey operations will be split into three 25 day cruises, with 5 days in port at the end of each cruise (Plate 1). A supply boat is expected to service the ship on occasions through each cruise, and advantage will be taken of this for BMR personnel to visit the operation for short periods.

The first cruise will cover the northernmost part of the survey area from near Ashmore Reef to Adele Island. It is hoped to run several profiles over the Scott Reef area to try to elucidate the deeper structure by gravity and magnetic methods. It may prove possible to determine the structural configuration along the edge of the Kimberley Block where the basement is postulated to rise along a broad ridge (Whitworth 1968, in prep.).

The area from Adele Island to just south of Broome will be covered in the second cruise. This cruise will cross the supposed seawards extension of the King Leopold mobile belt. The opportunity will be taken to run some traverses over the Rowley Shoals and into deep water. Near the coast, the ship should cross the volcanic plugs believed to exist off the Fitzroy Trough area.

The final cruise should help to define the relationship of the Barrow Island area to the thick sedimentary area further north. This plus the second cruise should determine just how far the Canning Basin extends offshore. Onshore tectonic trends can be tentatively traced out to the Rankin Bank but it is uncertain whether this is a result of Canning Basin structures continuing that far, or later movement along buried tectonic features.

6. BIBLIOGRAPHY

ARCO LTD, 1966 - Timor Sea seismic survey by Geophysical Associates Pty. Ltd. Subsidy Report 65/11042.

ARCO-AQUITAINE, 1967 - Sahul Shelf marine seismic survey by sparker method by Compagnie Generale de Geophysique. Subsidy Report 66/11088.

AUSTRALIAN AQUITAINE PET. PTY. LTD., 1966 - Timor sea aeromagnetic survey P.E. 221H (W.A.) and O.P. 100 (N.T.) by Compagnie Generale de Geophysique Subsidy Report 65/4613.

BOUTAKOFF, N., 1963 - Geology of the offshore areas of northwestern Australia A.P.E.A. Jour. 1963p. 10-18.

BURMAH OIL CO., 1964 - Australian northwestern offshore areas reconnaissance and submarine sampling report by A. Taube (unpublished report).

BURMAH OIL CO., 1965 - Northwestern Shelf marine seismic survey by Western Geophysical Co., Interpretation by Seismograph Services Ltd. Subsidy Report 64/4529.

BURMAH OIL CO., 1966 - Montebello-Mermaid Shoal area northwest Australian marine seismic survey by Western Geophysical Co. Subsidy Report 65/11015.

BURMAH OIL CO., 1967 - Rankin-Troubadour area (northwest Australia) marine seismic survey by Western Geophysical Co. Subsidy Report 66/11104.

BURMAH OIL CO., 1968a - Ashmore Reef offshore Western Australia marine seismic survey by Western Geophysical Co. Subsidy Report 67/11144.

BURMAH OIL CO., 1968b - Scott-Cartier area northwest Australia marine seismic survey by Western Geophysical Co. Subsidy Report 67/11173.

CONDON, M.A., 1964 - The geology of the Carnarvon Basin, Western Australia. Part 1: Pre-Permian stratigraphy Bur. Min. Resour. Aust. Record 1964/145.

CONDON, M.A., 1967 - The geology of the Carnarvon Basin, Western Australia. Part 2: Permian stratigraphy. Bur. Min. Resour. Aust. Bulletin 77.

FAIRBRIDGE, R.W., 1953a - Australian Stratigraphy. Univ. W. Aust. Text Book Board.

FAIRBRIDGE, R.W., 1953b - The Sahul Shelf, northern Australia, its structure and geological relationships. Jour. Proc. Roy. Soc. W. Aust. 37, p. 1-33.

FLAVELLE, A.J., 1968 - Canning Basin gravity surveys. Bur. Min. Resour. Aust. (in prep.).

FLAVELLE, A.J., GOODSPEED, M.J., 1962 - Fitzroy and Canning Basin reconnaissance gravity survey W.A. 1952-1960. Bur. Min. Resour. Aust. Record 1962/165.

GEOLOGICAL SOCIETY OF AUSTRALIA, 1962 - Geological notes in explanation of the tectonic map of Australia. Bur. Min. Resour. Aust. 1962.

GEOPHYSICAL ASSOCIATES PTY. LTD., 1966 - Timor Sea-Joseph Bonaparte Gulf marine gravity and seismic sparker survey northwest Australia. Bur. Min. Resour. Aust. Record 1966/116.

INGHAM, V., 1968 - Report on V.L.F.-Omega navigation. Geophysical survey of Timor Sea for Bureau of Mineral Resources Sept-Dec 1967 (unpublished report).

JONES, B.F., 1968 - Final progress report, marine geophysical survey 1967. Bur. Min. Resour. Aust. Record (in prep.).

McWHAE, et. al., 1968 - The stratigraphy of Western Australia. Melbourne Univ. Press for G.S.A.

REYNOLDS, M.A., et. al., 1963 - The sedimentary basins of Australia and New Guinea. Bur. Min. Resour. Aust. Record 1963/159.

SHELL DEVELOPMENT (AUSTRALIA) PTY. LTD., 1966a - An airborne magnetometer survey over the Arafura Sea N.T. (O.P.8, O.P.86, O.P.96, O.P.127, O.P.128) by Adastra Hunting Geophysics Pty. Ltd. Subsidy Report 65/4616.

SHELL DEVELOPMENT (AUSTRALIA) PTY. LTD., 1966b - Final report offshore seismic survey Arafura Sea N.T. by Western Geophysical Co. Subsidy Report 65/11044.

SMITH, E.R., 1955 - Progress report on a seismic survey of the Poole Range - Prices Creek area, Kimberley Division W.A. Bur. Min. Resour. Aust. Record 1955/35.

SMITH. E.R., 1961 - Broome seismic reflection survey W.A. 1954-1955. Bur. Min. Resour. Aust. Record 1961/57.

SMITH, E.R., 1966 - Timor Sea/Joseph Bonaparte Gulf marine gravity and seismic "sparkarray" survey, northwest Australia 1965. Bur. Min. Resour. Aust. Record 1966/72.

SPENCE, A.G., 1961 - Carnarvon Basin airborne magnetic and radiometric survey, Western Australia 1959. Bur. Min. Resour. Aust. Record. 1961/56.

TOMODA, Y., OZAWA, K., CEGAWA, A.J., 1964 - Gravity measurement in the Indian Ocean Bull. Geogr. Surv. Inst. Japan 10(1), p. 21-22.

UNITED GEOPHYSICAL CORP., 1968 - Final report, gravity, magnetic and seismic survey in the Timor Sea 1967. Bur. Min. Resour. Aust. Record (in prep.).

VALE, K.R., et. al., 1953 - Report on seismic survey of Nerrima Dome, Kimberley Division W.A. Bur. Min. Resour. Aust. Record 1953/72.

VALE, K.R., JONES, B.F., 1967 - Australian offshore exploration - the sedimentary environment and its coercive influence. Proc. 7th World Pet. Cong. 2 p. 927-947.

van ANDEL Tj., CURRAY, J.R., VEEVERS, J.J., 1961 - Recent carbonate sediments of the Sahul Shelf, northwestern Australia. Coastal and Shallow Water Research Conference N.S.F. and Office of Naval Research, Scripps Institute of Oceanography.

van ANDEL Tj., VEEVERS, J.J., 1965 - Submarine morphology of the Sahul Shelf, northwestern Australia. Bull. Geol. Soc. Am. 76 p. 695-700.

VEEVERS, J.J., 1967 - The Phanerozoic geological history of Northwest Australia. Jour. Geol. Soc. Aust. 14 p. 253-271.

VEEVERS, J.J., WELLS, A.K., 1961 - The geology of the Canning Basin. Bur. Min. Resour. Aust. Bulletin 60.

WEST AUST. PET. PTY. LTD., 1959a - Completion Report, Meda Well No. 1. Subsidy Report 62/1022.

WEST AUST. PET. PTY. LTD., 1959b - Completion Report, Samphire Marsh Well No. 1. Subsidy Report 62/1002.

WEST AUST. PET. PTY. LTD., 1960a - Completion Report, Frome Rocks Well No. 1. Subsidy Report 62/1029.

WEST AUST. PET. PTY. LTD., 1960b - Completion Report, Thango Well No. 1A. Subsidy Report 62/1054.

WEST AUST. PET. PTY. LTD., 1964 - Barrow Island seismic refraction project, Carnarvon Basin W.A. by Geophysical Services International. Subsidy Report 63/1536.

WEST AUST. PET. PTY. LTD., 1965 - Completion Report, Barrow Island Well No. 1. Subsidy Report 64/4030.

WEST AUST. PET. PTY. LTD., 1966a - Airborne magnetometer survey, offshore Canning Basin by Adastra Hunting Geophysics Pty. Ltd. Subsidy Report 65/4614.

WEST AUST. PET. PTY. LTD., 1966b - Barrow marine seismic survey, offshore northwest Australia, by Geophysical Service Inc. Subsidy Report 65/11031.

WEST AUST. PET. PTY. LTD., 1966c - Completion Report, Sahara Well No. 1. Subsidy Report 64/4129.

WEST AUST. PET. PTY. LTD., 1966d - Completion Report, Willara Well No. 1. Subsidy Report 65/4158.

WEST AUST. PET. PTY. LTD., 1966e - Dampier Land gravity survey by Wongela Geophysics Pty. Ltd. Subsidy Report 65/4816.

WEST AUST. PET. PTY. LTD., 1966f - Willara Hill seismic project by Ray Geophysics (Australia) Pty. Ltd. Subsidy Report 66/11081.

WEST AUST. PET. PTY. LTD., 1967a - Completion Report, Onslow Well No. 1. Subsidy Report 66/4218.

WEST AUST. PET. PTY. LTD., 1967b - Completion Report, Tortoise Well No. 1 Subsidy Report 66/4229.

WEST AUST. PET. PTY. LTD., 1967c - Lower Fitzroy Project Canning Basin reflection seismic and magnetometer survey by Geophysical Service International Subsidy Report 66/11111.

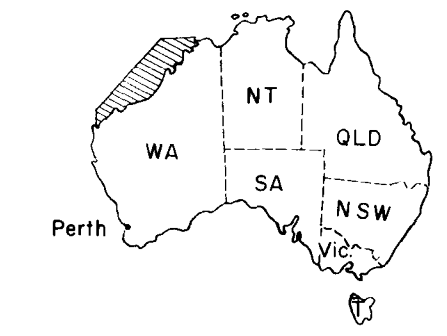
WEST AUST. PET. PTY. LTD., 1967d - Roebuck seismic survey Canning Basin Western Australia by United Geophysical Corp. Subsidy Report 66/11115.

WEST AUST. PET. PTY. LTD., 1968 - Offshore Onslow aeromagnetic project by Adastra Hunting Geophysics Pty. Ltd. Subsidy Report 67/4628.

WHITWORTH, R., 1968 - Reconnaissance gravity survey by helicopter of Arnhem Land (N.T.) and the Kimberleys (W.A.) 1967. Bur. Min. Resour. Aust. Record (in prep.).

WILLIAMS, L.W., 1968 - Petroleum exploration outlook for 1968. APEA Journ. 1968(1) p. 22-25.

PLATE 1



Survey area

Yampi 1:250,000 Map area

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968

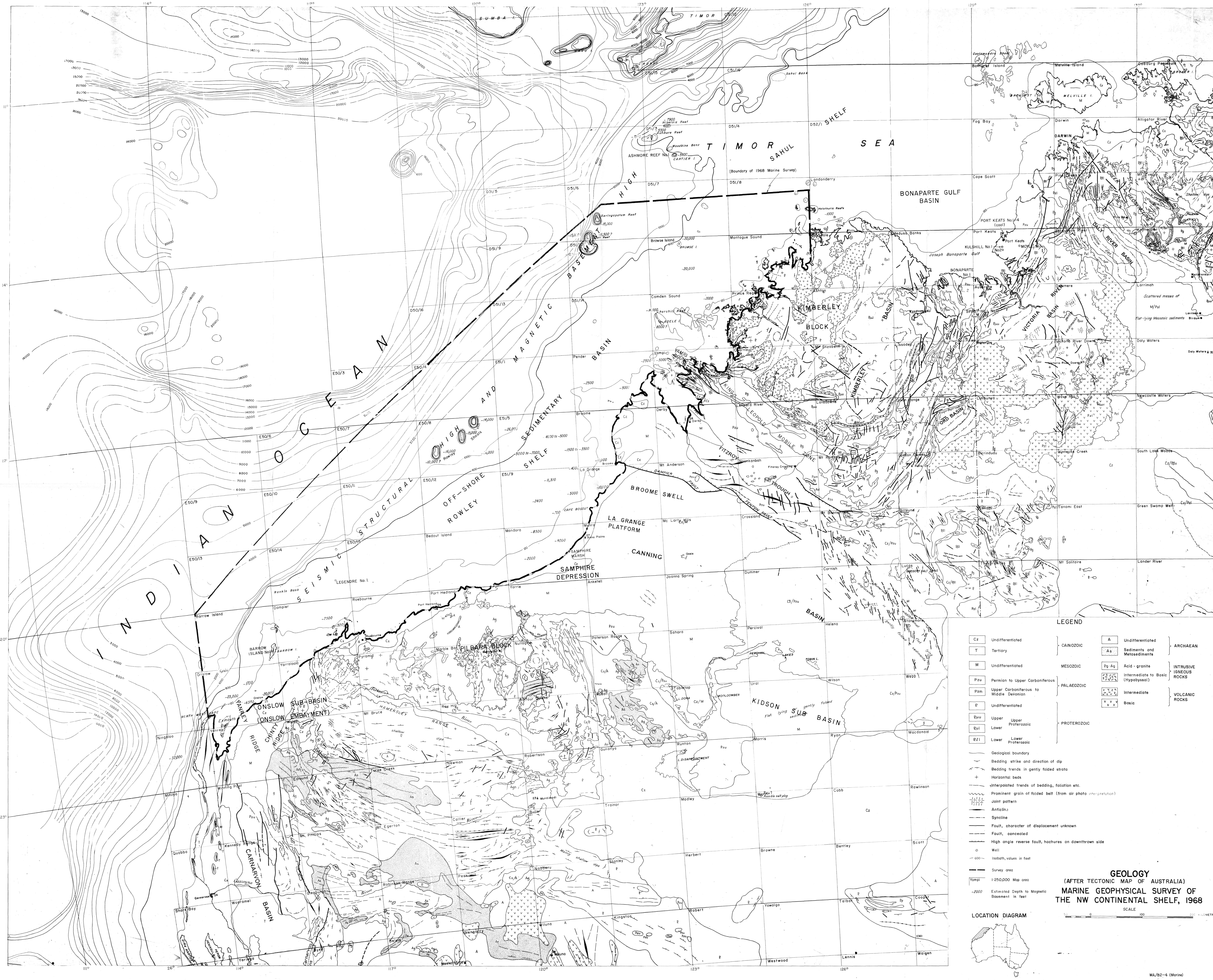
LOCALITY MAP

SCALE

50 0 50 100 150 KILOMETRES

TO ACCOMPANY RECORD No. 1968/1

WA/B2-5 (Marine)



GEOLOGY
(AFTER TECTONIC MAP OF AUSTRALIA)

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968

WA/B2-4 (Marine)

TO ACCOMPANY RECORD No. 1969/99, 1968/1

PLATE 3

MARINE GEOPHYSICAL SURVEY OF THE NW CONTINENTAL SHELF, 1968

BOUGUER ANOMALIES

SCALE

50 0 50 100 150 KILOMETRES

WA/B2-3 (marine)

APPENDIX A

ORGANIZATION OF THE SURVEY

A contract has been let to Ray Geophysics (Australia) Pty. Ltd. to carry out a combined marine gravity, magnetic and seismic survey on the North-West Continental Shelf for the Bureau of Mineral Resources. The contract calls for the survey to be carried out over a period of seventy-five fully operational twenty-four hour days; it is expected that the survey will be divided into three cruises each of approximately twenty-five days. The survey is to be started as soon as practicable after 1st August, 1968, and operations should be completed by 15th December, 1968. The survey will start from Broome, and Broome will be the base for operations. A shore station will be maintained at Broome for onshore recording of diurnal variations in magnetic field and VLF transmissions. Re-supplying or personnel rotation required during the course of a cruise will be done by a supply boat fitted with RDF.

The ship to be used on the survey is the M/V Robray 1, owned by Ray Geophysical Division, Mandrel Industries Inc., of Houston, USA She was built by the American Marine Corporation of New Orleans, Louisiana, was launched June, 1968, and was fitted out as a geophysical survey ship by early July, 1968. Specifications of the ship are given in Table 1. The Robray 1 did sea trials on 19th July. She left New Orleans on 21st July and reached Brisbane on 27th August.

BMR equipment will be installed in the ship at Brisbane. Trials of all equipment will be carried out on the way from Brisbane to Broome. A BMR systems engineer will be on board during this trip to supervise the setting up of the BMR equipment. The equipment on board ship comprises navigation, gravity, magnetic, seismic and general recording instruments. The equipment on shore comprises magnetic and VLF monitors. All of this equipment is listed below and is discussed in subsequent appendices. A flow chart is attached showing the signal flow of all shipboard information from generation to recording. Most of the seismic instrumentation, part of the navigation instrumentation and the shore installation equipment will be provided by the BMR. The rest of the equipment is provided by the contractor. All equipment will be operated and maintained by the contractor.

A suitable overall staff structure together with detailed duty statements for BMR and contractor's personnel has been put forward by the BMR. These documents are attached. Two surveyors from Department of Interior are listed. Names of key personnel from the BMR, Department of Interior and Ray Geophysics are listed.

Permission has been granted by the Director of the Bureau of Mineral Resources for a representative of the Burmah Oil Company, the major lease holders in the survey area, to be on board ship. He has also given permission for the Burmah Oil Company to place a Raydist operator with his equipment, Raydist Type N, on board the ship. Both of these arrangements are to be the subject of agreement between the Burmah Oil Company and Ray Geophysics and are not to directly involve the BMR in any way.

The more detailed information in the remainder of this appendix comes under the following headings:

1. Specifications of the Survey Ship

2. Shipboard Navigation Equipment
   - VLF Navigation System
   - Pulse Sonar Doppler System
   - ITT's Integrated Satellite Navigation System
   - Gyro Compass and Automatic Pilot
   - Electro-Magnetic Log
   - Ship's Radar
   - Fathometers
   - Anemometer
   - Side-Scan Sonar
   - Automatic Direction Finder
   - Star and Sun Fixes

3. Communications Equipment

4. Shipboard Gravity Meter

5. Continuous Profiling Seismic Equipment

6. Refraction

7. Shipboard Magnetometer

8. General Recording and Timing Equipment

9. Power Generators

10. Flow of Information between Instruments

11. Staff Structure and Duty Statements

    - Duties and Necessary Qualifications for Contractor's Staff

    - Duties for BMR Staff

    - Duties for Department of Interior Surveyors

12. Personnel

Plates accompanying this appendix are:-

A1. Geophysical and Navigational Instruments - Signal Flow

A2. Staff Structure suggested by BMR

1. Specifications of the Survey Ship

Name	Robray 1
Length	165'0"
Beam	36'0"
Draft	9'0"
Gross Tonnage	200
Crew	6
Accommodation for Geophysical Crew	29
Top Speed	12 knots
Operating speed	12 knots to 4 knots
Endurance	50 days

2. Shipboard Navigation Equipment

VLF Navigation System provided by the BMR comprising:

Tracor Inc -

1 VLF Receiver, Model 599G

2 Omega VLF Receivers, Model 599Q

1 Omega Gating Unit, Model 533S

1 Cardioid Unit

1 Filter 13.6 kHz

Sulzer Laboratories Division, Tracor Inc -

1 Frequency Standard, Model 5B, with associated Power Supply, Model 5P

1 Linear Phase Detector, Model 1

1 Model 401-M Clock

General Technology Corporation -

1 Rubidium Frequency Standard, Model 304B

1 Standby Power Supply, Model 312B

1 Standby Power Supply, Model 311A

Hewlett Packard -

1 5233L Electronic Counter

Westronics Inc -

1 Multipoint Strip Chart Recorder, Model M11B

Pulse Sonar Doppler System, Model 435, Edo Western Corporation

1 Pulse Frequency Tracker, Model 435

1 Nixie Tube Display Unit, Navtrak, Model 386

2 Transducer Unit

1 Towed Fish

ITT's Integrated Satellite Navigation System (which uses signals from the Navy Navigation Satellite System) comprising:

A Model 4007 AB Satellite Receiver interfaced with a PDP-8S, Digital Equipment Corporation, digital computer.

Gyro Compass and Automatic Pilot

1 Sperry Gyro Automatic Pilot Unit, Mark 27

2 Repeaters (Navigation Room and Auxilliary Steering Position)

1 Sperry Rand Course Recorder, Style No 80 HSP (Navigation Room)

Electro-Magnetic Log, Model UL-100-3, Chesapeake Instrument Corporation

Ship's Radar

2 Decca Marine Radar, Model 314. 6'0" slotted wave guide atenna, 9" diameter PPI display, 0.5 to 48 n.m. range, X Band, 9380 - 9440 MHz

Fathometers

1 ELAC Deep Sea Sounding Equipment with Echograph Type LV17S/L in Navigation Room

Ranges 0 - 230, 0 - 460, 0 - 920, 0 - 1840 Fathoms

Frequency 20 kHz

1 Raytheon Fathometer, Model DE721A, recorder in wheelhouse.

Ranges 0 - 100, 90 - 190, 180 - 280 feet or fathoms.

Anemometer

1 Danforth White Anemometer, showing wind speed and direction on 6" dial meters in wheelhouse

Side Scan Sonar

1 Simonsen Radio Sonar, Model SJ2A, Sonar Hull Unit Type 583-121, with additional vertical transducer, operating frequency 49 kHz

Automatic Direction Finder

1 Raytheon Model 358A, operating in the beacon, broadcast and marine radio bands from 190 to 2800 kHz

Star and Sun Fixes (BMR and D of I)

3 Sextants

1 Pointer

3. Communications Equipment

1 Raytheon Marine Radio, Model Ray 75A-3C, 75 watt

1 Raytheon Marine Radio, Model Ray 55A, 55 watt

3 SSB Transceiver, RF Communications Inc., Model RF 201M for ship to shore station radio telephone

4. Shipboard Gravity Meter

1 Stabilized Platform Shipboard Gravity Meter, La Coste Romberg Inc., Serial No. S 27 with associated control equipment

1 Servo Writer II multipen strip chart recorder, Texas Instrument Inc, Model FL04W60 recording gravity, spring tension, cross-coupling and average beam position

2 Esterline Angus dual pen recorders recording horizontal accelerations at long and short time constants

5. Continuous Profiling Seismic Equipment supplied by BMR comprising:

EG and G 21,000 Joule Sparker System -

2 Electrode Arrays, Model OC 402

2 Modified Electrode Arrays

9 Power Supplies, Model 232

4 Trigger Units, Model 231

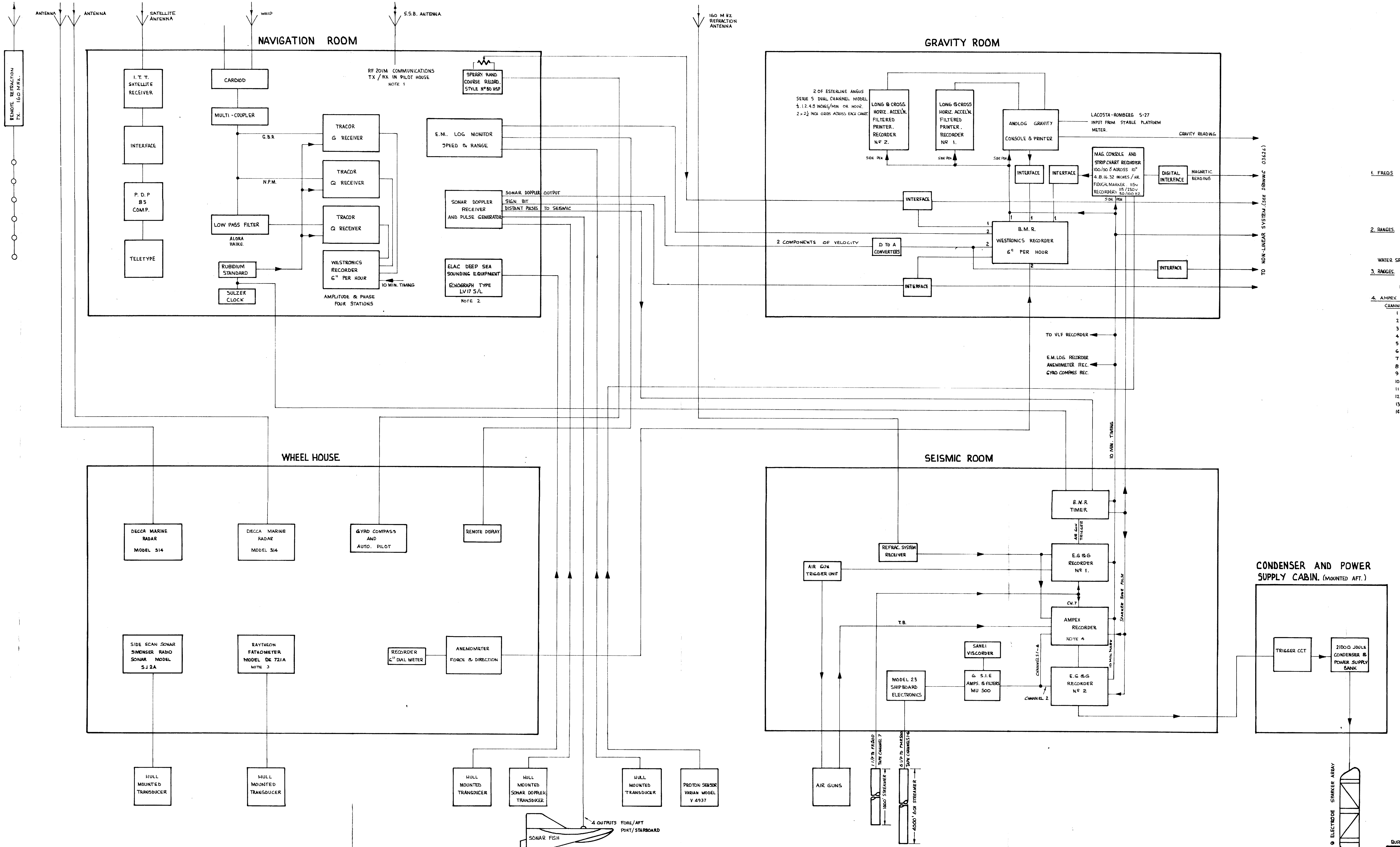
9 Capacitor Banks, Model 233

2 Seismic Recorder, Model 254

DATE	DRAWN BY	AMENDMENTS	ISSUE
22·10·68	R MACAULAY	REDRAWN	3
28·7·69	R. MACAULAY	TITLE CHANGED.	4

PLATE A1

GEOPHYSICAL & NAVIGATIONAL INSTRUMENTS & SIGNAL FLOW.



NOTES

1. FREQS
   - 1.–2·292 MHz
   - 2–2·83 MHz
   - 3–4·1365 MHz
   - 4–6·2075 MHz
   - 5–8·2765 MHz
   - 6–12·414 MHz
   - 7–16·537 MHz
2. RANGES.
   - 0–230 FATHOMS
   - 0–460 "
   - 0–920 "
   - 0–1840 "
   - WATER SPEED ADJUSTABLE 1400-1600 m/s
3. RANGES. 0–100, 90–180, 180–280 } FEET & FATHOMS
4. AMPEX RECORDER.

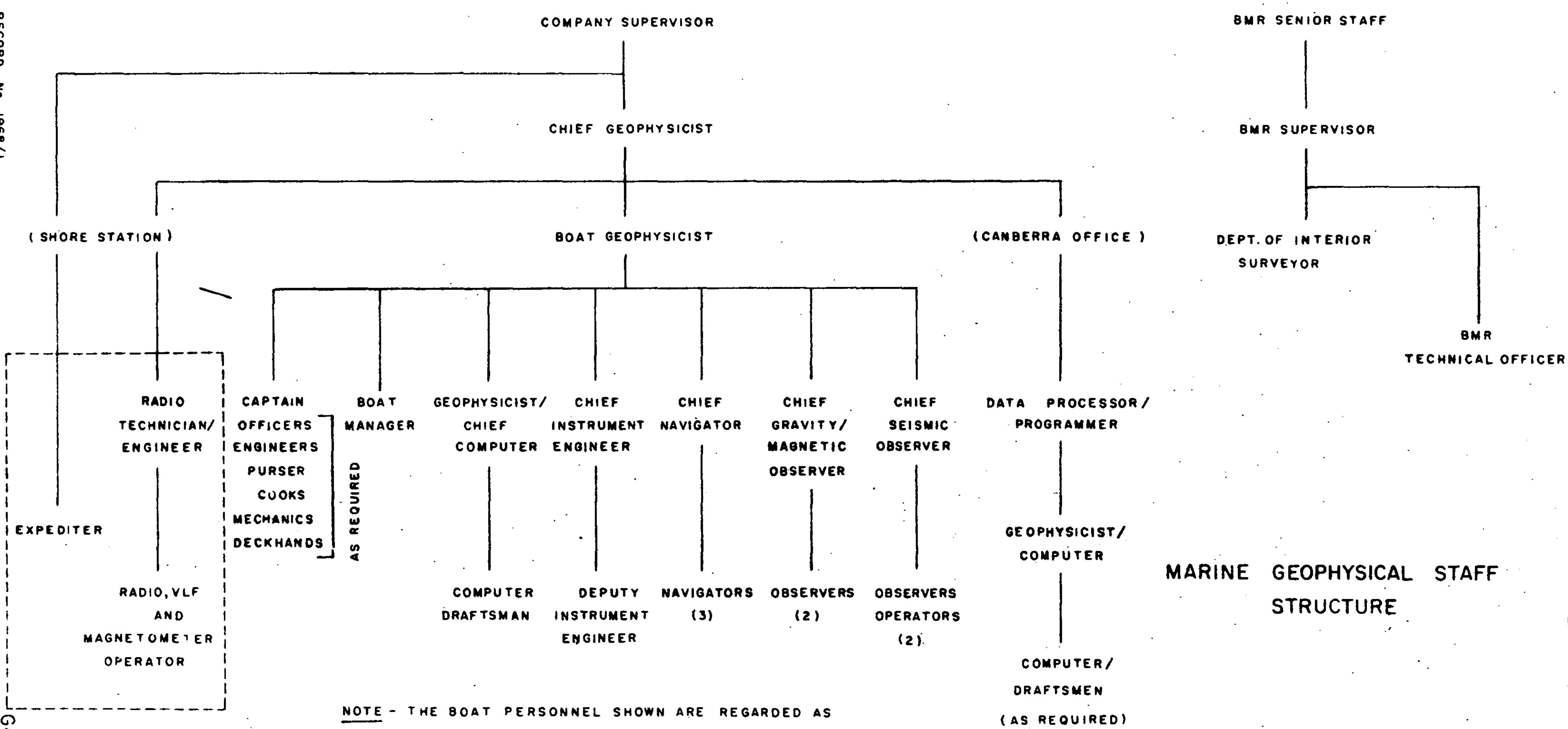
CHANNEL Nº	INFORMATION
1	6000' STREAMER
2	6000' STREAMER
3	6000' STREAMER
4	6000' STREAMER
5	6000' STREAMER
6	6000' STREAMER
7	1000' STREAMER.
8	REFRACTION
9	SPARE
10	AIR GUN T.B.
11	SPARKER TIME BREAK
12	100 Hz
13	SPARE
14	10 MIN TIMING

TO ACCOMPANY RECORD No. 1968/1

BUREAU OF MINERAL RESOURCES GEOLOGY AND GEOPHYSICS

DRAWING AND SHEET Nº	TITLE
SMZ	GEOPHYSICAL & NAVIGATIONAL INSTRUMENT & SIGNAL FLOW ABOARD ROBRAY I. 1968.

TO ACCOMPANY RECORD No 1968/1



NOTE - THE BOAT PERSONNEL SHOWN ARE REGARDED AS THE MINIMUM REQUIRED ON BOARD AT ANY TIME WHILE AT SEA.

MARINE GEOPHYSICAL STAFF STRUCTURE

PLATE A2

G449-16A

Chesapeake Instrument Corporation -

1 Six Channel Seismic Streamer, Model 23

1 Model 23, Seismic Electronics

1 Single Channel Seismic Streamer, Model 12

1 Model 12; Seismic Electronics

Marine Cable Reel, capacity 10,000 feet, for Model 23 supplied by Ray Geophysics

Geotech Division, Teledyne Industries -

1 Hydrostreamer Cable, Model 24257

1 Depth Monitor and Control Unit, Model 25643

1 Streamer Cable Reel, Model 26170

Dresser SIE Inc MU 500 Master Unit comprising -

6 TGA-1 Amplifiers

1 MC-100 Master Control Unit

1 GCU-1C Gain Control Unit

3 DLC-1 Dual Low-Cut Filters

3 DHC-1 Dual High-Cut Filters

6. Refraction Seismic Equipment

Air Gun Equipment supplied by Ray Geophysics -

2 Bolt Associates Sound Sources, Model 1500B, 300 Cubic inches, 2000 p.s.i.

2 Air Compressors, 2000 p.s.i.

1 Air Gun Trigger Unit

Sonobuoy Equipment supplied by the BMR -

Sonobuoy, Model SSQ - 41,

50 Channel 1
10 Channel 4
10 Channel 5
10 Channel 6

4 Sonobuoy Receivers, Model AN/ARR26

2 Power Supplies PP 468/ARR26

2 Control Panels

1 Aerial

7. Shipboard Magnetometer

1 Direct Reading Proton Magnetometer, Model V4937, Varian Associates

8. General Recording and Timing Equipment

1 Ampex, 14 Channel Tape Recorder, Model FR1300 (BMR)

Shipboard Gravity Data Acquisition System 124841, Non Linear Systems Inc comprising:

1 Series DC6ST Digital Clock

1 Series 2300 Scanner

1 Series XZ Digital Voltmeter

1 Series 2610 Serializer

1 Digital Stepping Recorder DSR 1400 Series (Digi-Data Corporation)

1 Six Channel Visible writing oscillograph, Visigraph, Model PR-101, Sanei

1 Marine Seismic Timer, Model STM1, BMR

9. Power Generators

2 General Electric, 100 kVA, 3 phase, AC 60 Hz, 110V and 220V, Ships Main Generators

2 5kVA Kohler Generators (2 cylinder Lister Diesels, air cooled)

10. Flow of Information Between Instruments

The principle information centres on the ship are the navigation, seismic, and gravity and magnetic rooms and the bridge. The flow of information into and between the various instruments in these centres is available by "Talk-a-Phone" between each of these centres, the office and the after deck, where most of the cables and external sensors are handled. Small transceivers are used to communicate between after deck and bridge; these are more efficient in overcoming the high noise level on the after deck.

11. Staff Structure and Duty Statements

The overall staff structure suggested by the BMR is shown in the diagram in Plate A2.

Proposed duties and necessary qualifications for contractor's staff and duties for BMR staff and Department of Interior Surveyors are given below.

Duties and Necessary Qualifications for Contractor's Staff

Company Supervisor:

Duty: Responsible for overall management of project

Qualification: Both a competent geophysicist and a competent manager.

Chief Geophysicist:

Duty: Responsible for defining technical standards of performance for equipment and personnel. Defining proper work schedules and lines of communication to ensure proper integrated performance of total systems and proper flow of data through to final reduction and presentation. Responsible for ensuring that all necessary parameters are properly recorded to facilitate later data processing, and for preparing both progress and final reports.

Qualification: Highly qualified and experienced professional geophysicist with extensive experience in gravity and associated ADP.

Boat Geophysicist:

Duty: Most senior person on boat other than for the legal responsibilities of captain pertaining to safety. Responsible for ensuring that all operations including boat handling, navigation and instrument operating are carried out to ensure the best quality geophysical data and general attainment of objectives. Ensures that preliminary data reduction is carried out on board for progress reports and to adequately monitor and assess results being obtained to ensure quality control and recognition of desirable program modifications.

Qualification: Well qualified and experienced geophysicist of normal party supervision level. Must have gravity experience.

Geophysicist:

Duty: Under supervision of the Chief Geophysicist responsible for data organisation on shore, handling the flow to and from the computing centre, review and, where necessary, interpretation of computer output, and in charge of computers and draftsmen preparing final presentation.

Qualification: Professionally qualified geophysicist and experienced senior computer. Experience with ADP.

Chief Instrument Engineer:

Duty: Supervision of technician/engineers and all scientific equipment. Responsible for adequate repair and maintenance schedules, quality control routines, and the execution of modification and integration of systems as required from time to time.

Qualification: A professionally qualified electronics engineer with extensive experience with geophysical field equipment; would normally be the specialist in one of the four system groups i.e. Gravity/Magnetics; VLF/Sonar Doppler; Satellite Doppler/Computer; and Seismic.

Technician/Engineers:

Duty: Each a specialist and, under the Chief Instrument Engineer, on permanent call and responsible for maintenance and quality control of one of the four system groups.

Qualification: Good trade qualifications in electronics. Experience at senior observer level and in laboratory design and development.

Chief Navigator:

Duty: Responsible to the Boat Geophysicist for plotting and integrating all navigation data to extent possible on board. Supervises production of position location maps, produces preliminary time co-ordinate plots and time-velocity curves. Supervises shift navigators and ensures the proper dropping and observation of buoys. Takes astro and land fixes as required. Is on permanent call.

Qualification: Must be a qualified surveyor/navigator with considerable experience.

Navigators:

Duty: Shift duty on reduction and plotting of navigation data and operation of sonar doppler under general supervision and direction of Chief Navigator. Responsible for continuously reporting to Chief Navigator and/or Boat Geophysicist position of actual traverse relative to planned traverse.

Qualification: Competent and reliable computors with higher secondary education.

Chief Operator:

Duty: Responsible for ensuring good observing practices compatible with instructions issued by Chief Instrument Engineer and Boat Geophysicist. Operates shift but also on intermittent call. Supervises consumable recording stores etc. and generally responsible for regular and proper care of recorded data and delivery to Boat Geophysicist.

Qualification: Trained operator of experienced seismic observer level. Electronic trade qualification desirable. Sound training in operation and routine checking of all instruments essential.

Computers - Draftsmen:

Duty: Assistance to geophysicists in data handling and presentation.

Qualification: Competent and reliable computers and draftsmen with higher secondary education.

Duties for BMR Staff

BMR Senior Staff:

Composition: Includes senior geophysicists, draftsmen, finance officer etc. responsible for the contract letting, project definition, final acceptance, payments etc. Complimentary to the role of BMR supervisor.

BMR Supervisor:

Duty: Responsible for preparing background information and material, preparation of preview report for guidance of contractor, detailed supervision of project, review of all data and preparation of a final interpretative report complimentary to contractor's final report. Will be reviewing preliminary gravity results, seismic sections etc. on board as they are produced. Copying facilities must be adequate to provide him with working copies. Also certifying officer for services rendered. Will spend substantial time on boat and normally maintain direct communication with Company Supervisor, Chief Geophysicist, and Boat Geophysicist.

BMR Technical Officer:

Duty: Will give assistance and advice on design, installation, and maintenance of BMR equipment; will assist BMR supervisor in review of data as it is prepared.

Duties of Department of Interior Surveyors

Duty: Responsible for assessing performance of navigation system both as a total system and with regard to its respective components. Both will spend substantial time on boat and will take astro fixes and land shots etc. and will cooperate to relieve the Chief Navigator of most of this task.

More particularly their duties will be:

(1) Star fix

- (a) morning twilight
- (b) evening twilight

(2) Sun position lines

- (a) morning
- (b) noon fix for lat
- (c) afternoon

(a) and (c) to correspond with satellite fix if available.

(3) Obtain fixes on coastline and offshore islands at times of satellite fix and when opportunity arises.

(4) Tabulate differences in all fix comparisons for future assessment of systems at completion of contract.

(5) Keep notes on problems encountered in systems.

(6) Keep notes on drift rates and comparisons of diurnals by ship and shore monitor.

(7) Assist Contractor in setting up system and seeing that BMR requirements are adopted.

(8) As time permits, assist contractor as required.

(9) Report on navigation to BMR geophysicist.

Surveyor (s) will not be required to stand watch keeping duties and will be responsible to the BMR for ensuring (1), (2) and (3). Other assistance will be as time permits to enable systems to function smoothly and with optimum efficiency.

12. Personnel

The following senior and key personnel have been nominated by the Contractor:

Scientific Advisers

Gravity - Dr. Lewis Mott-Smith
C.F. Sellers

Magnetics - E.W. Frowe
T.O. Hall

Seismic - Ray Hope

Navigation - Dr. Lewis Mott-Smith

Data Processing - Dr. T. Cantwell

Supervisor	L. Twining
Party Chief	S.K. Paul
Electronics Supervisor	D. Edwards

Chief Scientist	D. Krotser
Chief Gravity and Magnetic Interpreter	A.P. Thyssen
Chief Navigator	J.V. Carpenter
Chief Seismic Observer	H. Gaussirian
Chief Gravity Observer	L. Lanners
Computer Programmer and Data Processor	R. Leeder

BMR Geophysicists supervising the contract will be K.R. Vale, A. Turpie and R. Whitworth. BMR Technical Officer will be J.K. Grace.

Department of Interior surveyors will be V. Ingham and I. Rank n on the first cruise.

APPENDIX B

MARINE SURFACE GRAVITY

Measurement of gravity at sea on a surface vessel is a comparatively recent technique dating only from 1957, when Worzel made the first extensive gravity measurements using a Graf Askania sea gravity meter on a stabilized platform. (Worzel, 1959). Since that time parallel developments of the Graf Askania and the La Coste and Romberg sea gravity meters have taken place. A comprehensive discussion of the problems involved in the measurement of gravity at sea, the theory of the measuring technique and the history of the development of the La Coste and Romberg surface meter are given in a recent paper by La Coste (1967). Many statements in this appendix are taken unchanged from that paper. La Coste gives references to papers describing the development of the Graf Askania.

The La Coste and Romberg marine surface gravity meter is basically their land meter, with certain necessary modifications. The first La Coste and Romberg meter for use at sea was mounted in gimbals with correction being made for swinging of the gimbals (La Coste, 1959). All La Coste and Romberg meters up to 1965 were the same and these meters are still in use. The later adaptation of the meter is mounted on a stabilized platform (La Coste et al, 1967). Some further modifications were made to improve the meter and to make it suitable for this type of mounting.

The discussion of the meter in this appendix starts with a discussion of the land meter and then goes on to discuss the modifications required to convert it to a marine surface meter.

The apparent force acting on the beam of a marine surface gravity meter includes various acceleration effects for which corrections must be made. These are vertical accelerations, cross-coupled horizontal accelerations and the Eotvos centripetal acceleration.

A surface gravity meter was first used in Australia by Geophysical Associations under contract to the Bureau of Mineral Resources in 1965 to survey an area in the Bonaparte Gulf (Smith, 1966). The meter used was La Coste and Romberg meter No. S8, a gimbal mounted meter. Meter drift was assumed negligible and no correction was made. The assumption was checked by wharf ties. The precision of the gravity measurements was somewhat better than anticipated and their probable error based on differences in corrected gravity at line intersections and at underwater gravity meter stations, was 2.0 mgals. L.L. Nettleton comments that as far as he knew this was probably the most accurate survey of its kind which had been made to that time (Geophysical Associates, 1966). Navigation was by Toran which was accurate, with a maximum error less than 50 metres, but which could only be used during daylight hours after the skywaves ceased in the morning; an average usage was 8½ hours per day. Recordings were made along 3232 nautical line miles of traverse at an average speed of 7.2 knots in 62 operational days at sea.

A second marine gravity survey was carried out for the Bureau of Mineral Resources in 1967 by United Geophysical Corporation, extending the area of the previous survey to the north and east (Jones, 1968). The gravity meter used was the Graf Askania Gss2 geogravimeter, type C, serial No. 27. The meter was newly assembled when it was used on this project. Gravity meter drift with time is usually largest when the meter is new and gradually decreases over a period of months or years. On the trip from Brisbane to Darwin the meter was tied to base stations at Brisbane, Cairns, Thursday Island and Darwin, also after each cruise the meter was tied to this Darwin base. The meter drift curve obtained from these ties shows a drift rate of 7.2 mgal per months decreasing to less than 3 mgal per month. The fact that scale factor also enters largely into this comparison throws a certain amount of doubt on the drift values obtained from Brisbane to Darwin. A calibration figure was determined over the Brisbane calibration range and assumed to apply throughout the gravity range of the survey. During the survey the average gravity mistie at line intersections was 2.5 milligals. It is not known to what extent navigational errors in measuring velocity and position contribute to the gravity misties. The navigational methods to be used in the present survey are described in Appendix E; the principal technique for the 1967 survey was a VLF phase comparison method. The average navigation misties at 42 buoyed intersections was 1.2 nautical miles. There was not sufficient control to obtain a good estimate of the overall accuracy of the navigation system. To set against the reduced accuracy of the navigation system is the fact that operations continued 24 hours per day, so that 13 050 nautical miles were surveyed at a speed of 8 to 10 knots in 70 operational days at sea.

The present marine surface gravity survey to be carried out in 1968 by Ray Geophysics for the Bureau of Mineral Resources extends south-east from the area already surveyed over the North West continental Shelf. The gravity meter to be used on the 1968 survey is the latest La Coste and Romberg meter on a stabilized platform. The meter serial number is S27. In the BMR's earlier surveys it had been attempted to use an underwater meter as a sub-standard to control the surface gravity meter data. However the confidence in the meter to be used in this survey is such as to make this procedure unnecessary. The drift of the meter is very small being a fraction of a mgal per month. The meter has been used previously by Ray on a 2 month survey off Senegal. The navigation system has been improved since 1967 by the addition of satellite Doppler and an improved sonar Doppler. It is expected that the mean deviation of the misties of corrected gravity at line intersections should be less than 2 mgals.

The more detailed discussions in the remainder of this appendix are under the following headings -

1. The La Coste and Romberg gravity meter
2. Theory of the zero length spring gravity meter
3. The La Coste and Romberg marine surface gravity meter
4. The stabilized platform
5. Vertical accelerations
6. Horizontal accelerations
   - inherent cross-coupling
   - imperfection cross-coupling
7. The Eotvos effect
8. Gravity meter calibration
9. Gravity reductions

Several plates are included in this appendix; these are -

Plate B 1	-	Schematic diagram of the La Coste and Romberg gravity meter.
Plate B 2	-	Vector diagram of zero length spring.
Plate B 3	-	Vector diagram of positive length spring.
Plate B 4	-	Block diagram for La Coste and Romberg air-sea gravity meter.
Plate B 5	-	Block diagram of stabilized platform.

1. The La Coste and Romberg Gravity Meter

The acceleration of gravity can be measured by dynamic or static means. The most important methods which have been used are -

dynamic - measurement of the acceleration of a falling body.

- measurement of the period of a swinging body.

- measurement of the period of vibration of a stretched string.

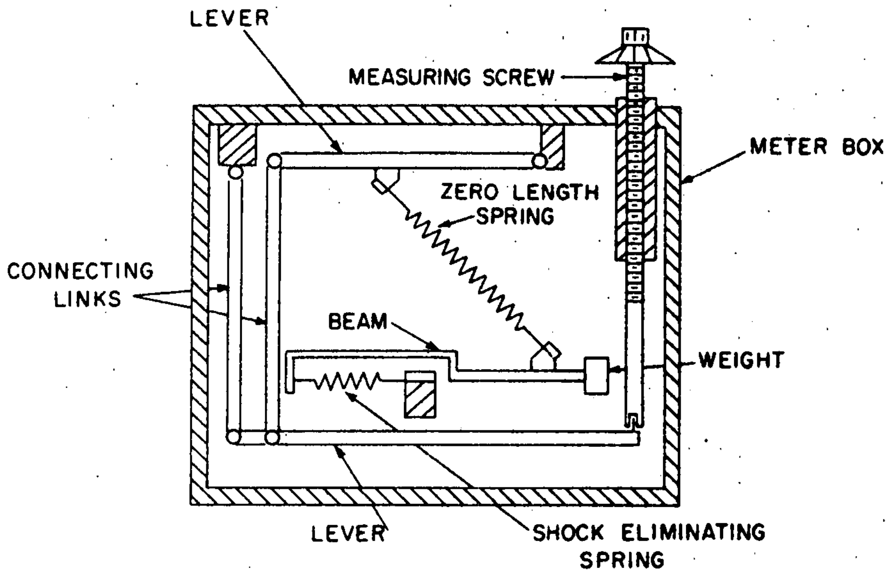
static - instruments using the spring balance principle.

- gas pressure gravimeters.

These methods and instruments are described in text books (e.g. Heiskanen and Vening Meinesz).

The La Coste and Romberg gravity meter (US Patent 2, 293, 437; 1942) is a static instrument working on the spring balance principle. It is basically the same instrument as the La Coste seismometer (La Coste, 1934 and 1935). A schematic diagram of the gravity meter appears in plate B1. The suspension has a long period and high sensitivity by virtue of the beam being supported at its centre of gravity by a zero length spring which has its point of support near to vertically above the beam's axis. The system of levers controlled by the measuring screw raises and lowers the suspension point of the zero length spring and returns the beam to the null position. The position of the beam is indicated by an illuminated cross hair mounted near the weight and viewed by a microscope. One turn of the knob is approximately equal to 1 mgal. The scale on the knob is divided into 100 divisions, so that one knob division is equal to $^1/100$ mgal. The full range of the meter, which is worldwide, is about 7000 mgals.

Long period vertical seismometers or gravity meters are subject to drift arising from changes in the spring or from changes in the buoyancy of the air. Even when the units are sealed or compensated for these effects, it is difficult to maintain stability at periods exceeding 30 seconds (Runcorn). The La Coste and Romberg gravity meter is compensated for variations in buoyancy. However a long term drift occurs due to variations in the spring.



PRINCIPLE OF OPERATION

(U.S. PATENT NOS. 2 293 437 – 2 377 889)

SCHEMATIC DIAGRAM OF THE LACOSTE AND ROMBERG GRAVITY METER

PLATE B2

VECTOR DIAGRAM
ZERO-LENGTH SPRING

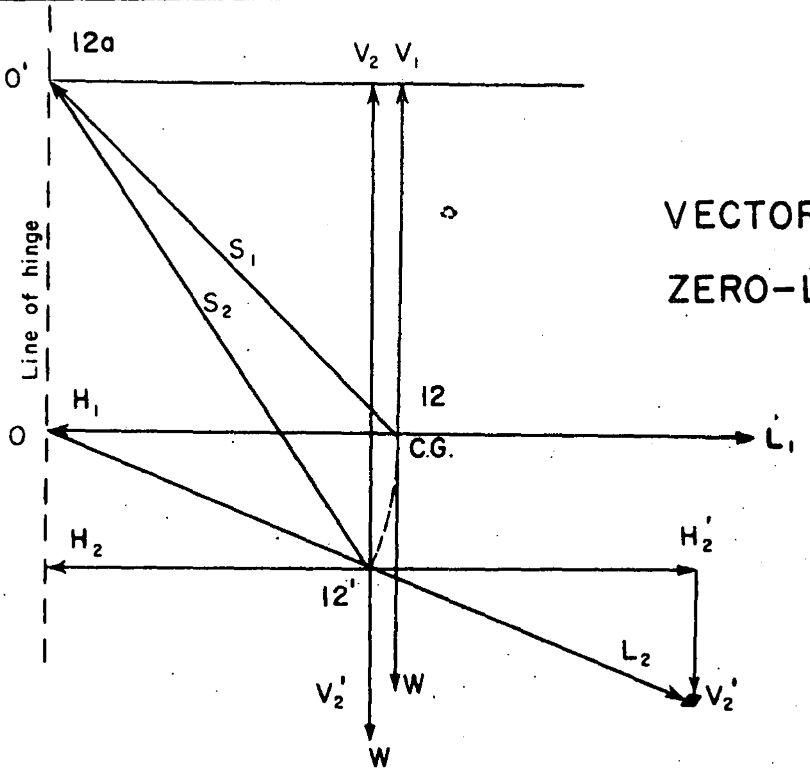
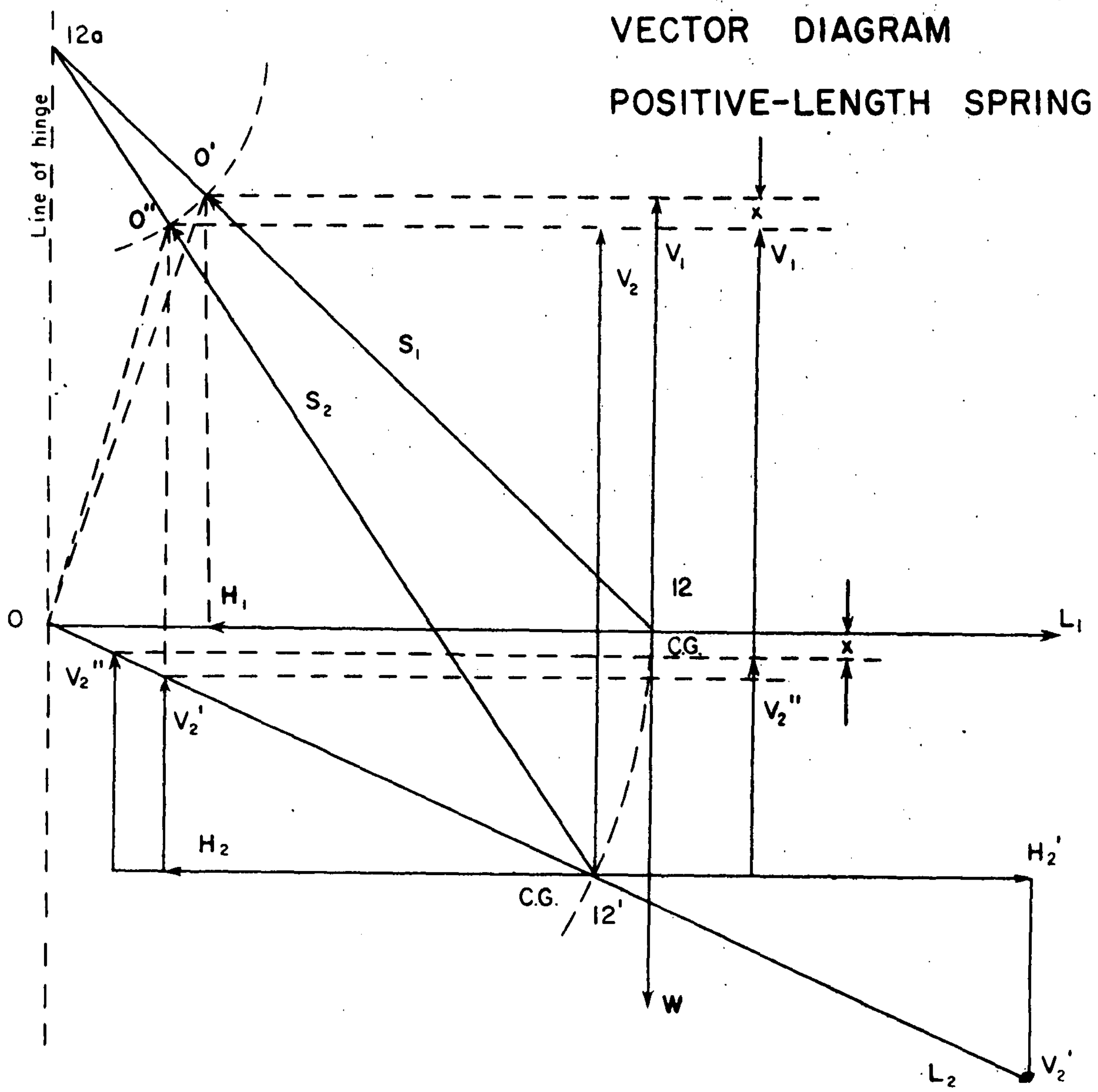


PLATE B3

VECTOR DIAGRAM
POSITIVE-LENGTH SPRING



2. Theory of the Zero Length Spring Gravity Meter

A zero length spring is described by the equation -

$$T = kl$$

i.e. the tension in the spring (T) is directly proportional to its length (l). Theoretically the ends of the spring would come together when the spring was allowed to contract. However before this could happen the spring would reach a minimum length l_o when the turns of the spring were in contact. Hence in the collapsed position the spring must be stressed by an amount

$$T_o = kl_o$$

which force must be overcome before the spring starts to stretch.

The principle of operation of the zero length spring gravimeter is illustrated by the vector diagram in plate B2 (Western Geophysical Co.). The weight of the beam must be such that the system is in equilibrium when the centre of gravity is in position 12; the system will then be in equilibrium when the centre of gravity is in position 12' or any other position, i.e. the system is in neutral equilibrium. Since no restoring force is produced by displacement the period of the beam is infinite. Any small change in the gravity force will cause an unlimited motion of the beam till it comes against the stops. The system is infinitely sensitive to changes in the gravity field. This only occurs when the spring is zero length and its point of suspension is vertically above the beam's axis.

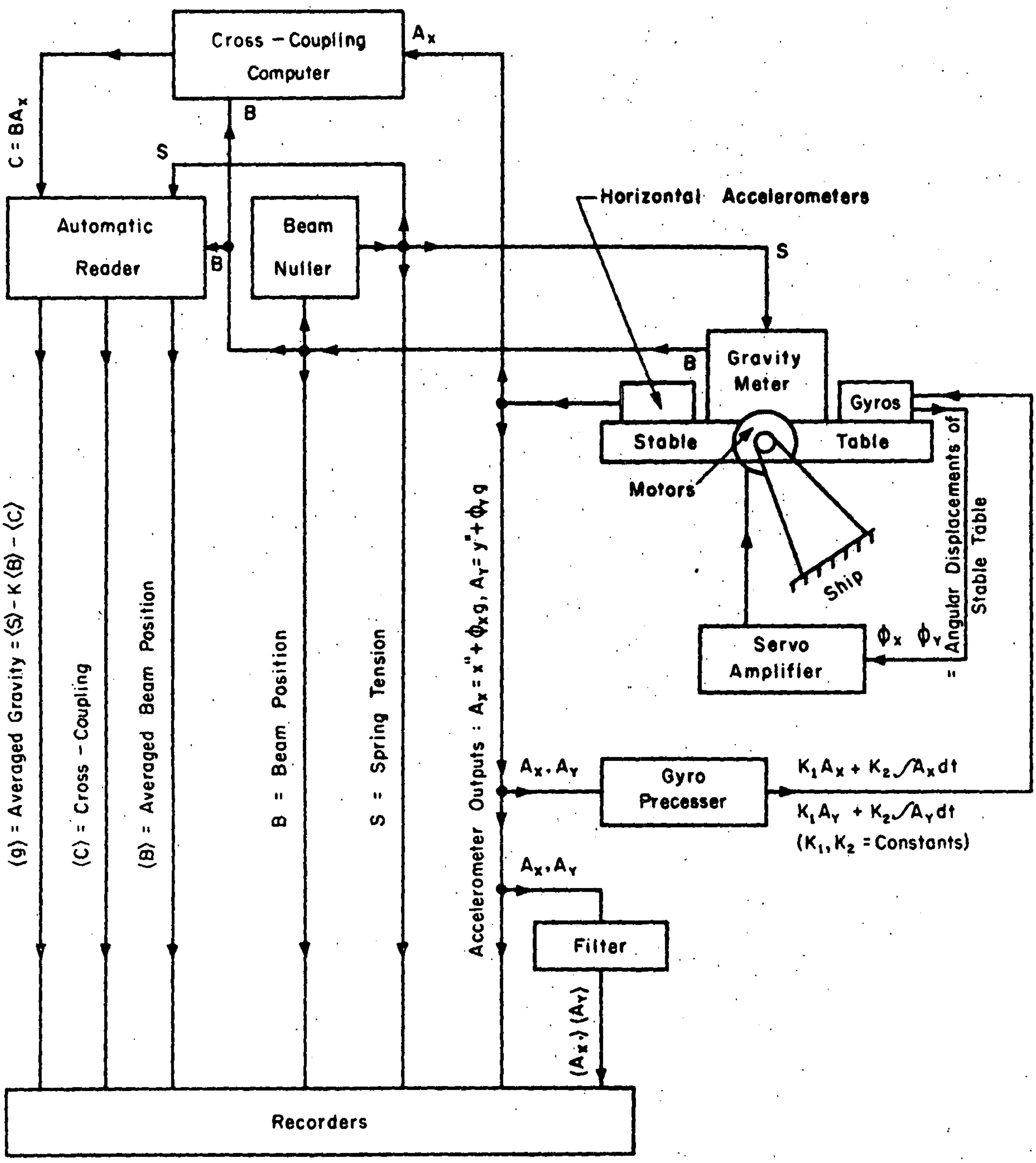
Small variations from this system produce a system with a long period and a high sensitivity to changes in the gravity field. Normally the spring is made slightly greater than zero length. In this case, when the beam is displaced from the equilibrium position a small restoring force is exerted by the spring. This is illustrated by the vector diagram in Plate B3 (Western Geophysical Co.). To adjust the period and sensitivity of the meter, the entire instrument is tilted in the plane of the beam and spring. When 00' is vertical the period of the beam approaches infinity; further rotation to the left will cause instability. Normal adjustment provides a slightly positive length, and the line 00' to the right of the vertical by a small amount, about 3 minutes. The setting up procedure ensures a sensitivity as quoted by the maker (approx. 1 mgal per turn) with the beam horizontal in the reading position. The period of the system is then about 18 seconds.

3. The La Coste and Romberg Marine Surface Gravity Meter

The La Coste and Romberg marine surface gravity meter was until 1965 mounted on gimbals. The meter was basically a land meter but with a beam of increased moment of inertia, high damping and a photo-electric reading system. Reference was made to two long period (2 minutes) horizontal pendulums to establish the true vertical.

A later adaptation of the La Coste and Romberg meter was designed for use mounted on a stabilized platform. Several reasons existed for the change to a stabilized platform and the redesign of the meter (La Coste et al, 1967). The previous meter was designed to operate at vertical and horizontal accelerations of $\pm$ 50,000 mgals. At greater horizontal accelerations the Browne correction (see for example La Coste, 1967) becomes so large that a digital computer is required to give adequate accuracy. There is no Browne correction required for a meter mounted on a stabilized platform. The gimbal mounted meters were capable of withstanding vertical accelerations several times greater than $\pm$ 50,000 mgals but their linearity was not sufficient to make errors small beyond this limit. The meters had been suspended at the proper distance below the gimbal joint to make negligible all acceleration forces normal to the sensitive axis of the meter, and therefore it was not necessary to make the beam, and the springs in the fine wires providing a hinge for the beam, very stiff. However, stiffness makes it easier to achieve high gravity meter linearity and in the later meter stiffness with respect to unwanted modes of motion was increased by a factor of 40 without noticeably affecting stiffness in the desired mode. This modification made it easy to attain sufficient gravity meter linearity to limit vertical acceleration errors to less than 1 mgal at vertical accelerations of 0.1 g. The modification also made negligible the imperfection type of cross-coupling. A further modification to the later meter was to approximately double the damping so as to reduce the inherent type of cross-coupling effect. The increased damping permits operation at vertical accelerations of $\pm$ 0.5 g at a 7 second period or at $\pm$ 1g at a 3.5 second period without having interference between the beam and case of the meter.

The high damping of the meter resulted in a response which is controlled primarily by the damping; and, therefore, the rate of motion of the beam, rather than its deflection, is a measure of the short term gravity difference. That is to say, if the gravity meter is not balanced, the beam moves at a rate proportional to the amount of imbalance. At the same time a slow acting servo-mechanism moves the spring support, controlling the spring tension, to return the beam to the null position. The equation of motion of the beam is



BLOCK DIAGRAM FOR LACOSTE AND ROMBERG AIR-SEA GRAVITY METER

$$g + \ddot{Z} = \left(\frac{K}{m}\right).S - \left(\frac{F}{m}\right).\dot{B}$$

when $\ddot{Z}$ = vertical acceleration

S = vertical component of the length of the spring

$\dot{B}$ = velocity of the beam

F = damping factor.

The beam will reach 0.6 of its steady state velocity in a time $^1/F$ when an input step function is applied to it. A typical value of the time constant is 4×10^{-4} sec. This time constant is so much smaller than any time over which gravity readings are averaged that transients may be neglected. It may be noted that the marine meter forms a dynamic means of measurement of gravity. A block diagram for the La Coste and Romberg sea gravity meter is shown in Plate B4.

An analog computer referred to as the automatic reader computes an average value of gravity by filtering the spring tension, filtering and differentiating the beam deflection, filtering the cross-coupling and then adding these processed variables. The filtering is the same for each variable. The value of gravity computed by the reader is recorded on a strip chart recorder. Spring tension, averaged beam position and cross-coupling are also recorded, so that gravity can be computed even though there is a malfunction in the reader. Filtered and unfiltered horizontal accelerations are recorded for monitoring purposes.

4. The Stabilized Platform

Another reason given for the change to a stabilized platform mounting was that inertial quality gyros had become available with estimated lives of 1½ years as against a previous 7 weeks. Inertial quality gyros have more than sufficient accuracy for shipboard gravity meter operation while the overall performance of long-period pendulums is marginal.

In order to determine what accuracy is required in the stabilized platform, it is necessary to compare how the gravity meter reading is affected by errors in verticality. When the sensitive axis of the gravity meter departs from the vertical by an angle e, the error in measuring gravity will be

$$e_g = g \cos e - a_h \sin e - g$$

where g = gravity

a_h = horizontal acceleration

since e is small this becomes

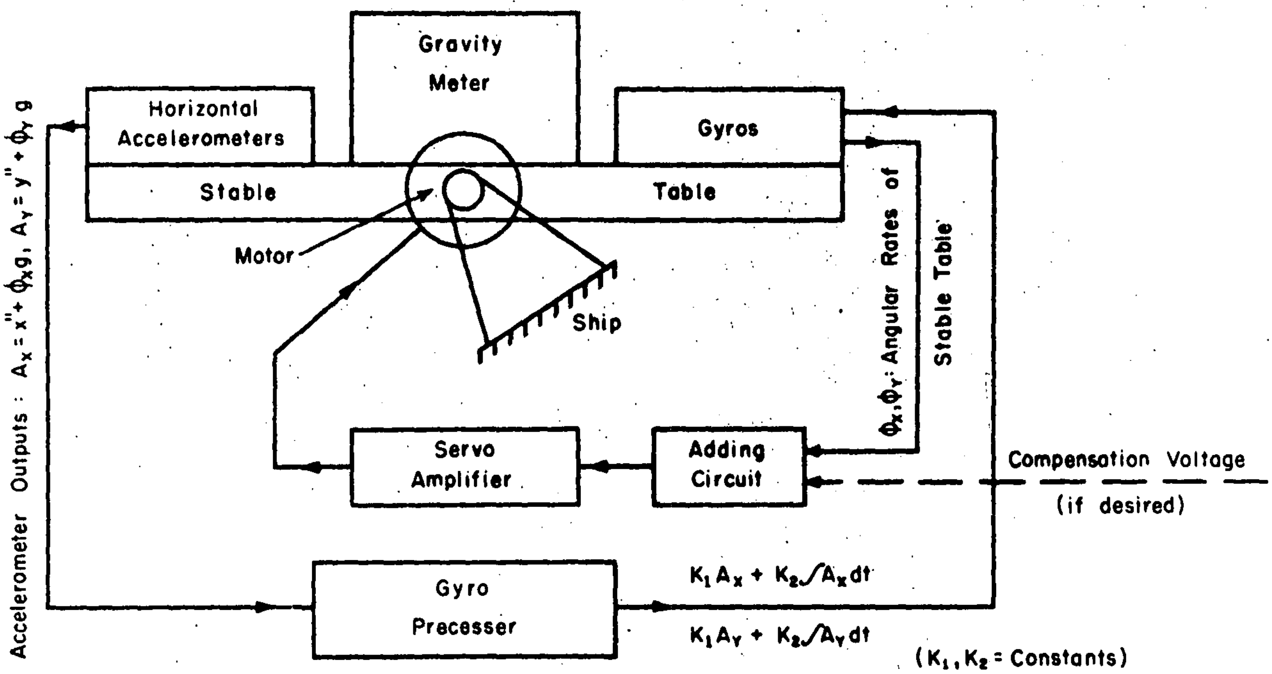
$$e_g = -a_h e - g\frac{e^2}{2}$$

The second term is the static error which exists even where there is no motion and for a 1 mgal accuracy it requires an accuracy of 5 minutes, which is not hard to obtain. The steady state and long period verticality errors have been checked at sea by comparison with oil filled levels which filter out short term variations. Where the ship was travelling in a straight line these errors were found to be less than 1 minute.

The first term depends on horizontal acceleration and represents an effect which is similar to the inherent cross-coupling effect described later. If the gravity meter beam is in the null position with the centre of gravity of the beam in the same horizontal plane as the beam axis, horizontal accelerations will produce no torque. A variation from level of the gravity meter case will tilt the beam and make it sensitive to horizontal accelerations. The error will normally be small but a stabilization error with the same period as a horizontal acceleration and in phase is extremely important. For a 1 mgal error a short term accuracy of 8 seconds is required for a horizontal acceleration of amplitude 50 000 mgals in phase with the stabilization error. For a platform with a stabilized reference of period 2 minutes this would include horizontal accelerations of all periods up to 24 seconds. La Coste (1967) discusses the variation of stabilization error with period of the stabilized reference. He concludes that a period of 2 minutes is sufficient. The period of the stabilized platforms used with the La Coste and Romberg gravity meters may be switched to either 4 minutes or 6 minutes. It is difficult to check directly the component of stabilized platform error in phase with the horizontal acceleration. However the accuracy that has been achieved in measuring gravity in laboratory and sea tests shows that the requirements have been satisfied. It is fortunate that this requirement is only for short term errors in phase as it is difficult to maintain an accuracy of 8 seconds for long periods of time (La Coste et al, 1967).

A block diagram in plate B5 indicates the operation of the stabilized platform. This diagram shows only one of the two required vertical erecting units. In the unit shown the gyro conrols a servo amplifier and meter that makes the platform follow the gyro. A function of the error signal from each of two horizontal sensing accelerometers is fed to the corresponding gyro to precess it gradually to bring the reference line on the platform to vertical.

The stabilized platform is shock mounted to reduce higher frequency accelerations on meter and platform. Gravity meters have certain resonant frequencies that must be avoided. The resonant frequencies are generally higher than 10 per second and it is possible to avoid them or



BLOCK DIAGRAM OF STABILIZED PLATFORM

shock mount to eliminate them. Another reason for shock mounting is that high frequency accelerations act on any lack of balance in the platform to produce torques which must be counteracted by the servos, and servo gain falls off at high frequencies.

5. Vertical Accelerations

As stated previously a gravity meter on a ship at sea is subjected to instantaneous vertical accelerations that may be greater than 0.1 g. The force measured by the meter will be the sum of the gravity and the vertical acceleration. The meter is sufficiently sensitive to measure to 1 mgal and yet is so heavily damped that it does not hit its stops when subjected to periodic vertical accelerations of 500 000 mgals. The high damping reduces greatly the effect on the beam of these short period accelerations. However, averaging or filtering of the output is also necessary. If a simple averaging process is used over the time interval T then

$$\frac{1}{T}\int_0^T (g + \ddot{Z})\, dt = \bar{g} + [\dot{Z}]_0^T / T$$

Therefore the averaged gravity measurements must be corrected by an amount equal to the changes in vertical velocity during observation divided by the time of observation. There can be no long term change in $\dot{Z}$ since the vertical acceleration of the ocean surface due to tides is negligible. It is therefore only necessary to filter out the wave frequencies (La Coste, 1967).

Because the accelerations are so great, the gravity meter and filter responses must be extremely linear to avoid errors being introduced in the averaging process. La Coste (1967) gives an example where he shows that over a damped velocity range corresponding to a vertical acceleration range of 0 to 0.1 g the damping coefficient cannot vary by more than 1 part in 100 000 in order to preserve an accuracy of 1 mgal.

6. Horizontal Accelerations

Inherent Cross Coupling -

As in the case for off-level errors, when the gravity meter beam is horizontal in the null position, horizontal accelerations will produce no torque. When the beam is deflected from the null position by vertical accelerations, allowing horizontal accelerations to produce a torque, the effect is an interaction of vertical and horizontal accelerations and is called cross-coupling. The cross-coupling effect will be small in most cases. It is important when vertical and horizontal accelerations have the same period and, in the case of an over-damped meter, when the waves are circularly polarised, as is the case with sea waves (La Coste and Harrison, 1961; La Coste et al, 1967).

La Coste (1967) gives an example for a recent La Coste and Romberg meter where the meter is taken round a circular path with an acceleration amplitude of 0.1 g giving rise to a cross coupling error of 49 mgals.

Corrections for cross-coupling errors in La Coste and Romberg meters is made by a simply analog computer which multiplies horizontal acceleration by angular displacement of the beam.

Imperfection Cross-Coupling -

Imperfections in gravity meter construction may cause the gravity reading to be sensitive to horizontal acceleration. Examples which have been given are -

- the inertia of the spring causes it to bow and shorten (Harrison, 1960).
- elasticity in the wires forming the beam hinges allow the beam to move horizontally changing the beam's moment (La Coste et al, 1967).
- lack of symmetry in construction (La Coste et al, 1967).

Imperfection cross-coupling is claimed to have been made negligible in the La Coste and Romberg meter by careful design and adjustment (La Coste et al, 1967).

7. The Eotvos Effect

A correction must be made to gravity measurements made by a moving meter for the centripetal acceleration experienced by a body moving over the curved earth. This correction is known as the Eotvos correction and its value (La Coste, 1967) is

$$E = (R\phi + h)(2V\phi Ve + V^2)/R\phi^2$$

where ϕ is latitude

$R\phi$ is earth's radius

h is height above sea level

$V\phi$ is speed of rotation of earth's surface

V is velocity of body on earth's surface

Ve is easterly component of V.

The V^2 term would occur if the earth were not rotating. The $V\phi$ Ve term is due to the vertical component of the Coriolis force $2\Omega_\wedge\bar{V}$, where $\bar{\Omega}$ is the vector rotation of the earth and $\bar{V}$ is velocity relative to the earth.

At speeds less than 15 knots the Eotvos correction can be approximated by E = 7.5 cos ϕ mgals/knot of east-west speed.

It is apparent that navigational errors may often be the most serious limitation on the accuracy of gravitational measurements made on moving platforms. At the equator, a 0.13 knot error in east-west speed will cause a 1 mgal error in Eotvos correction.

8. Gravity meter calibration

The contract requires the marine gravity meter to be calibrated on an Australian calibration range before the start of the survey. Preferably it should also be recalibrated at the end of the survey. The only calibration ranges along the expected track of the ship in Australian waters are Brisbane and Townsville.

It should prove possible to remove the meter from the ship and read it without moving all the associated analogue computers and electronics with it. If not, it would prove difficult to transport the meter in a vehicle.

There are three possible ways of calibrating the meter. They are given below in order of accuracy and preference. The first is by far the most preferable.

1. Removal of meter from ship and calibration on a land calibration range.

2. Calibration by A-B-A between two ports without removing the meter from the ship. The gravity values at the wharves must be known, and the drift must be linear over the time concerned.

3. Calibration by tying in to a series of ports at which the gravity values are known. This requires the drift to be a simple and discernible function of time, so that the changes caused by gravity variation may be separated from drift effects.

9. Gravity Reductions

the output of data from the ship is expected to be a listing of meter readings at ten minute intervals. However, there is a possibility that recording at one minute intervals with subsequent digital filtering will be required. Time will be recording as DDHHMM as before. The exact format of the meter reading will depend upon the meter. The Eotvos corrections will be available in a similar form. These data will be used in a computer program to obtain station position, number, time and corrected gravity value in mgals on an arbitrary datum.

First, though, the effect of meter drift must be removed from the results. As the drift must be derived from all available data, it would be simplest to reduce the drift control stations separately. As the meter readings and times of traverse intersections will have been abstracted by hand, the values will be readily available.

Gravity readings taken while the ship is alongside the wharf at Broome will be used for primary drift control. The multiple values obtained for traverse intersections will supply secondary control. The values will be affected by errors in velocity and estimation of position of intersection, so they will be of lower significance than the primary control. However, they must be checked for compatibility with the drift estimated from the primary control, and if necessary the drift curve revised.

It is envisaged that the drift will be interpolated to intermediate times by means of a low order polynomial curve fitted to the control values. All the results will then be run through the computer and drift corrected values obtained. The corrected multiple values obtained at traverse intersections will be used to assess the accuracy of the observations. The RMS difference at the intersections should be less than 2.0 mgals.

After ensuring that the drift control is adequate and properly applied, the results will be adjusted by least squares. To facilitate this, the data will be handled in runs, where a run consists of all the stations between two consecutive nodes. Some runs could contain up to 100 stations. The computer should first supply reduced gravity values, i.e. gravity values relative to the starting node of the run, before commencing the least squares phase. The gravity nodes used in the adjustment will consist of traverse intersections as free nodes, and the wharf at Broome harbour and any other selected points as fixed nodes. The final output of the reduction program will be station position number and final adjusted gravity value in a format suitable for inputting to the BMR. Bouguer anomaly program. The output should also include a listing of node to node differences and the adjustments applied to them. The mean and standard deviation of the adjustments should be provided.

The sorted listings of gravity will then be used, along with sorted listings of position and water depth, in a program that will compute Bouguer anomaly values for several different densities, one of which, will be 2.2 gms. The BA values computed using 2.2 gms/cc will be presented at 1:250 000 scale on a digitally plotted BA map. It is expected that contouring will still be done by hand, but the possibility of computer contouring should not be excluded. A sorted listing of principle facts must be provided in a form compatible with other BMR programs.

REFERENCES

HEISKANEN, W.A. and VENING MEINESZ, F.A. 1958 - The Earth and its Gravity Field. McGraw-Hill Book Company Inc.

LA COSTE, L.B.J., 1934 - Physics, 5, pp. 178-180.

LA COSTE, L.B.J., 1935 - Bull. Seismol. Soc. Amer., 25, pp. 176-179.

LA COSTE, L.B.J. and ROMBERG, A., 1942 - US Patent No. 2,293,437.

HARRISON, J.C., 1960 - The measurement of gravity at sea. Methods and techniques of Geophysics, Vol. 1. Edited by S.K. Runcorn, Interscience Publishers, N.Y. and London.

WESTERN GEOPHYSICAL COMPANY 1950 - Theory and Operation of the Western Geophysical Company Gravimeter (unpublished).

LA COSTE, L.B.J., CLARKSON, N. and HAMILTON, G., 1967 - La Coste and Romberg stabilized platform shipboard gravity meter. Geophysics 32, pp. 99-109.

LAFEHR, T.R. and NETTLETON, L.L. - Quantitative evaluation of a stabilized platform shipboard gravity meter. Geophysics, 32, pp. 110-118.

NETTLETON, L.L., 1966 - Marine Surface Gravity and Seismic Sparker Survey, Timor Sea - Joseph Bonaparte Gulf, Northwest Australia. Final Report for BMR (unpublished).

JONES, B.F., 1968 - Timor Sea Marine Surface Gravity, Seismic and Magnetic Profiling Survey. Bur. Min. Resour. Aust. Record (in preparation).

GEOPHYSICAL ASSOCIATES PTY. LTD. (L.L. NETTLETON), 1966 - Timor Sea/Joseph Bonaparte Gulf Marine Gravity and Seismic Sparker Survey, North-west Australia, 1965. Bur.Min.Resour.Aust.Record 1966/116.

NETTLETON, L.L., 1966 - See Geophysical Associates.

SMITH, E.R., 1966 - Timor Sea/Joseph Bonaparte Gulf Marine Gravity and Seismic Sparkarray Survey Northwest Australia 1965. Bur. Min. Resour. Aust. Record 1966/72.

WORZEL, J.L., 1959 - Continuous gravity measurement on a surface ship with the Graf sea gravimeter. J. Geophys. Res., 64, pp. 1299-1315.

APPENDIX C

THE SEISMIC SYSTEMS

The principal use of the seismic method on the 1968 survey will be a continuous seismic profiling method using a spark array and a 6 channel streamer. Data will be obtained for a later 6 fold CDP stack. It is intended that for surveys after 1968 the six-fold seismic data will be processed "on-line" by a system having a small general purpose digital computer at its heart. The 1968 records will be recorded on analogue magnetic tapes. The future "on-line" system will be used to process the records played back from these tapes.

During the 1968 survey refraction soundings will be made once every two or three days. It is hoped to determine the distribution of velocity with depth in the sedimentary section and to correlate refraction events with reflection events as a diagnostic means. To enable this to be done the refraction line will be recorded continuously from small source-to-sensor distance up to the limit of the system range; this limit is about 15 miles. The refraction system will work simultaneously alongside the sparker reflection system.

The discussion below will be under the following headings:

1. Continuous seismic Profiling
   - General
   - Energy Source
   - Hydrophone Streamers
   - Recording Equipment and Timing Unit
   - Operation
2. Refraction Seismic
3. Testing of the Seismic Equipment
4. Processing of the Sections Obtained with the Continuous Seismic Profiler
5. Processing of Refraction Sections.

Several plates are included with the appendix:

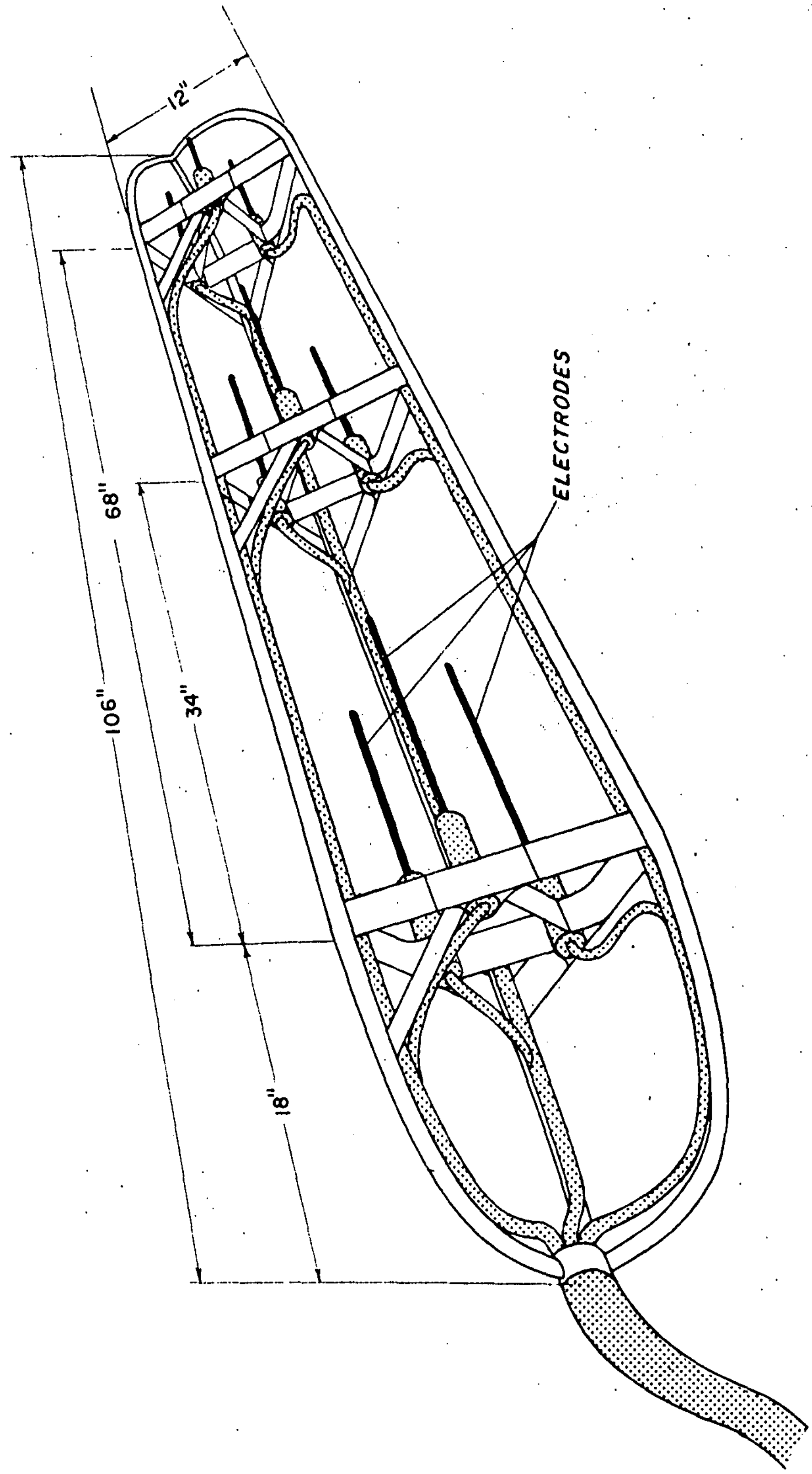
1. Continuous Seismic Profiling

General - 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 to increase the penetration have been directed towards increasing the power of the source and decreasing the frequency. There has also been considerable improvement in the receiving equipment used (Caulfield, Hoskins and Nowak, 1965).

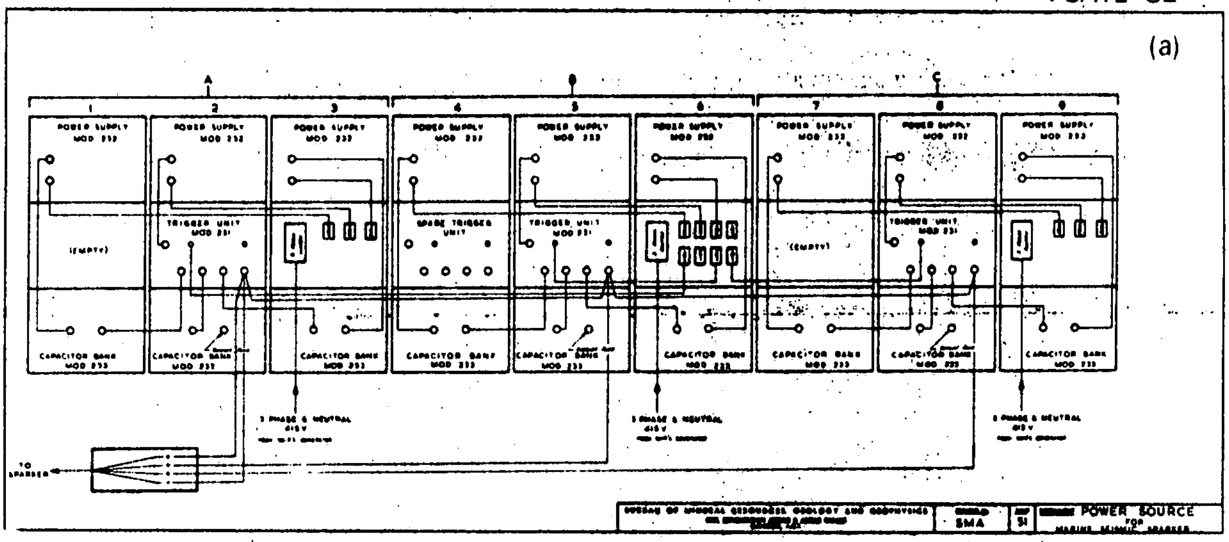
An early development was the use of an electric spark discharge as an under water sound source (sparker). The sparker was applied early in the piece to the study of sub-bottom structure by Woods Hole Oceanographic Institute (Knott and Hersey, 1956).

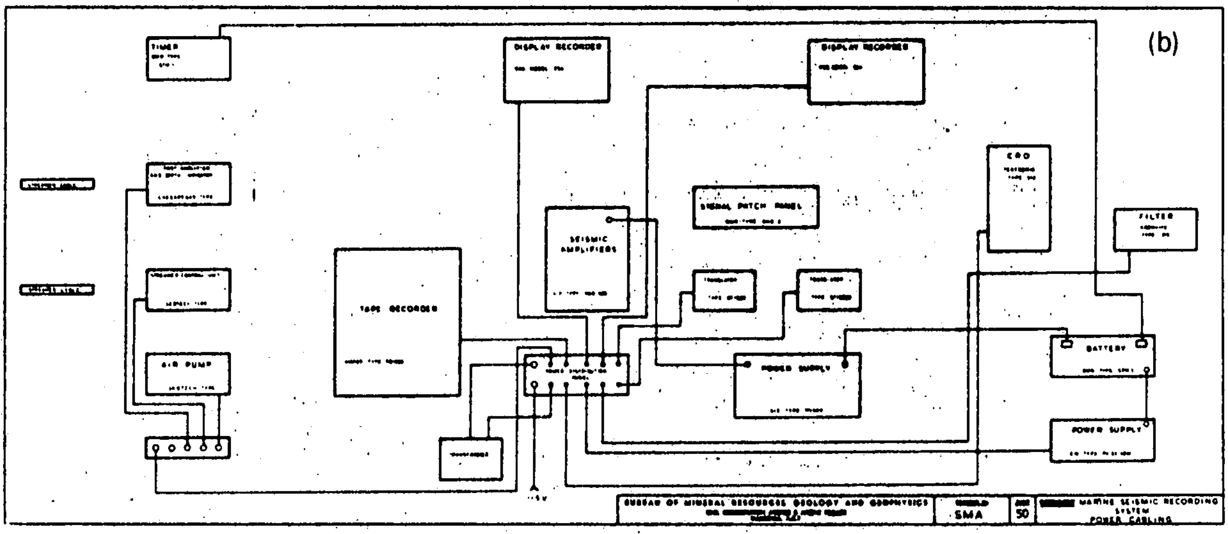
Penetrations of the order of 15,000 feet have now been recorded with high power sparker units. A number of other repetitive sources have been developed such as the air gun. The air gun produces a low-frequency pulse by releasing compressed air confined in a towed chamber which is submerged in the water. Other repetitive sources are the gas gun, the gas hammer (Dynoseis), the gas sleeve (Aquapulse), the vibrator (Vibroseis), the caged charge (Flexotir) and the exploding wire (Wassp) - see for example Ocean Industry, May and June, 1968.

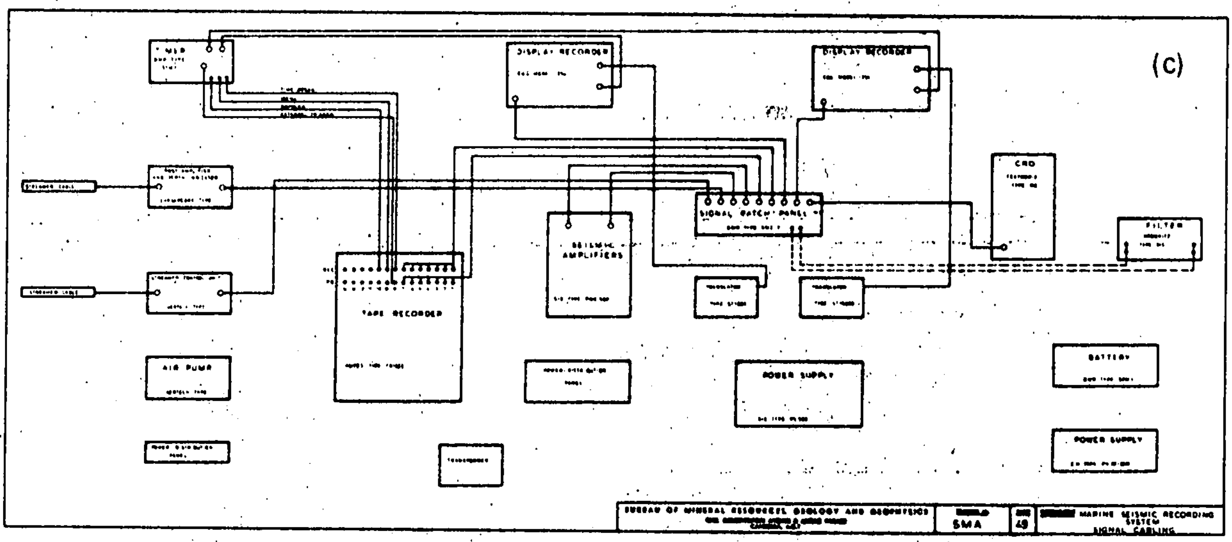
A 21,000 Joule sparker energy source will be used during the 1968 survey. The seismic energy will be detected on a six channel hydrophone streamer. The leading hydrophone will be towed 1000 feet behind the source and the other hydrophones will be at 600 foot intervals behind. Also,

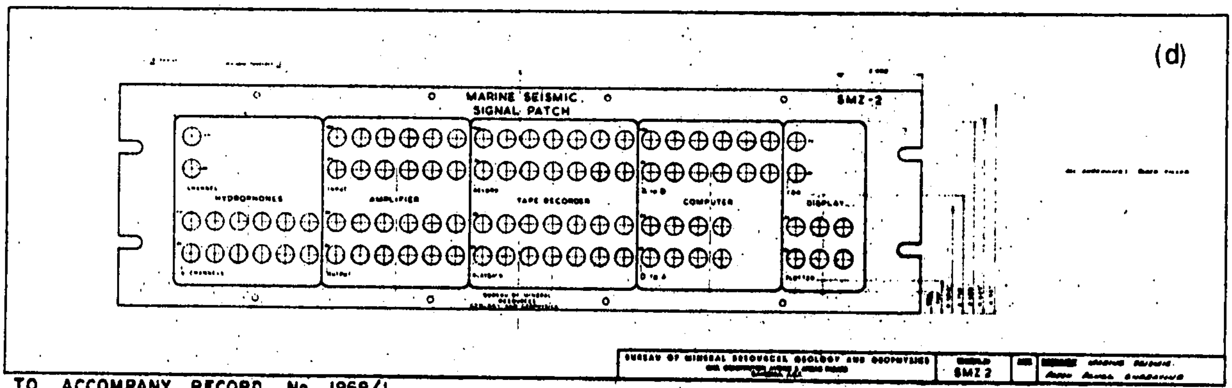


9 ELECTRODE SPARKARRAY









TO ACCOMPANY RECORD No. 1968/1

G85/2-2A

a single channel streamer will be towed to obtain high resolution shallow information. The hydrophones will be towed at depths between 25 and 35 feet. The hydrophone outputs are amplified by preamplifiers within the streamers and then by seismic amplifiers on board ship. The amplified outputs from the leading hydrophone of the six channel streamer is recorded on a facsimile recorder to 2.5 or 4 seconds. The shallow information is recorded on a second facsimile recorder to 0.8 second. All channels are recorded on a 14 channel magnetic recorder.

The boat will travel at a speed of about 10 knots. The interval between shots will be normally adjusted to just greater than 4 seconds to give an exact distance between shots of 75 feet. The adjustment will be automatic by an output from the sonar Doppler navigator. Distances between shots of 50 and 100 feet may also be used.

Energy Source - The sparker system used by the BMR was developed and manufactured by Edgerton, Germerhausen and Grier (E G and G). It uses an array of sparkgaps to increase the power and low frequency content of the pulse. A sketch of the sparkgap array and a schematic diagram of the power source for the array are to be found in plates C1 and C2 respectively.

The total system is a threefold system comprising three identical subsystems. Each sub-system comprises four basic components which are power supply, capacitor bank, trigger unit and transducer. There are three power supplies, model 232, three capacitor banks, model 233, and one trigger unit, model 231, to each sub-system. One sparkgap array, E G and G model OC402, comprises the transducers for all three sub-systems and a mounting frame. A heavier modified version has now been provided by BMR. The model 232 power supply works off 110 or 220 Volt AC at 50 or 60 Hz and requires a mean 2000 Watts in operation. The model 233 capacitor bank has a capacity of 320 micro Farad which at a voltage of 3500 Volts stores an energy of 2000 Joules. The model 231 trigger unit contains a 160 micro Farad capacitor bank which stores an energy of 1000 Joules; it also contains a sparkgap modulator which switches the current from the total capacitor bank to the transducer. The transducer consists of three electrodes at the corners of a triangle of 6 inch side. The transducers are mounted inside a triangular tubular stainless steel framework of which the longitudinal members are at the corners of a triangle of 12 inch side (see Plate C1). The framework is connected to the common side of the capacitor bank outputs and forms the other common electrode for all the sparkgaps. The three transducers from the three sub-systems are at intervals along the framework and are separated by about 2½ feet.

The following is a brief description of the operation of the system. The power supplies provide high voltage DC at 3000 to 4000 Volts to the capacitor banks. A trigger pulse, keyed from the recorder unit, causes the sparkgap modulators in all three sub-systems to become conducting simultaneously. The capacitor voltages are applied to the electrodes of the transducers. Arcing takes place through the sea water to the tubular steel frame. The capacitors discharge through the transducers. The total energy available to each transducer is 7000 Joules, making a total of 21 000 Joules to the total threefold array.

The power available and therefore the number of power supplies determines the maximum repetition rate. A perfect power supply could deliver only half the input power to the load. Three power supplies, model 232, have a total input power of 6 kilo Watts. The formula recommended by the manufactures is:

minimum firing interval

$$= \frac{1}{\text{maximum repetition rate}}$$

$$= \left(\frac{\text{total energy stored}}{\text{half power input}} \right) \times 1.6$$

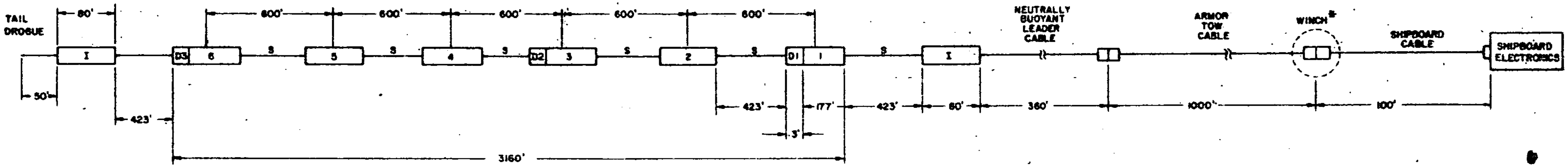
For each sub-system this becomes

minimum firing interval

$$= \left(\frac{7000 \quad (\text{Joules})}{3000 \quad (\text{Watts})} \right) \times 1.6$$

$$= \quad 3.7 \text{ Second}$$

The equipment to be provided by BMR includes a fourth trigger unit, model 231, which is not normally connected and is intended as a spare. Spare power units and capacitor banks are not supplied but each group of three may be isolated while repairs are carried out. The power supplies and capacitor units are mounted in 9 racks each of which occupy about 7 square feet of floor space (30" x 30"). Air conditioning or forced air ventilation is required to prevent overheating. The power units should preferably be installed separately from the recording equipment and, in



I VIBRATION ISOLATOR MODULE
S NEUTRALLY BUOYANT SPACER CABLES
1,2,3,4,5,6 HYDROPHONE SENSOR STATIONS
D1,D2,D3 DEPTH SENSOR SECTIONS

*WINCH NOT SUPPLIED BY CIC

FIGURE 1 SEISMIC STREAMER CONFIGURATION

(a)

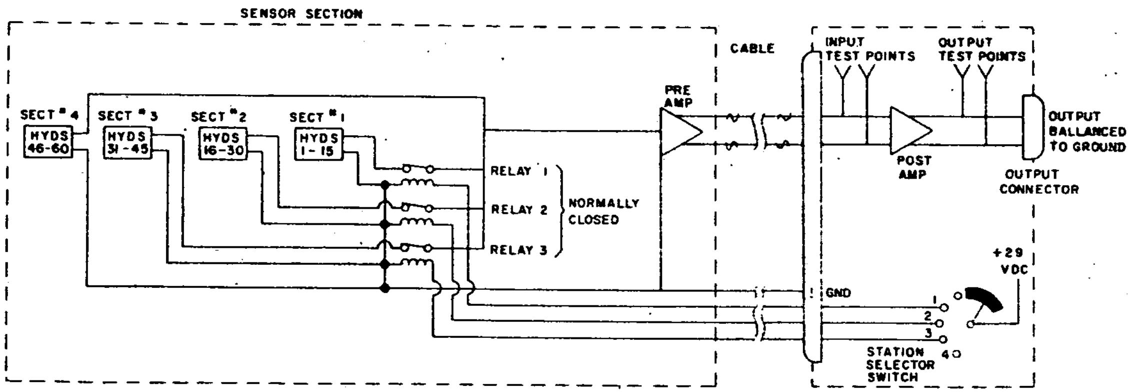


FIGURE 2 SIGNAL FLOW SCHEMATIC OF A TYPICAL STATION

(b)

PLATE C3

order to keep the leads supplying current to the electrodes to a minimal length, as close as possible to the boom from which the sparkarray is towed. Accomplete set of cables is supplied with the equipment. A generator of 35 KVA is required. It is thought best to reserve a generator for the spark system alone because of the pulsed nature of the loading. It is essential that an emergency reserve power source be available.

It is thought that the sparkgap array, or transducer fish, should be towed at a depth of about 30 feet. During the 1965 and 1967 surveys, the fish was towed at a depth of 10 to 15 feet. In order to attain greater depth without lengthening the leads the fish has been redesigned by the BMR. It will be made of heavier material and will be fitted with an elevated towing attachment, variable weight and depressing fins. Plastic tubing should be carried on the boat to attach to the sparkarray to monitor the depth. This tube may be linked to the Geotech pneumatic depth sensing system described in the section on hydrostreamers. Two arrays E G and G. model OC 402, will be provided as emergency spares. Two 100 meter transducer cables are supplied and additional lengths are available if required.

Hydrophone Streamers - The main hydrophone streamer to be used on the 1968 survey is a six channel neutrally buoyant cable built by the Chesapeake Instrument Corporation (model 23). Acceleration cancelling hydrophones are encased in an oil-filled flexible housing. A sketch of the cable configuration is shown in Plate C3A. A signal flow schematic for a typical channel is shown in Plate C3B.

The six sensor stations are each 3 inches in diameter and 177 feet in length. The sensor stations are separated by 423 feet of one and one quarter inch diameter, neutrally buoyant, spacer cable. At the forward and rear ends of the streamer there are 80 foot, 3 inch diameter "dummy section" vibration isolators, separated by 423 foot neutrally buoyant spacer cables from the first and last sensor stations. The dummy sections and spacer cables decouple the tow cable and drogue motions from the hydrophone sensors. The total length of cable is about 4200 feet. The tow cable consists of 1000 feet of counter-wound double-armour cable and a 360 foot neutrally buoyant leader.

Each sensor station has 60 hydrophones (model PC-100) at 2.35 feet spacing. These are wired in parallel in 4 groups of 15; 46 through 60 are permanently connected to the preamplifier; 31 to 45, 16 to 30 and 1 to 15 are normally connected to the preamplifier but may be disconnected separately by relays activated from shipboard. The active length at each station may thus be reduced in steep dip areas. All sensor stations are identical. The flexible housings for these active sections are made of nylon reinforced neoprene hose which carries the towing strain and has a breaking strain of at least 10 000 lb. The compressibility of the hose material matches that of sea water, so that acoustic matching is achieved. The sensitivity of the hydrophones is about 1 millivolt/microbar independent of number of hydrophones and over a bandwidth of 6Hz to 3kHz. Manufacturer's specifications state that the towing noise at a speed of 10 knots is less than the ambient ocean noise at frequencies down to less than 50Hz.

Aft of 1, 3 and 6 sensor stations there are depth sensor modules. Their outputs are indicated on meters on shipboard and they have a range to 100 feet depth.

The mixture of oils with which the six sensor sections and the two dummy sections are filled is designed to make them neutrally buoyant or slightly positively buoyant in seawater. The eight spacer sections are designed to be slightly positively buoyant. One pound lead sheets are attached to the spacer cables to trim the streamer to neutral buoyancy. The depth at which the cable streams is determined by the length and weight of armoured tow cable which is let out.

At 10 knots the cable drag is 3/4 lb per foot. The axial strength of the spacer cable is 6000 lb. The total drag amounts to about the safe limit of stress the cable can take. The cable should not tow a heavy buoy which would float if the cable parted, nor should it tow a depth controller such as the CONDEP. A very light buoy attached to a long light rope, presumably equal in length to the greatest expected depth of water, is recommended by Chesapeake. Such a buoy could house a beacon.

The second hydrostreamer, towed for the purpose of recording shallow information at high resolution, is the model 24257 manufactured by the Geotech Division of Teledyne Industries. It has one 40 foot length active section which contains 25 Geospace MP-7 crystal element hydrophones spaced 1.5 feet apart and connected to a preamplifier. In addition, a separate set of six hydrophones 1.5 feet apart in the centre of the active section is connected to another preamplifier. The 10 or 40 foot active sections can be selected by switching on the ship. The active section is encased in a 1 1/4 inch diameter oil-filled PVC tube. The depth of the active section may be monitored and it may be controlled pneumatically with a control system on the ship (Geotech Model 25643). The depth is measured by measuring the pressure in a tube, attached to the active section and open at the bottom, which is pumped with air until the pressure does not increase further. The system has a frequency response of 35-2500 Hz. The tow cable is 600 feet long. The system is designed for towing speeds of 3 o 10 knots.

A third hydrostreamer is carried as a spare for either of the other two. It is a Towflex, model 12, manufactured by the Chesapeake Instrument Corporation and is similar to that used for the Bureau's 1965 survey (Smith, 1966). Its single active section is 170 feet long and contains six Chesapeake PC-100 pressure compensated, acceleration cancelling hydrophones spaced at 30 foot intervals in a 3 inch diameter, oil-filled hose. The hydrophones are arranged to provide bottom directivity in the region of 75Hz. The frequency response is fairly flat from 3kHz down to 50Hz; below 50Hz it falls off with a slope of 6 dB per octave. An impedance matched preamplifier is mounted in the active section. The active section is neutrally buoyant and is towed by 400 feet of neutrally buoyant cable and 800 feet of 2000 pound breaking strength tow cable. A 20 foot isolating section decouples the active section from the tow cable. On the 1965 survey a similar cable gave good results at ships speeds of about 7.5 knots, but increases in this speed resulted in serious noise increases (Smith, 1966). On the 1967 survey the cable gave fairly good results at 10 knots but there was a several dB increase in noise from 8 to 10 knots. Over areas of particular interest ship's speed was reduced from 10 to 8 knots.

Recording Equipment and Timer - The outputs from the preamplifiers in the six-channel streamer will be fed into an SIE model MU500 six-channel seismic amplifier unit, comprising six 7GA-1 amplifiers and three dual DHC-1 and DLC-1 filter units. The amplifier outputs are recorded on six channels of an Ampex, Model FR1300, 14-channel type, magnetic recorder which can record in either direct or FM modes. FM recording will be used. The magnetic tape is 1 inch wide and comes in 3600 foot reels. Tape speeds available are 60, 30, 15, 7½, 3 3/4, 1-7/8 and 15/16 i.p.s. A speed of 115/16 i.p.s. will be used for this survey. The output from one channel, which can be selected, will be recorded on an EG and G. model 254 facsimile recorder. This recorder records in a variable density form on a wet electrochemical sensitive paper. The recording head is a helical wire mounted on a revolving drum which presses against a steel blade electrode. As the helix wire electrode revolves, its contact point with the steel blade electrode sweeps across the paper. The sweep time across the paper is switchable to 2.5 or 4 seconds. The output of the single channel, high resolution streamer will be recorded on another channel of the Ampex tape recorder. It will also be displayed on a second EG and G., model 254, facsimile recorder, with a sweep time of 0.8 second. The model 254 recorders have been modified to a triggered, one shot, mode of operation by the use of stepping motors. The sweeps on the two recorders may be triggered at the spark instant or at preset delays after the spark instant. The delays are preset by s separate controls for the two recorders and are variable in 0.1 second steps up to 10 seconds. These delays allow sub-bottom section under deeper water to be recorded at the normal sweep speed.

The paper speed control has a multi-rotation position indicating dial. The paper drive only operates when the sweep is operating and there will therefore be one paper drive step per shot. Since the distance between shots is controlled, by an output from the sonar Doppler, to be constant, the horizontal scale on the seismic section will be automatically controlled to a constant distance scale. However, when the sweep speed is changed the paper speed will be affected in the inverse ratio. It is therefore necessary to have a calibration chart for the paper speed control with separate calibration curves for the 4.0 second and 2.5 second sweeps on the one recorder and for the 0.8, 4.0 and 8.0 second sweeps on the other. (The 4.0 and 8.0 second sweeps are required for refraction recording - see next section).

Also housed with the recording equipment is the BMR Timer, model STM 1. This unit provides time marks for all recorders, trigger pulses for the seismic sparks and pulse trains necessary to drive the stepping motors. Seismic trigger intervals are available from 2 to 10 seconds in 0.1 second steps or in intervals of distance equal to 50, 60, 75, 100 or 150 feet. Input to the timer is taken from the Rubidium frequency standard in the VLF navigation system. A pulse output with the pulse frequency proportional to speed is taken from the sonar doppler unit to a counter in the timing unit. The spark interval is then controlled so that the distance between sparks remains constant although speed may vary.

Operation - The continuous seismic profiling equipment will operate continuously. When the boat has moved 300 feet, the reflecting point for the second sensor will coincide with the reflecting point for the leading sensor at the earlier shot. This will again be true from second to third sensor and so on. It is therefore necessary, for the purpose of common depth point stack ng, to trigger the spark at distances which are integral parts of 300 feet. It is intended that a 75 foot interval be used. At a speed of 10 knots, an interval of 75 feet will correspond to a time between sparks just greater than 4 seconds. The ship's speed will be kept as high as possible consistent with safety and good seismic results. It is intended to operate at 10 knots all of the time.

2. Refraction Seismic

The refraction source will be 2 air guns each of 300 cubic inch capacity. These will be towed behind the boat at 30 feet distance and 30 feet depth. They will be triggered from the BMR timing unit at equal distance intervals. The simultaneous triggering of sparker and air gun will minimize the interference of the one with the other. Corresponding to the 75 foot sparker interval the possible air gun intervals are 150, 225 or 300 feet. At a speed of 10 knots these intervals will correspond to time increments of 9, 13 and 18 seconds or repetition rates of 6.7, 4.5, and 3.4 blasts per minute. Compressed air at 2000 psi will be supplied by two compressors each of 150 cubic feet per minute capability. This air supply will be sufficient to provide 6 blasts per minute. It is intended to use the highest possible repetition rate to increase resolution and to compensate for any poor traces.

Recording will be done by telemetery. A sonobuoy (model SSQ-41) will be dropped at the start of the refraction line. The sonobuoy comprises the following functional assemblies: hydrophone, sonic preamplifier, sonic amplifier, VHF transmitter, power converter, antenna and termination mass. Underwater sounds are detected by the hydrophone; its output, in the 10-500 Hz range, is amplified and frequency modulates the transmitter. The VHF signals are received by the receiver (model AN/ARR 26) on board the survey ship. The aerial on the sonobuoy is short; propagation is line of sight and may be interfered with by waves, on occasion. Maximum range expected is 15 miles. Source-to-sensor distance will be computed from the water wave time of travel. Any drift of the sonobuoy will thus be compensated. Power consumption of the unit may be switched so that the operational life of the battery is either 1 hour or 3 hours. It is expected that this switch will normally be used in the 3 hour position. The sonobuoys are self-scuttling after not less than 6 hours and not more than 24 hours in the sea.

The PMG's Department has authorised the use of the following sonobuoy frequencies: 162.25, 164.50, 165.25 and 166.00 MHz; these frequencies correspond to sonobuoy channels 1, 4, 5 and 6 respectively. The emission and power authorised are F2 and 1/4 Watt respectively. A condition of the approval is that HQ Operations Command RAAF, Penrith, New South Wales, is notified of the times and locations of usage and that approval may be withdrawn without prior notice on the request of the Defence Department. The number of sonobuoys made available by the BMR will be 50, 10, 10, 10 of channels 1, 4, 5 and 6 respectively.

The output from the receiving set (model AN/ARR 26) will be recorded on channel 11 of the 14 channel Ampex magnetic recorder and on the facsimile recorder which is normally used to record shallow reflection information. In order to obtain a 4 or 8 second sweep on the facsimile recorder, it will be necessary to change the drive motor and gear box assembly. This is a two minute operation. A delay of up to 10 seconds in 0.1 second steps may also be applied to the sweep. At 15 miles maximum source-to-sensor distance the water wave will have a travel time of 16 seconds. With 9 or 13 seconds between blasts it may be possible to time the water wave at the further distances on the second sweep; otherwise a rate of drift of the sonobuoy may be computed at the shorter distances and extrapolated to the greater distances.

The receiver (model AN/ARR 26) is designed for use on board an aircraft. The power supplies required are 400Hz, 115 Volts, 300 Watts, and 24 Volts DC. Two Hewlett Packard 24 Volt 50 Amp supplies will be provided by the BMR. One of these will drive a 400Hz inverter and will also provide the 24 Volts DC for the receiver. The other supply will provide the DC for the seismic amplifiers and the timing unit. There will be more than sufficient 24 Volt DC power available and all systems could probably run off one unit in the event of unit failure.

3. Testing of the Seismic Equipment

The operator should watch continually the seismic outputs on the two facsimile recorders to monitor the performance of the seismic equipment. He should check that the recording paper is running smoothly, free from wrinkles, that a good contrast is being obtained on the record and that timing lines are clear.

All signals in the system are brought to the patch panel (Plate C2D) where they are easily monitored. Each hour the operator should use the CRO to check:

- that the signals coming from all six channels in the Chesapeake cable, from the single channel Geotech cable and from the time break trace are at the correct level.

- that the seismic amplifier outputs are at the correct level.

- that all playback levels are correct.

At the end of each line the operator should switch in turn to each of the six channels in the Chesapeake cable and record at least ten sparks on the facsimile recorder. He should then switch to playback on each of the six channels in turn and again record at least ten sparks on each. He should check the resulting records for similarity. He should switch the Geotech cable output to playback and record ten sparks. Again he should check the resulting records for similarity.

It is required to test the dynamic range of the recording equipment. An oscillator signal will be recorded on the tape at 100% modulation and then at lower levels reducing in 10 dB steps down to -60 dB. The playback of this record will show when the signal-to-noise ration is unity. An oscillator is provided with the seismic amplifiers. This test will require a wiggle line recorder. Alternatively the same cycle of switching might be repeated several times by the timer and the presentation could be variable density. The test should be carried out daily.

It is required to check the head alignment on the magnetic recorder. This may be done by firstly scribing a fine line accurately at right angles to the length of the tape. The alignment of the resulting pulses on playback will show the alignment of the playback heads. If an oscillator signal is then recorded on all heads in parallel, the playback of this signal will indicate the alignment, of the recording heads. It should be sufficient to carry out this test once for all and then repeat it only if future work is done on the head banks. A multi-channel wiggle trace recorder will be used. The alignment of the traces on the recorder must first be checked.

4. Processing of Sections obtained with the Continuous Seismic Profiler

There are seven main stages in the processing of the marine seismic records. The contractor will be responsible for the first two stages only, but notes on the remaining five steps are included for the contractor's information. These steps are:-

(a) Copying of records on board ship for immediate interpretation.

(b) Transparent Xerox copying of the original plus titling.

(c) Six-fold stacking for removal of multiple reflections.

(d) Laser scanning for improvement of record quality.

(e) Reduction of records to optimum size for later reanalysis.

(f) Presentation of sections at a scale of 1:250,000.

(g) Microfilm storage for convenient data retrieval.

The reflection cross-sections recorded on the ship will be annotated with station position number at half-hourly intervals plus other relevant information, such as direction of traverse, time started and so on. Subject to commencement or end of a traverse the sections should be recorded in runs of convenient period and starting time, such as six hour period starting at 0000Z. Changes in course should be marked by a significant break in the continuity of the section and should be suitably labelled. The records are to be copied in short sections on a pressure (not roll feed) machine by dye line or other suitable process on board the ship. The period covered by the dye-line print should be an integra part of the main record length (e.g. 1, 2, or 3 hours). A one hour period would probably be the most convenient for this purpose.

The transparent Xerox copy of the original will be made on shore. The transparency will be reversed if necessary such that west or south is to the left on E-W and N-S traverses respectively. All recording parameters and relevant information will be noted on record labels provided by the BMR. These labels will be attached to the right hand end of the transparent copy.

Stacking of the six channel recordings made on magnetic tape will be carried out by the BMR, where it is considered necessary. It is expected that it will be done in real-time on digital equipment being bought by the BMR for this purpose. In future it is hoped to have the equipment on board the survey ship, but this year's survey results will be used partly for data improvement and partly as a dry-run for system de-bugging.

Laserscanning of selected records will be done within the BMR. Copies of the original or 6-fold stacked records will be made on 35 mm film for use in the laser scan equipment. The system will output the processed record section on 35 mm, which may then be used in later stages of processing.

The optimum size to which records should be reduced for later reanalysis in uncertain at the moment. It is expected to be in the region of 4:1 to 6:1 from the original record size. A reduction of 6:1 is approximately 1:250 000 scale and it is possible that the reduced section could be used directly in presentation at that scale.

Microfilm storage will probably be in the form of 35 mm aperture cards, rather than rolls of film. The highest possible reduction consistent with adequate resolution should be used to minimise the number of cards required.

The following outlines the problems and possibilities in stages (a) to (g) of part (1). All of these steps except (f) will require microfilming of the original and/or improved sections, possibly with subsequent enlargement for step (e). It would therefore be advantageous, both in man-hours and cost, to combine as many of these objectives as possible into a single operation.

A 35 mm film transparency of the original or stacked seismic record is required for laser scanning. To minimise loss of resolution, the reduced record section should occupy the full width of the film. The useable width on a 35 mm film is about one inch, so, as the paper record is about 12 inches wide, a reduction of about 10:1 is required. The recorder should be geared to produce about 15 inches of record section per hour. A single negative will then cover about one hour in time or ten miles in horizontal distance. Thus about 1600 35 mm transparencies will need to be taken for possible subsequent laser scanning.

The results are to be stored on microfilm at a suitable scale of reduction. It is likely that two parallel runs will need to be stored, one run with the untouched original sections, the other with the stacked, laser scan filtered sections. The form could be in rolls or aperture cards. It is felt that aperture cards are the best system. They can be comprehensively labelled, easily sorted and abstracted with no risk of damage by using dummy cards. Rolls are liable to scratching and a large quantity of data must be handled when looking at a particular section with consequent risk of mishap. Aperture cards would occupy more space, but as 1000 cards only occupy a volume about 12" x 8" x 3", the disadvantage is slight.

The transparency used in the laser scan apparatus has to be immersed in oil, so two copies of seismic section reductions will be required, one for laser scanning and the other for data storage. To maintain high fidelity in the copying, two separate transparencies of the original section must be made. The two copies can usefully be at considerably different scales.

The degree of reduction that can be used to speed up visual analysis without loss of resolution is uncertain. It will certainly lie in the range of 2:1 to 10:1 and is likely to be around 6:1, or a horizontal scale of 1:250,000. This ratio corresponds to a reduced record width of about two inches. If the BMR is prepared to go to 70 mm for the photography in stage (g), it is possible that stage (e) could be combined, with it. If photography is restricted to 35 mm film, microfilming and enlarging will be needed.

Should the photography from stage (d) be used in stage (e), enlargement of about 1600 transparencies would be needed, plus the cutting and taping together of the enlargements. Should 70 mm film of stage (g) be used, direct copying plus taping and so on would be required. This would be the most laborious and time consuming part of the processing, so any method that reduces it would be most useful. The scale of the laser scan section is fairly rigidly defined, but the microfilm scale is not too important as long as resolution of the enlargements is not impaired. If a 6:1 reduction is too poor for visual analysis there would be little justification for 70 mm photography in the microfilming because of the extra costs and effort involved. With 35 mm film a reduction of 20:1 seems quite feasible, and 30:1 may be possible. On enlargement to around 6:1, only 800 or possibly 500 enlargements would be needed, reducing the work involved to about one half, or possibly one third.

It is intended to present the seismic, gravity and magnetic results in the form of profiles on a single map at 1:250 000 scale. Usually the seismic sections are hand-drawn and show the major reflections and faults, and are annotated to draw attention to features not readily recognised at that scale. Should the photographic reduction to 6:1 show these features sufficiently well, it could be used directly in the presentation. The 6:1 transparencies could be attached directly to the map showing plotted positions and a ribbon profile map produced. The vertical scale would be about one second per inch so there should be little trouble with overlapping profiles as long as the traverse lines are reasonably parallel.

Should the 6:1 reductions be too poor for use in presentation, the hand-drawn sections drawn on board the ship will be used. It would still be most efficient, however, to provide the reductions for visual analysis in sections as long as possible, reducing the number of enlargements and the amount of handling required afterwards, i.e. producing them from 20:1 to 30:1 microfilm reductions rather than laser scan scale transparencies.

5. Processing of Refraction Sections

The refraction section will be copied on board ship for immediate interpretation; a transparent xerox copy will be made later on shore; all recording parameters and relevant information will be noted on record labels provided by the BMR; these labels will be attached to the right hand end of the transparent copies. All of this will be done by the contractor as for the continuous profiler sections.

Computation and interpretation will be done on board ship by BMR personnel as described in Appendix F.

On shore the sections will be microfilmed for storage on aperture cards, again by BMR.

REFERENCES

GEOPHYSICAL SOCIETY OF HOUSTON, 1968 - Sources of seismic Energy for Marine Exploration, Parts 1 and 2. Ocean Industry Part 1 - May, 1968. Part 2 - June, 1968.

KNOTT, S.T., and HERSEY, J.B., 1956 - High resolution echo sounding techniques and their use in bathymetry: Deep Sea Research, Vol. 4, pp. 36-44.

CAULFIELD, D.D., HOSKINS, H., and NOWAK, R.T., 1965 - Improvements in the continuous seismic profiler.

APPENDIX D

THE MAGNETOMETER SYSTEM

A continuous profile of the earth's total magnetic field intensity will be recorded using a model V4970 proton precession magnetometer manufactured by Varian Associates. The sensing head is in a water-tight unit which is 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 is presented on a 5 digit electronic counter, and an analogue strip chart recorder. It will also be recorded on one channel of the 14-channel Ampex magnetic tape recorder (see Appendix C). The magnetic data are accurate to ± 1 gamma (± 1 count) and the range of the magnetometer tuning is 20 000 to 100 000 gammas. Cycling time can be operated from an external source.

It is desirable that the sensitive periods of the magnetometer be inter-timed with the sparker discharges to avoid interference from that source. The magnetometer will also, then, be triggered through the seismic timing unit (see Appendix C) from the sonar doppler output. The cycling rate will probably be each 75 feet. This means that a time of about 4 seconds will probably be used for this survey. The analogue recorder produces a 5 inch chart and a scale of 100 gammas will probably be used (20 gammas per inch). The complete magnetometer comprises:

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.

The record obtained on the ship will contain the effects of diurnal variation and other fluctuations of the earth's field. To allow removal of these effects a monitor station will be established in the Broome area and operated by the contractor. For convenience this will be sited near the VLF monitor station (see Appendix E), although sufficiently far away from extraneous radio noise. The magnetometer to be used at the monitor station is a type manufactured by the Bureau and will be provided by the Bureau on loan to United for the duration of the survey. The magnetometer is a continuous recording type with a readout in inverse gammas. The reading has an equivalent one gamma accuracy.

MAGNETIC REDUCTIONS (1)

The ship's magnetometer readings will be digitally recorded at one minute intervals. The magnetic diurnal variation will be monitored by a magnetometer on shore. If digital recording is available for the shore magnetometer, values will be obtained at one minute intervals also. If not, generally ten minute values will be abstracted from the analogue records and one minute values obtained by interpolation. If proven necessary, additional readings will be taken to define significant variations. Regional corrections will be computed by interpolation from data at one degree intervals provided by the BMR.

Processing will be done by computer. The absolute values corrected for diurnal variation will be used to check traverse intersections, and should prove to be one of the most sensitive indirect methods. Tabulation of the one minute values should be made to aid the closure checking, and for these purposes it would be best to handle the data in blocks preferably 24 hours long as a days values could be output by the computer on a single page.

(Ship's Mean Value) = (Ship's Reading) - (Diurnal Variation)

(Anomaly Value) = (Mean Value) - (Regional Value)

It may be necessary to carry out least squares adjustments of the corrected values if closure errors are not small. However, it is expected that the diurnal corrections should be reasonably correct even at large distances from the monitor station. A magnetic anomaly value closure diagram must be made up to investigate this point.

The computed profile anomaly values should be sufficiently close together to meaningfully sample all disturbances on the ship's record. These disturbances are caused by diurnal variation (time dependent), local variation in anomaly values (position dependent) and course changes. Because of the comparatively low ship's speed of 10 knots, the diurnal variation and local anomaly features will have about the same period. It is therefore essential that the diurnal variation is effectively removed from the computed profile values. At a minimum, each cycle of variation should be sampled at least twice, on the peak and the trough. It is not expected that more frequent than one minute sampling will be needed as significant disturbances should exceed two minutes in period, or one third of a mile in wavelength at 10 knots.

To facilitate check ng of removal of diurnal effects and for use in the profiles at 1:250 000 scale at a later stage, the computer processing will include Calcomp plots of original values, diurnal variation and corrected profiles. It would be best to plot

(a) ships profile minus regional

(b) diurnal variation

(c) corrected profile

as there will be no systematic trend in any of the plots. The profiles must be inspected for faithful representation of significant features and adequate removal of diurnal effects in the corrected profile. If possible the time intervals should be converted to distance corresponding to the ships speed. The corrected profile may then be pantographed down to 1:250 000 or could perhaps be produced at that scale.

For the production of magnetic profiles on 1:250 000 map sheets, the station plots will have a straight line of best fit drawn through them to act as a baseline for plotting the profiles. If the deviation of the ships track from the baseline exceeds about four miles, the baseline will be broken into two or more linear segments. Where possible, the lines should be E-W or N-S if the original traverses were intended to be in these directions. The BMR drawing office will indicate where the baselines are to be drawn on a dyeline copy of the contractor's plotted position map at the time that the position map is approved.

The magnetic profiles are to be drawn through the computed profile values using the ships magnetic record where necessary. As one minute values correspond to about 1 mm at 1:250 000 scale for a ship speed of 10 knots, linear interpolation will usually be quite adequate. The values should be plotted perpendicular to the baseline at a scale of 200 gammas to 1 inch. An arbitrary baseline value should be adopted for each segment such that all values in the segment are above the baseline, the lowest value being just above the baseline. The profile should be drawn north of the baseline for all segments except N-S segments where it should be drawn to the west of the baseline. The value of the baseline should be noted, with the profile identification, along the baseline.

MAGNETIC REDUCTIONS (2)

Because of the uses of the magnetic data, some form of convenient preservation of basic data for later data processing is necessary. For example, tabulation of Ship Mean Values is required to aid closure checking, but regional corrections cannot be applied until positions are finalised. The following technique is recommended.

```
  READ SURVEYING, DAYNO
  N = O
  READ DAY, HOUR, MIN, SHIFT
2 IF (DAY EQ DAYNO) 1, 2
1 I = HOUR + 1  &  J = MIN + 1
  SHIPIV (IJ) = SHIPF
  N = NH N + 1
  IF (NEQ.1440) 3, 1
3 CONTINUE
```

SHIPF = Ships reading

SHOREF = Shore reading

SHIPIV, SHOREIV the equivalent in dimensional variable format

The process is repeated for SHOREF making interpolation to one minute values if necessary. The time may have to be computed within the program, depending on how the data is collected. It is necessary to determine the mean value at the shore station. As this is a function of time, mean values for each day must first be obtained and the secular variation determined before the tabulation of Ship Mean Values can be commenced. Therefore the data will have to be output from the above program.

```
e.g. PUNCH    SURVEYNO, DAYNO
     PUNCH    ((SHIPIV(IJ), J = 1.60), I = 1.24)
     FORMAT   (16F50)
     etc.
```

Then at a later date, after determination of the secular variations which will almost certainly be a linear function of time

```
READ SURVEYNO, DAYNO, SHOREMV             MV = mean value
READ ((SHIPIV(IJ), J = 1,60), I = 1, 24)  IV = instant value
etc.
SHIPMV(I,J) = SHIPIV (I,J) - SHOREIV(I,J) - SHOREMV
PRINT SURVEYNO, DAYNO, ((SHIPMV(I,J), I = 1, 24), J = 1,60)
FØRMAT (X,212, 3(20(5X, 2(4(3F5.0,X),X)/)/))
```

The above would supply the required tabulated output, and have the basic data in a form ready for plotting profiles. Time would be implicit in the format. One could then -

```
READ SURVEYNO, DAYNO, SHOREMV
READ ((SHIPIV (I,J), J = 1,60), I= 1,24)
etc.
READ DAY, HOUR, MIN, LAT & LONG
```

(from final position output; which would have either explicit or implicit format for time).

Regional values would then be obtained by interpolation with regard to position and converted to line (or the magnetic data converted to a position dependent format).

Then -

```
SHIPIAV (I,J) = SHIPIV(I,J) - REGIONAL (I,J)
TIME = 60.0 x HOUR + MIN
PLOT (TIME, SHIPIAV, 4) etc.
DV(I,J) = SHOREIV(I,J) - SHOREMV
PLØT (TIME, DV(I,J), ) etc.
AV(I,J) = SHIPIAV (I,J) - DV(I,J)
PLOT (TIME, AV, 4), etc.
```

If the ships velocity is fairly constant the Anomaly Value profile could be reduced to 1:250 000 and accepted as a position plot or otherwise it might be best to do the reductions in terms of position.

SHIPIAV = Ship instantaneous anomaly value

DV = Diurnal variation

AV = Anomaly value

APPENDIX E

THE NAVIGATION SYSTEM

To fully utilize the recent improvements in sea gravity meters, navigation control should be such that systematic errors due to inaccuracies in position and velocity are of the order of one milligal while short term relative errors may be as low as 0.25 milligal. In the area of the 1967 and 1968 surveys, this implies knowing the ship's position to within about a minute for the latitude correction, and its velocity to about 0.1 knot for the Eotvos correction. The requirement for reoccupation of stations is not so stringent in this reconnaissance type survey as would be the case in more detailed work. Navigation control is considered as having three main aspects:

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

It is convenient to discuss the navigation system under these headings. A fourth section is included on processing of navigational data. A list of navigational equipment is in Appendix A.

1. Geographic Position

Determination of position will be carried out primarily from satellite Doppler fixes at about 2 hourly intervals with intermediate VLF or LF radio fixes. Other navigational aids will be radar positioning from known objects, star fixes, Raydist and sonar Doppler.

VLF and LF Radio Fixes - Radio transmissions in the range 10 to 30 kHz (VLF), are propagated in a duct between the earth's surface and the ionespheric D layer and are affected by diurnal variations to a lesser degree than higher frequencies. The transmissions suffer little attenuation and have world-wide range. Transmitters which are stabilized in frequency to a high degree of accuracy may be used for navigation. The phases of two (or more) suitably oriented stations are measured by VLF tracking receivers which make phase comparisons of the received signal with a stabilized local oscillator. Phase differences are output to a graphic recorder.

The diurnal variation in transmission time repeats itself from day to day and drifts in a predictable way from month to month making correction possible and necessary. Correction must also be made for local oscillator drift.

There are three basic techniques for obtaining navigational information from VLF transmissions.

The first mode is absolute position determination from three OMEGA transmissions. Lane identification is established by the programed transmission of both 10.2 kHz and 13.6 kHz. Only four of the intended eight OMEGA transmitters have been established and this type of navigation is not possible at present in the survey area.

The second mode is relative navigation (range-range) where lane count is established by starting from a known point and finding new positions relative to that point, measuring phase changes in the two or more transmissions being recorded.

The third mode is differential (or co-location) navigation and is the same as the second mode except that a fixed monitor in the centre of the survey area measures variations in transmission times to be applied as corrections. Depending on the relative positions of transmitters and receivers the variations measured may be applicable with sufficient accuracy for distances up to a thousand miles from the monitor station.

Only limited data are presently available regarding the potential accuracy achievable throughout the world with OMEGA and other VLF navigational aids. Tests indicate that an absolute accuracy of 1-2 miles in position fixing should generally be possible in a geographical region where three or more OMEGA transmitters provide favourable coverage. Much of the presently observed error in position fixing accuracy arises from a lack of knowledge regarding the correct values to be used in propagation correction tables. These propagation corrections are published as tables showing the appropriate phase variations as a function of time of day, season, latitude and longitude.

The third mode using a fixed monitor station obviates the necessity for accurate phase prediction tables. It was therefore decided at the start of the 1967 survey to work in this mode.

The VLF and OMEGA stations recorded during the 1967 survey were:

GBR Rugby, England 16.0 kHz

NPG Jim Creek, USA 18.6 kHz

NWC Northwest Cape, Aust. 15.5, 19.8, 22.3 kHz
on successive weeks.

OMEGA (Haiku) Hawaii 10.2 and 13.6 kHz

OMEGA (Aldra) Norway 10.2 and 13.6 kHz

OMEGA Trinidad 10.2 and 13.6 kHz

Three TRACOR phase tracking receivers (2 Type 599Q, 1 Type 599G) are used on board the survey ship and at the shore monitor station. OMEGA transmitters are programmed on a time sharing basis. The Type 599Q receiver allows simultaneous phase measurement of four OMEGA transmissions, or the phase measurement of one non-OMEGA transmission. The Type 559G receiver measures the phase of one VLF transmission.

For plotting the VLF phase changes on navigation charts it is expected that the contractor will draw up a special set of charts. TRACOR have a computer program for computing the latitude and longitude values of the VLF isophase contours. Corrections are made for the ellipticity of the earth in the program.

Successes and failures experienced in monitoring the various VLF transmissions during the 1967 survey are described by V. Ingham.

Of the Omega transmissions, only Aldra was monitored successfully during the whole of the survey but even this transmission was noisy. The azimuth of Aldra made it suitable for determination of latitude. Loss of signal from Haiku varied from 3 hours per day in September and October, at the start of the 1967 survey, to 16 hours per day in December, at the end of the survey. Standing wave effects were observed on the Haiku signal between the hours of 1600 and 0600 GMT. A cardioid antenna will be used to cancel the reverse path signal during the 1968 survey. Haiku is well situated for determination of longitude. Good signal strength was received from the Trinidad Omega station. However, the value of these transmissions in a "Range-Range" determination were indeterminate because of the nearness of the transmitter to the antipode. VLF signals propagate with a greater attenuation in the westward direction and less in the eastward direction because of interaction with the earth's magnetic field. Thus at Darwin the shorter path is westward from Trinidad but transmission is attenuated more than over the longer eastward path. Mr. William F. Donnell, Senior scientist of TRACOR, has suggested that, by setting a cardioid antenna to null the westward transmission, it might be possible to use the eastward transmission, along with Aldra and Haiku, for a form of hyperbolic navigation.

Omega transmissions on 10.2 kHz proved unreliable and the 13.6 kHz transmissions were used throughout. The strong signal from Northwest Cape interfered with the weaker Omega signals. To reduce this interference the received signals were filtered by a low pass filter which produced an attenuation of 15 dB at 15.5 kHz and 20 dB at 19.8 and 22.3 kHz, the Northwest Cape frequencies; the attenuation at 13.6 kHz was small.

The VLF transmission from NPG on 18.6 kHz gives a longitude control alternative to Haiku. The signal was stronger than Haiku and the periods when signal was lost were somewhat less, but otherwise the transmission behaved in a similar fashion. A cardioid antenna will be required to discriminate against reverse path transmission. No input filter was required to discriminate against Northwest Cape during the 1967 survey. However, the present survey area includes the Northwest Cape station and signal strengths will be higher.

The VLF transmission from GBR on 16.0 kHz gives a latitude control alternative to Aldra. It was monitored during the first voyage of the 1967 survey in September and October and suffered very little from loss of signal. When it was monitored during the second half of the second voyage in November a good record was only obtained for about 12 hours per day. When Northwest Cape was transmitting with a power of 1 megawatt on 15.5 kHz it swamped the weaker GBR signal. A notch filter giving 25 dB attenuation at 15.5 kHz and 15 dB attenuation at 16 kHz improved the GBR signal-to-noise ratio but it was still poor. During the latter part of the survey it was preferred to monitor NPG and NWC for longitude control.

A further VLF station, NPM, Hawaii, 23.4 kHz, has been received strongly at Darwin, during the early part of 1968. This station has a higher frequency than Haiku and is closer than NPG and may not suffer from standing waves to the same extent. The higher frequency may allow better discrimination against Northwest Cape. NPM is an alternative station for longitude control.

The VLF transmission from Northwest Cape changed frequency every Tuesday requiring the computation of a new offset. The transmission was stopped for six hours each Wednesday for station maintenance. Fluctuations occurred in the apparent longitude obtained from this transmission when the ship was stationary. These fluctuations may have been caused by ground wave interference, due to the nearness of the transmitter. Other fluctuations may have been caused by the change of the path from all sea to land-sea. However, the loss of signal from the other VLF stations suitable for the determination of longitude made the use of Northwest Cape obligatory during the latter stages of the 1967 survey. Fluctuations due to propagation of other modes will increase as the transmitter is approached more closely. It is therefore doubtful whether the transmissions from Northwest Cape will be useful for much of the 1968 survey.

It is apparent that during the 1968 survey further input filtering will be required on VLF signals to discriminate against the powerful Northwest Cape transmission. It would appear that the discrimination should be increased by at least 20 dB on the 1967 performance, in order that reception should be effective at 100 miles from the transmitter. The fixed station at Broome will be 600 miles from the Northwest Cape and the transmission will be only a few dB greater than in the 1967 survey area.

A cardioid aerial system should be used at the fixed station to cancel backpath transmission from Haiku and NPG. Sufficient cancellation might be obtained with the one aerial as the azimuths of the two stations are similar. A cardioid aerial system should also be used on the ship. Since courses will be east-west and north-south, it appears possible to arrange a simple system.

The Omega filter in the non-Omega 599Q receiver will require to be replaced by a broad-band filter (letter to BMR from TRACOR dated 3rd April, 1968).

In the event that the Northwest Cape transmission is not usable it may be impossible to obtain a continuous determination of longitude by means of VLF transmission. It had been hoped that the Naval Wireless Station, Belconnen near Canberra, might transmit a stabilized LF signal at about 44 kHz. Although this will probably be done, it may not be in time for the start of the 1968 survey. However, provision is required to be made for the reception of this signal before the end of the survey.

The stabilized LF transmission from JG2AS/JJM6, Tokyo, Japan, on 40.0 kHz may be useful as a backup to the VLF in determining latitude. Provision will require to be made on one of the non-Omega receivers for the reception of this signal. This will involve the use of a harmonic of the local oscillator (letter to BMR from TRACOR dated 3rd April, 1968).

It may be expected that random variations in these LF signals may be greater than in the VLF signals. However it is intended that tests be carried out by the BMR prior to the survey on repeatability from day to day and place to place of the variations.

Satellite Doppler - the satellite Doppler system was not released in time for the 1967 survey. It should give an increase in accuracy to position fixing for the 1968 survey. According to Newton the error in computed position should be only a few hundred meters and possibly better than 200 meters. Guier states that with three operational satellites a fix should be obtained on average about once every ninety minutes.

Measurements with the satellite Doppler should be continued when the ship is stationary to obtain a measurement of the accuracy of the method and to measure any systematic error which might require to be applied as a correction.

Radar - A Kelvin Hughes Type 17 Radar was fitted in 1967 to assist in navigation. The range of the set was better than 20 miles and enabled many fixes to be obtained.

Expendable radar reflector buoys were laid at intended traverse intersections and when a 90 degree course change was to be made. Unfortunately success was not generally achieved in the early stages of the survey in relocation of the buoys. The failure of the buoys were due to:

- the initial faulty design of the mooring lines
- strong currents in parts of the Timor Sea
- a great depth of water at some positions.

Improvements were made to the design of the buoys and the dropping procedures during the survey and a high rate of success was then achieved. The buoys were equipped with radar reflectors and could be picked up at ranges of four to five miles.

It is intended that intersections and major course changes be buoyed where possible during the 1968 survey. On the north-west edge of the survey area the large depth of water will prevent the use of buoys.

Again fixes will be taken on known features. Radar reflectors might be put at surveyed positions on the coast to aid such fixes.

Sonar Doppler - the sonar Doppler equipment is more fully discussed under ship's speed. However, integrated outputs of fore-and-aft and athwartships velocities give relative position.

Star and Sun Fixes - these will be done regularly as thought best by the Chief Navigator and the Department of the Interior surveyors on board.

Raydist - a Raydist system is in use by Burmah Oil Company of Australia Limited, operators of permit to explore No. 213H. The system will be made available for use on the BMR survey and a receiver and operator will be put on board the survey ship by Burmah.

The Raydist system will provide continuous accurate positioning during daylight hours. The careful use of Raydist can establish position to within a few yards, however, under normal circumstances this may require the use of an aircraft to establish correct lane count at the start of a new day. To determine the lane count, position would require to be determined by other means to within a few hundred feet: this may be possible with satellite doppler.

This most accurate means of positioning should be used on all north-south tie lines and, as far as possible, at other important position checks such as the tie points on the east-west lines.

Trouble may be experienced with sky-wave interference.

Remarks - Although satellite doppler and Raydist are being used on this survey and will give an increased accuracy to position determination, it is wished to evaluate the "VLF plus sonar doppler plus radar" system.

V. Ingham, surveyor with the Department of Interior, who took part in the 1967 survey, concludes that the root mean square error of the VLF geographical positions may not be greater than one mile: the fact that the average gravity mis-tie was just over 2 milligals supports this conclusion. However, a statistical analysis of VLF geographical positions relative to true location was not possible because of lack of accurate data. During the 1968 survey satellite doppler and Raydist will give a large amount of accurate data for separate analyses of both VLF and sonar doppler systems.

2. Ship's Azimuth and Speed

The ship's secondary navigation system will be a sonar doppler navigation system working in conjunction with the gyro compass. The principal use of this system is for obtaining the ship's true speed and course.

The gyro compass will give the ship's azimuth probably to an accuracy of $\pm\frac{1}{2}$ degree.

The principle of the sonar doppler 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. The pitch, roll and heave of the ship and additional, unwanted motions of the ship with respect to the bottom are problems. 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.

This system operates in water depths as great as 600 feet, below which it operates from backscatter, giving ship's speed relative to the water mass at about 600 feet. Currents at this depth should not be too great on the continental shelf.

The system to be used will be one of two similar systems, either the Marquhardt Model 2015 or the Edo DSNS. In earlier CW systems cross-feed from transmitter to receiver reduced the dynamic range of the instrument. The above instruments use pulsed transmission to overcome this defect. They also use the same transducers for both transmission and reception. Tracking filters sort out the reflected signal from the noise in the Doppler signal. Trouble has been experienced with searching out the very low Doppler frequencies going through zero which occur in the measurement of the low athwartships velocities. It was suggested by the contractor for the 1967 survey, United Geophysical Co., that angling of the pairs of beams at 45° to the centre line of the ship might solve the problem. The Edo system measures temperature and salinity of the water and compensates. The Marquhardt system corrects for the temperature but it is not known whether it corrects for the salinity. The Marquhardt system indicates by lighting a globe that reflections are occurring at the bottom. This facility may be provided by Edo.

Edo has proposed that the transducer's be mounted in a "fish" which would be towed by the ship. Two advantages of this system are, firstly, that there would be less disturbance in the deeper water in which the fish was travelling and, secondly, that the survey boat would not require to be dry-docked to mount the transducers. It is not known at present how the attitude of the fish would be determined.

The accuracy of measurement of velocity is dependent on the accuracy of the gyro compass. With a Sperry Mark 14, which has an accuracy of ± 0.5 degrees, Edo claims an accuracy in velocity determination of 0.08% along track and 1.75% cross track. These accuracies would satisfy the specified requirements of the gravity work.

3. Relative Position of Lines

In 1967, for the purpose of making gravity loops, a number of tie-lines were run across the primary traverses. The primary traverses were mainly east-west, 9 nautical miles apart, with north-south tie-lines every 2 degrees of longitude. It was required that the tie points be established with as great an accuracy as possible. Radar reflector buoys were dropped at intended traverse intersections but only a limited success was had in relocating these buoys for reasons already mentioned.

The re-occupation of tie points served to check the accuracy of the navigation system and in particular the VLF system.

In 1968 traverse intersections will be buoyed where possible, i.e. in water depths to 1000 feet. In addition, tie points should be established by the most accurate navigational means available. In particular, north-south tie-lines should be run under the control of Raydist if possible. In most cases it will not be possible to place buoys at traverse intersections towards the western ends of primary traverses, because of the greater depth of water. If minor reorganisation can ensure that these points will be occupied under Raydist control then this should be done. Radar may be useful at inshore intersections.

4. Testing of the Navigational Equipment

When the ship is in Broome harbour, at the start of the survey, between cruises and at the end of the survey, the following tests will be carried out:

- A comparison will be made between VLF receivers. The one good quality transmission will be recorded on all three receivers. Any differences measured will indicate differences in the individual receivers. This test has detected a previously undetected fault in a frequency synthesizer. The test should be carried out on both shore and ship installations.
- A phase comparison will be made between the Rubidium Frequency Standards in ship and shore installations. The Sulzer Laboratories Crystal Oscillator, model 5B, will be compared against the General Technology Rubidium Frequency Standard on board ship using the Sulzer Linear Phase Comparator, model 1. The Crystal Oscillator and Linear Phase Comparator will be transported to the shore monitor station where the Crystal oscillator will be compared in phase against the Rubidium Frequency Standard.

Measurements with the satellite doppler should be continued when the ship is stationary to obtain a measurement of the accuracy of the method and to measure any systematic error which might require to be applied as a correction.

5. Processing of Navigation Data

On the 1967 marine geophysical survey, the determination of position was based upon a combination of VLF observations, astro and land fixes, and buoy intersections. An intuitive assessment was made of the relative reliability of each observation, and the data weighted accordingly. This included the rejection of dubious fixes and intersections as well as poor VLF fixes.

Position fixes extracted from the VLF data at half-hourly intervals were plotted against time, treating latitude and longitude as independent parameters. Smooth lines were drawn through the observations, with times of course and speed changes denoted as breaks in the slope of the line. The smooth lines were nearly always drawn as straight line segments for the longitude values. The lines were then adjusted to the weighted astro and land fixes, ensuring that the position of an intersection had only one value.

Significant variations of observations from the smooth line were investigated further to see if any explanation could be arrived at. Standing wave and diurnal effects were eliminated as much as possible. Waves in the positions determined using NWC were ignored as they were believed to be caused by sky-wave interference effects close to the transmitter. Standing wave effects were removed by drawing mean lines through the quasi-periodic lane count plots. Standard diurnal variations were determined at the shore monitor and were assumed to be the same at the ship's position and corrected accordingly. Drift of the ship's atomic frequency standard was determined by comparison of the VLF determined positions with astro fix values against time.

On the 1968 survey, data will be collected in a manner facilitating later computer orientated reduction. This will require some changes in the present method of data collection and navigation. There are some features of the VLF system, not yet clearly understood, that do not allow immediate recognition of perturbations in the conditions of propagation. As it is essential that the ship's position is accurately known on the spot, the navigation will be based on sonar doppler plus ship's heading with continual updating of position by satellite doppler fixes.

Such an approach will not only simplify preliminary on-board data reduction, but will also allow the data to be gathered in a more suitable fashion for computer reduction. VLF position determination will be carried out at times of satellite doppler fixes only to keep a check on VLF data quality and drift in the atomic frequency standard. This will maintain the VLF navigation system in a state of readiness should the satellite - sonar doppler system break down.

One of the objectives of the survey is the assessment of the VLF - satellite doppler and sonar doppler - satellite doppler navigation systems. Determination of the absolute accuracy of each system is required. A comparative study with regard to reliability, technical and operational difficulties and optimum modes of recording data is also needed.

Each system is discussed separately below, but it is useful to introduce some ideas and terms at this stage that will be used later.

The ship's movement during the course of the survey will give a network of intersecting traverse lines. As none of the navigational methods are exact, differing values will be obtained at traverse intersections, each of which is marked by a buoy. The VLF and sonar Doppler determined positions of a point will differ from that determined by a satellite Doppler fix. The network will therefore need to be adjusted to integrate the results. Objective adjustment and analysis of the results is required. The most common method of adjustment is by least squares, and this is the technique that will be used.

Position determination by VLF is probably good to $\pm$ 1 mile after all corrections are applied. Sonar doppler derived positions in deep water are influenced by currents which cannot be determined, so the overall accuracy is perhaps of the same order as the VLF system. Satellite doppler, radar and good astro fixes have an uncertainty of 1/4-½ mile. Therefore, relative to VLF and sonar doppler, these determinations maybe considered as exact or fixed, as any errors in them have negligible influence on the overall accuracy.

Significant events that take place during the survey are changes in course and speed, intersection of traverse lines, and astro, radar and satellite doppler fixes. It is convenient to call the corresponding points nodes. They can be usefully separated into two types, fixed nodes such as satellite doppler fixes which are relatively accurately determined (see previous paragraph) and upon which the network is forced, and free nodes such as traverse intersections whose positions are adjustable but with the degree of adjustment restricted by certain conditions.

Although objective analysis has been emphasized some intuitive assessment of data quality will still be required. After checking the satellite and other fixes, the consistent and reliable values will be adopted as fixed. Buoy intersection determinations will need to be checked for evidence of buoy drift, and so on. Each stage of data reduction must be rigorously inspected for detection and removal of errors, and this is often best done by inspection of analogue records.

Only then will the network be adjusted by least squares on a computer. The BMR will provide a computer program with which the least squares analysis may be carried out. The contractor may, if he so desires, make his own arrangements for computer reduction but the program performances and accuracy must be acceptable to the BMR. Further the input and output of the data must be presented to the BMR in a form suitable for subsequent input to other BMR programs.

Least squares analysis can be carried out on consistent data in any form. If errors in the data are both random and independent, then an assessment of observational errors and the accuracy of the final adjusted data may be obtained. The method adopted in 1967 considered latitude and longitude to be independent. If these values are computed from VLF data such an assumption is untrue, but the method is fairly straightforward and allows easy integration of data from many sources. With VLF as the main source of data, the least squares analysis should be carried out with respect to lane counts, errors in which are random and independent. These require other data such as fixes to be converted to lane count form, which can be done quite easily.

The method by which the positions of the nodes are determined is not relevant to the least squares analysis which is quite general. All that is necessary is that the data is consistent in form. It is expected that these positions will be derived from the VLF navigation system, but, should it break down, positions could be derived from ship's heading and sonar doppler for example. After suitable conversion this data can then be used in the adjustment phase.

VLF and Satellite Doppler - The VLF system records the lane count from various low frequency transmitters in centicycles at half minute intervals on an analogue record. Diurnal shifts in the lanes due to variation in ionospheric conditions and interference of short and long path signals downgrade the accuracy. Therefore a shore station is used to monitor the diurnal variation, but there is no way of determining the effect of standing waves on the monitor record. So it is absolutely essential that these standing waves are reduced to negligible proportions on shore by using directional aerials to reject the longpath signal. If the amplitude ratio can be reduced to - 26 dB, the error will always be less than one centicycle, or about 0.2 km. Keeping the error below 1 km would require a ratio of about - 10 dB. A figure somewhere between these values should not be difficult to achieve.

The continued movement of the ship defines standing wave effects fairly well should interference be significant. Therefore unless directional aerials on the ship can reliably reduce the phase errors, it would be better to record them in full along with continuous monitoring of signal amplitude. The errors can then be reduced to small proportions by applying corrections derived from the amplitude ratio and times of maxima and minima.

As many VLF stations as possible will be continuously recorded. Data redundancy will then enable statistical checks to be made on the quality of the results. It should also allow hyperbolic path difference techniques to be applied. This is simplified if the transmitting stations are on the same frequency, such as the OMEGA stations. North West Cape (NWC) will not be used because of sky-wave interference close to the transmitter and erratic frequency shifts.

There are difficulties involved with completely automated reduction of VLF data at our present state of knowledge. These include disruptions to lane counts caused by other transmitters of similar frequency switching on and off, periods of station identification and erratic frequency shifts of some VLF transmitters. The following assumes that lane count values will be taken from the VLF records manually after visual correction for such errors.

Lane count values will be abstracted at ten minute intervals corresponding to gravity station times. Values will also be obtained for every satellite doppler and other fix, and at traverse intersections and changes in speed and course. i.e. at times of all nodes. This will require hand computation of crossing times on both ship courses using the radar range and bearing to the buoy plus ship's speed on the original course with a cross-check through water depth. The shore station will also abstract ten minute values continuously, and the other position values when supplied with the necessary times.

Only satellite doppler fix positions will be reduced to latitude and longitude on board the ship. This will maintain the VLF, system in a sufficient state of readiness should other navigational systems fail. The ship's atomic frequency standard will also be continuously monitored using this data, and a progressive plot of the drift maintained.

The ship's amplitude records will be inspected and amplitude ratios and times of maxima and minima abstracted. It will be necessary to plot the positions of maxima and minima to ascertain whether or not they are caused by standing waves.

No further VLF data reduction will be done on the ship. This approach should simplify the navigator's task and enable the data to be collected in the most useful form. It must be noted that the proposed system requires continuous quality control of the data i.e. optimum receiver gain, continual inspection of lane count and amplitude records for recording quality and so on. All relevant information such as times and details of speed and course changes, alterations to receiver gain and loss of phase lock, must be meticulously recorded.

Station lane count values corrected for oscillator drift, diurnal variation and standing waves will be computed in the shore office, preferably by computer. Plots of lane counts versus time must be drawn up, and should include positions of all fixes and traverse intersections. Visual inspection for systematic errors and general data quality will be made. Any further corrections considered necessary will be applied. After this point, data reduction through to the final plotted station positions will be done by computer.

At this stage, the data will be in the form of a listing of station number, time, and corrected lane counts in order of time for the whole survey. It will be necessary to split it into runs between consecutive nodes, fixed or free. Node values will be repeated so that each run has a node at the beginning and end. Smooth lines will then be fitted to each run by least squares. Proper choice of free nodes should limit the polynomials fitted to first or second order. It is unlikely that a polynomial of higher than third order could be justified. These curves must then be inspected for mis-match at nodes, large discrepancies would suggest errors still remain in the data, or one or both of the lines are poorly defined. In theory, the fitted curves should be continuous, but small discrepancies will not significantly affect the results.

The smoothed lane counts will be used in the final least squares reduction, which will be done independently for each lane count. It is expected that the reduction will take place in three stages. First only the free nodes and one fixed node will be used. This will give an assessment of the accuracy of the VLF navigation system on its own. The second reduction will use the free nodes and half the fixed nodes. Alternate fixed nodes will be used in the reduction, and the values computed for the remaining fixed nodes will be compared with their true values. This will give the accuracy of the total system. Lastly, all nodes will be used to obtain the final adjusted values. If the number of fixed nodes is far in excess of the number of free nodes, the standard deviation of the adjustments should be equal to the accuracy of the final positions computed in the second stage. It is possible that evaluation of the relative accuracy of VLF and satellite doppler may modify the mode of reduction envisaged.

The final adjusted values will be used to compute latitudes and longitudes, which will then be fed into an automatic station plotting program for final map production. The station positions will also be used in computer reduction of the gravity values to Bouguer Anomalies. They may also be used to derive the eastward component of velocity. Errors in the Eotvos Correction are probably the major cause of errors in the Bouguer Anomalies. It would therefore be advantageous to compare the VLF derived velocities with values obtained by other methods. However, because of the high degree of smoothing applied to the VLF data, any small velocity variations will have been eliminated. The most accurate Eotvos Corrections would therefore be obtained from the sonar doppler system.

<u>Sonar Doppler</u> - The sonar doppler system determines the forward speed and sideways drift of the ship. It also provides the integrated total distance covered by the ship. When combined with the ships heading, it may be used to give position determinations entirely independent of the VLF system. It is expected that on-board navigation will be carried out in this manner, continually updating the ship's position by satellite fixes. The small jumps in the ship's course will probably not exceed $\pm$ 1 mile, so the results will be more than adequate for navigation and preliminary gravity reductions.

For final determination of position by this method, the predicted positions using one satellite fix will have to be adjusted so that the ship's course passes through the next satellite fix at the right time. This will require a small rotation and adjustment to the path length obtained from the integrated sonar doppler output. For small adjustments between fixed points, independent adjustments in latitude and longitude with proportional adjustments for intermediate points will be sufficient.

The system data outputs may be used to compute northerly and easterly components of velocity and integrated distance.

$$V_e = V_f \sin \Theta + V_r \cos \Theta \quad \text{..........(A)}$$

$$D_e = \int_0^T V_f \sin \Theta \, dt + \int_0^T V_r \cos \Theta \, dt \quad \text{..........(B)}$$

$$D_n = \int_0^T V_f \cos \Theta \, dt + \int_0^T V_r \sin \Theta \, dt \quad \text{..........(C)}$$

where V_e, D_e = easterly velocity and distance, D_n = northerly distance, V_f = forward speed, V_r = drift to starboard, Θ = ship's heading. Equation (A) maybe used to compute Eotvos correction directly as $E = 7.503 \cos \phi \cdot Ve$ ....(D)

where ϕ = latitude, E = Eotvos correction

An analogue computer could be built to carry out any of these tasks on-line using a suitably smoothed heading from the ship's gyrocompass, and outputs from the sonar doppler. The Eotvos correction could be applied automatically to the gravity meter output to provide observed gravity values. An additional correction for the time-constant of the gravity meter would also have to be applied. The latitude and longitude figures could be treated in an identical fashion to that proposed for the VLF system, the data adjusted and reduced by least squares.

Should these analogue corrections be applied on-board, it is important that the original outputs are recorded in case of failure, errors in equipment function and any recomputation thought desirable at a later stage.

REFERENCES

INGHAM, V., 1968 - Report on VLF-Omega Navigation. Geophysical Survey of Timor Sea for the Bureau of Mineral Resources. September - December 1967. Department of Interior Report (unpubl.).

NEWTON, R.R., 1964 - Everyman's Doppler Satellite Navigation System. Applied Physics Laboratory, The Johns Hopkins University, Report No. TG-590.

GUIER, W.H., 1965 - Satellite Navigation Using Integral Doppler Data. The AN/SRN-9 Equipment. Ibid. Report No. TG-690.

APPENDIX F

DATA COLLECTION AND REDUCTION

In the preceding appendices dealing with particular disciplines, separate outlines have been given of the processing required for the data from the various sources. In this appendix a comprehensive and more detailed discussion is given of the checking and processing of all data.

The one independent parameter common to all types of data collected is time. Should any dubious data need to be checked, the original records are looked up by date and time, and so on. Therefore, for convenience, the station numbering system should be based on time. Further, the system should be common to all forms of data, be it navigation, gravity, magnetic or seismic, for cross-correlation purposes.

Errors in measurement of gravity are distributed linearly between intersections in the network of traverses with the values of gravity at the intersections adjusted by least squares. Accurate location of the points of intersection is important. All available data must be used to check these locations.

The data gathering system is to be orientated towards computer reduction of all data. Only those analogue reductions necessary for preliminary study and analysis will be done on the ship. It is therefore essential that on-board data checks are carried out meticulously and continuously to ensure that the quality of the results is always maintained at the highest possible level consistent with the aims of the survey.

The preliminary data reduction on board ship of navigational, gravity, magnetic and seismic data will be at hourly intervals and allows an interpretation of results as the survey proceeds. It is required for three reasons:-

1. to see whether the data gathering techniques might be modified in difficult areas to assist reduction.
2. to see whether the survey program could be usefully supplemented in areas of special interest.
3. to allow immediate availability of preliminary results to interested parties.

With regard to the third reason, the maps produced on board will form the basis of progress reports to the BMR during the survey and they will be circulated with a short text (i.e. a final progress report) to a limited number of interested parties as a preliminary report shortly after the end of the survey.

Because of the requirements for reduction of data by digital computer, it will be advantageous to record original data digitally. A digital recording system has been provided by the contractor and it is intended to record gravity and magnetic outputs digitally. A list of other parameters which might with advantage be recorded digitally is given later under 'Digital Recording System'.

The final section of this appendix gives a detailed description of the steps required in the digital processing of all data.

The discussion below is therefore under the following headings:

1. Station numbering system
2. Location of traverse intersections
3. On board data checks:
   - Raydist
   - Satellite Doppler
   - VLF
   - Sonar Doppler
   - Gravity
   - Magnetic
   - Water depth
4. On board data reductions:
   - Navigational
   - Gravity
   - Seismic
   - Magnetic
5. Digital recording system
6. Proposed reduction techniques:

- VLF data reduction
- Preparation of data and least squares adjustment
- Velocity computation from VLF data
- Sonar Doppler reduction
- Preparation of data and least squares adjustment
- Comparison of Eotvos Corrections
- Merging of data from VLF and Sonar Doppler
- Preparation of data and least squares
- Bouguer Anomaly reduction
- Station plot and contouring
- Magnetic reductions

1. Station Numbering System

For the raw data to be acceptable to most of the BMR reduction programs, the station positions have to be identified by an 8-digit number. Combining both of these prerequisites, the station position number will be given by -

SSDDHHMM

where SS is the survey number, 01 to 99, assigned to the survey beforehand; DD is the survey day starting from 01 (should the survey be likely to run for more than 99 days, two consecutive survey numbers will be allotted e.g. day 87 0487HHMM; day 116 0516HHMM) and HHMM is the time in hours and minutes.

Data will usually be presented in the form;

station position number, time, observed parameters. The above numbering system will allow station numbers to be computed from the times so only time and observed data need be recorded. Using time as part of the numbering means that numbers can be allotted at one minute intervals should it be required, such as in the magnetic observations.

Normally, stations will be at ten minute intervals numbered directly from the time. However, when traverse lines intersect, two station numbers would be given to the same point. As the times of intersection on each track will need to be computed by hand using all available cross-checks, the observed parameters will have to be inserted into the data listing manually. These common points or free nodes will be given separate numbers starting from SSDD9001. A similar problem exists for the satellite Doppler and other fixes in the navigation system, which will be numbered from SSDD7001 and observed values inserted into the listings manually.

Time will be recorded in the form DDHHMM, where DD, HH and MM have the same meanings as before. Time is more conveniently handled within the computer in consistent units so the computer would calculate

$$\text{STNNUM} = 35 \times 10^6 + \text{DD} \times 10^4 + \text{HH} \times 10^2 + \text{MM}$$

$$\text{TIME} = \text{DD} \times 1440 + \text{HH} \times 60 + \text{MM}$$

2. Location of Traverse Intersections

The determination of the position of a traverse intersection will be particularly critical in the deep water at the western ends of the E-W traverse lines where it will be impossible to use buoys. A check through water depth is most useful where the depth is varying rapidly. The method would be most sensitive in determining the intersection on an E-W line. Regional magnetic gradients are about 10 gammas/mile N-S, so, if the accuracy of the ships readings corrected for diurnal variation is about 2 gammas, the magnetic results should be useful in determining the intersection on the N-S lines. Corrected observed gravity can also be used, but errors in the Eotvos correction reduce the usefulness of the parameter in this regard.

After determination of the intersection points as functions of time, all the differing forms of data will be adjusted by least squares, except for the magnetic results. It is expected that the errors in the magnetic results should only be a few gammas. However, should this prove untrue, least squares adjustment will have to be applied. Obviously, if the magnetic data has been used to estimate intersection positions, least squares adjustment would be meaningless.

3. On Board Data Checks

To facilitate data collection, the VLF system will be maintained in a state of readiness but little computation and plotting of positions will be done by this method. Some checks will have to be carried out with this in mind. Cross-checks between the various navigation systems will be used to assess accuracy as well as for internal quality control.

Raydist - It is desirable that the following checks should be carried out on the Raydist system. The actual arrangements are a matter of concern between Ray Geophysical and B.O.C.

1. A raydist fix should be obtained for every satellite fix possible. The relative error should be plotted to check the overall accuracy. A rectilinear latitude-longitude error plot should suffice.

2. Deviations that occur at nightfall should be inspected to see for just how much of the day Raydist can be used. Burmah Oil Co. believe that close to the net, reasonable values can be obtained 24 hours a day.

3. Errors should be checked against position in the network. There may be systematic errors with distance because of uncertainties in wavelength.

Satellite Doppler - The following checks should be made on the satellite Doppler navigation system:

1. Maintain cross-checks with other systems
2. When in one position for any length of time, obtain repeated observations. The system accuracy in the absolute sense should be found to determine systematic errors on the geoid or differences in the origin and co-ordinates used in the various surveying systems. Repeatability in terms of scatter should also be measured. Plots on rectilinear latitude-longitude co-ordinates would be the most useful way of showing the errors.
3. Every possible satellite fix should be obtained right from the beginning of the survey.

VLF - The following data checks should be made on the VLF navigation system:

1. A VLF fix should be made at the time of every satellite fix to maintain the system on standby. This will require the transmission of satellite fix times to shore and the return of diurnal values uncorrected for clock drift.
2. Bound up with (1) above is the determination of the drift of the atomic frequency standards. This will be done in three stages: ship and shore independently, and for the difference between them. (a) For the monitor station; the phase value for each of the transmitters will be measured at the same time each day, when the diurnal value should be fairly close to the same value. A plot against time should be made, and the drift rates relative to the transmitters determined.

(b) A similar approach should be made for the ship. The nearest satellite fix in time to the standard time in (a) should be used, and the difference between the predicted and observed lane count values plotted against time. Unless there are fairly large changes in position, the plot should be of the same quality as in (a) above.

(c) The difference between observed and predicted values of lane counts for each transmitter after correction for diurnal variation should be plotted against time for every satellite fix. This will give the drift in phase between ship and shore as transmitter drift will cancel out. It should also demonstrate whether or not the diurnal variation being applied is reasonable. If the diurnal correction is considerably different at ship and shore, a diurnal wave will be seen in the drift plot. This method when suitably smoothed will also give the best drift determination, as it should be little affected by seasonal variations in the ionosphere unlike (a) and (b).

3. The accuracy of the diurnal corrections will be tested mainly by 2(c) above. However, whenever the ship is stationary away from Broome, direct comparisons will be made. Also, the mean diurnal variation at the monitor will be determined by abstracting hourly values from the 10 minute listings and averaging these hourly values over a suitable period of time, 10 days say. Signficant deviations of the daily diurnal from the mean diurnal maybe local, so the plot from 2(c) will be inspected at such times to determine whether or not the same deviations occur at the ship. If they do, then almost certainly the deviations have been introduced in the diurnal correction, and the mean diurnal would be a better form of correction to apply. These tests should be carried out concurrently with the survey in case the method of data collection could be usefully altered.

4. Occasional checks at times of unusual phenomena such as the sudden shift in phase at dawn and dusk should be made, possibly against Raydist position fixes at short time intervals. If the shift can be reliably correlated with localized phenomena, such as LMT of sunset say, more accurate corrections may be applied to the data.

5. Progressive misclosure diagrams for the network in terms of lane count for each transmitter should be maintained. This will require the abstraction of VLF fixes for intersections of traverses, and calculation of the free node-free node interval in lanes.
6. The times of maxima and minima of amplitude should be plotted on the VLF charts at the corresponding positions to check whether or not standing-wave effects are present. The use of directional aerials should keep the effect small.
7. Check on return to port using the Sulzer clock.

Sonar Doppler - The following data check should be carried out on the sonar Doppler navigation system:

1. The errors in dead reckoning position at one satellite fix relative to the previous fix using sonar Doppler should be determined. This will give a reasonable assessment of the navigation (as opposed to position) accuracy. Large errors should be investigated. The most likely error would seem to be in bearing rather than distance travelled, if the claimed system accuracy is correct. Then a small rotation to the ships track should bring the D.R. position very close to the satellite fix position.
2. Should high currents be suspected, checks against other systems should be made if possible.
3. Average velocities should be checked against mean velocity between satellite fixes occasionally.
4. Approximate misclosure diagrams for northings and eastings should be maintained, as long as course changes are not very frequent.

Gravity - The following checks should be made on the gravity data:

1. Drift control of the gravity meter must be maintained at all times. Primary control will be readings at the wharf in Broome. Other values may be obtained on the trip from Brisbane to Broome. A further value about a fortnight after the end of the survey is stipulated. Lower order values will be obtained at intersections of traverses and these must be compatible with the primary control. This will require Eotvos Corrections to be computed for the times of intersection.

2. A progressive misclosure diagram must be maintained for the gravity network. Large errors should be rechecked. A standard deviation of misclosures of about 4 mgals is expected.

3. Periodic tests of the paper recorder scale value will be needed for the preliminary reductions.

Magnetic - The following check should be made on the magnetic data:

1. A progressive diagram of misclosures in the magnetic network should be maintained. This will require transmission of times of traverse intersections to shore and the return of the diurnal variation values. This should primarily check errors in the position of intersections. The absolute field values after correction should be the same on each track at the intersection point as well as misclosures being small.

Water Depth - A check should be made on water depths at traverse intersections. This and magnetic are the two most sensitive indirect methods for determining errors in the positions of intersection points. Note that the tidal variation is high near the coast lowering the value of the check, but such places are where buoys are more likely to be found again.

4. On Board Data Reduction

It is required to reduce survey data on board ship to produce maps and plots from stations at one hourly intervals.

Navigation - It should be possible to derive station positions, in these preliminary plots, mainly from satellite Doppler fixes. Interpolation between fixes may be assisted by VLF, sonar Doppler or EM log.

Gravity - The gravity data will be reduced at one hourly intervals using preliminary meter drift rates and positions and no misclosure corrections. Should the data indicate anomalies of interest of less than two hourly period (or twenty mile wavelength), then half-hourly values should be calculated for such areas.

The preliminary Bouguer anomaly values should be contoured at 10 mgal intervals and reproduced on a progressive Bouguer anomaly map at a scale of 40 miles to the inch. A copy of this map is to be provided with the progress report at the end of each cruise.

Magnetic - Similarly, one hourly magnetic values will be read off the analogue records, corrected for diurnal variation at the shore monitor, and plotted on a progressive map at 40 mile to the inch scale.

The resulting values should be compared with the regional magnetic values provided by the BMR to see whether or not there are significant departures from the regional values.

A copy of the magnetic map is to be forwarded with the monthly progress report.

Seismic - Computation and interpretation on seismic records will be done by BMR personnel.

Significant reflections will be followed on the continuous seismic profiles. Plotted sections at 1:250 000 distance scale and 1" = 1 second time scale will be produced and displayed on 1:250 000 map sheets.

Refraction events will be timed, and time-distance curves will be plotted. The refraction events will be correlated with reflection events on the continuous seismic profiles where possible, and dips will be measured on the continuous seismic profiles. Velocity information will be extracted, corrected for dip.

5. Digital Recording System

The system can record 10 analogue inputs and 3 digital inputs. The inputs are recorded in 6 character words up to a maximum total of 150 characters.

A considerable number of parameters could be usefully recorded for later digital processing. It is as yet uncertain whether or not suitable interfacing with the A/D converter will be available for all of these parameters. There is also uncertainty concerning just what outputs are available from the gravity meter and the sonar Doppler system.

It would be advantageous for further processing to record the data channels listed below in order of preference:

Time DDHHMM	1 channel	Digital
Gravity	1 channel	Digital
Magnetometer	1 channel	Digital
Sonar Doppler Forward and sideways dist.	2 channels	? Digital
Sonar Doppler Forward and sideways speed	2 channels	? Analogue
Gyrocompass	1 channel	Analogue
VLF Lane Count	4 channels	Analogue
? EM log	1 channel	? Analogue
? Water depth	1 channel	? Digital

6. Proposed Reduction Techniques

VLF Data Reduction

1. Punch up ship VLF lane counts and water depth, and shore VLF lane counts for every 10 minute interval from beginning of survey (? or cruise).

Ship: time, 4 lane counts, water depth

Shore: time, 4 lane counts

*N.B. There will be a maximum of four useable VLF station signals in the survey area. Time is DDHHMM.

If the data sheets can be easily joined to form one source document, the data will be punched on one card, giving about 13 000 cards (? about 11 000 cards if days in port are ignored). However, the possibility of punching up two sets of cards should not be disregarded.

2. Punch up lane count index corrections a_i and drift rates b_i and the time periods during which they are to be applied.

*N.B. a_i are the differences between ship and shore receivers at the commencement of the survey when the boat was at the wharf in Broome plus the theoretical lane count values for that point. b_i are the drift rates in the lane counts, caused by relative drift of the ship and shore frequency standards. The b_i should be the same for all transmitters of the same frequency, and are determined on board the ship by comparison of satellite fixes and VLF fixes corrected only for a_i over the length of the survey (? or cruise) and by direct comparison with a Sulzer oscillator transferred between the ship and shore stations while the ship is in port.

3. (a) Read in the a_i and b_i and relevant times
   (b) Convert times to minutes

4. (a) Read in each set of time, ship and shore lane counts and water depth.
   (b) Compute station number by prefixing time with survey number SSDDHHMM
   (c) Convert time to minutes
   (d) Compute corrected lane counts $c_i = Ship_i - (Shore_i + a_i + b_i t)$
   (e) Write station number, time, 4 corrected lane counts, water depth on the drum (? tape, ? disc).

*N.B. Continue until all cards read in, data corrected and written on the drum.

5. Punch up times of significant changes in ships course or speed, i.e. times of discontinuity in $^{dc}/dt$ where c is lane count.

*N.B. The predicted values of $^{dc}/dt$ and maximum acceptable scatter for each lane count during each interval could also be punched up, but it would seem better to use the actual data to define them.

6. Punch up parameters defining the smoothing operator to be applied to lane count values between discontinuities in $^{dc}/dt$.

*N.B. For example, parameters could be the number of points in operator and weights to be applied.

7. Read in times of discontinuities.

8. Read in operator parameters.

9. (a) Read in VLF data from drum (? tape, ? disc)
   (b) Determine mean and SD of difference between consecutive lane count values for each period between discontinuities.

*N.B. (9) could be combined with (4), with (5), (6), (7) and (8) being combined with (2) and (3).

10. (a) Read in VLF data again

    (b) For each period between $^{dc}/_{dt}$ discontinuities, test the difference between consecutive readings. If the difference varies from the mean value determined in (9) by more than 2 xSD(?) print an error message and replace by previous value plus mean. Place a counter on the error messages, and if error frequency exceeds 4 in every 100 values, terminate processing.

* System must be able to take care of times when there are no values due to poor VLF reception etc. The probability of getting 4 errors in 100 values when the general level of errors is 1% is only about 1%.

11. (a) Compute latitudes and longitudes using spherical trigonometry formulae unless the spheroidal form is almost as fast, for all possible combinations of stations (a maximum of 6 for 4 VLF stations)

    (b) Print station time, mean latitude, mean longitude, number of combinations, and either individual values or deviations from thé mean.

    (c) Identify stations where results are probably in error. Terminate if too many values are suspect.

*Spherical trigonometry should be about 100 times faster than iterative spheroidal solution. Positions will be computed on the sphere and transformed onto the spheroid. A simple maximum limit to the deviations around the mean lat and long should be sufficient to identify times of unacceptable scatter in results.

12. (a) Compute the latitude and longitude on the spheroid of every tenth value

    (b) Transform the positions of all intermediate points on the spheroid by linear adjustments between these values.

    (c) Print out the differences between spheroid and sphere positions for every tenth value.

* This approach should make the computations about 10 times faster than computing positions on the spheroid. The difference print out will enable a check to be kept of the transformation.

Another approach is to compute the adjustments from sphere to spheroid at suitable intervals (one degree say) in advance and then compute adjustments to be applied by interpolation.

13 (a) Save up to 290 values of lat and long, or all the values from one discontinuity to the next whichever is the least (it is very unlikely that there will be 7290 values in a run)

(b) Apply smoothing operator with taper at beginning and end. The operator should be predetermined from initial data provided in October.

(c) Plot unsmoothed and smoothed values against time; 1/10 inch = 10 minute of time; 1/10 inch = 1 minute of lat and long.

* It should be possible to plot unsmoothed values as discrete points, then smooth and put into original position and plot as a continuous curve. The termination of smoothing at turns is to prevent smoothing out of turns affecting nearby values; particularly at intersections at ends of traverse lines.

14. Output a list of station number, time, latitude, longitude and depth suitable for input into next program.

Preparation of Data and Least Squares Adjustment

1 (a) Punch up list of fixed nodes giving station number, time of occupation, and latitude and longitude (or gravity) of fixed position.

(b) Punch up list of free nodes giving station number and times of occupation. There may be more than one time.

Note that a separate number sequence will be used for fixed and free nodes that will not be deducible from the time.

2 (a) Read in lists of fixed and free nodes.

(b) Convert times to minutes

(c) Sort into a list in time sequence of the nodes occupied and the time of occupation. The free nodes may appear in this list several times.

3 Read in listing of data at 10 minute intervals.

4 Compute the corresponding VLF (or sonar doppler or gravity) value at the times of node occupation by interpolation from the 10 minute data listing.

5 (a) Build up data files for running the Least Squares Program

(b) Abstract first free node in time sequence and compute differences of every 10 minute point and fixed node up to and including the next free node.

(c) Write differences on drum (or tape or disc)

(d) Repeat using second free node as origin, and so on, until all data split into free node-free node links with data as differences relative to first node in link.

* The data is now in a form ready to run on the Least Squares Program.

** NOTE: It may be necessary to obtain time values at node points for gravity as the period of features being looked for can be of the order of 5-10 minutes, rather than use interpolation as for the VLF and Sonar Doppler.

6 Run least squares program.

Velocity Computation from VLF Data

1. Read in listing of station number, time, latitude and longitude from VLF least squares output using all fixed nodes.

2. (a) For ten minute values compute VE and VN

$$VE = ({}^{d\lambda}/dt).\ R.\cos\phi$$
$$VN = ({}^{d\phi}/dt).\ R$$

where ϕ = latitude, λ = longitude, R = radius of spheroid at Broome

3. Compute Eotvos Correction

$$EC = 7.49VE\cos\phi + (VE^2 + VN^2)/R$$

Smooth Eotvos Correction to remove kinks at fixed and free nodes. A preset filter will probably be sufficient.

4. Output a listing of station number, time, latitude, longitude Eotvos Correction, and water depth.

Sonar Doppler Reduction

1. Punch up station number, time of occupation, and latitude and longitude of starting point.

* Should errors accumulate too rapidly for the whole survey (or cruise) to be reduced in one go, the numerical integration may be split into parts, each starting at a known point. As the least squares program operates on differences, this is not very likely.

2. Punch up gravity meter drift constants a, b and the time periods during which they are to be applied where drift = a + bt. Possibly a second order curve for the whole survey may be adequate.

3. (a) Read in station number, time, latitude and longitude
   (b) Read in drift constants and time periods
   (c) Convert time to minutes

4. (a) Read in data on digital tape, 200BPI, with data at one minute intervals. Abstract time, true course, true speed, raw gravity (and possibly magnetic which may be stored on drum (or tape or disc)).
   (b) Compute station number
   (c) Convert time to minutes
   (d) It may be necessary to carry forward the numerical integration to a 10 minute point before commencing main 10 step integration cycle.
   (e) Numerically integrate latitude and longitude over ten minute interval from one ten minute point to the next.
   (f) Compute Eotvos Correction over ten minute interval symmetric about a ten minute point.
   (g) Correct gravity results for drift and compute average gravity value over ten minute interval symmetric about a ten minute point.
   (h) Output listing of station number, latitude, longitude, gravity and Eotvos Correction at 10 minute points, analogous to the VLF listing.

Formulae to use

$d\phi = V.\cos\Theta.dt/2\pi R$

$d\lambda = V.\sin\Theta.dt/2\pi R\cos\phi$

$EC = 7.49.V.\sin\Theta.\cos\phi + V^2/R$

where ϕ = latitude, λ = longitude, Θ = heading, dt = time interval R = radius of spheroid at Broome, V = velocity, EC = Eotvos Correction.

* The gravity, and velocity may require some smoothing, as straight averages can produce amplitude inversions.

It is possible that the Sonar Doppler system output may be in a different form than true course and true speed.

5. The listing is then input to the program for preparation of data for least squares for position determination.

Preparation of Data and Least Squares Adjustment

As for VLF.

Comparison of Eotvos Corrections

1. (a) Input listings from VLF reductions

   (b) Input listings from Sonar Doppler reductions

2. (a) Plot VLF Eotvos Corrections against time

   (b) Plot Sonar Doppler Eotvos Corrections atainst time

   1/10 inch to 10 minutes of time

   1/10 inch per mgal of E.C. Range from +75 to -75 mgals

   (c) Plot difference of Eotvos Corrections against time

   1/10 inch to 10 minutes of time

   1/10 inch to 1/10 mgal of difference ? Range from +10. to -10 mgals?

* This will give 100 ft of plot

3. (a) Visual analysis of the two systems Eotvos Correction determinations.

   (b) Select best corrections from the systems and define areas where they are applicable for use in merging program.

Merging of Data from VLF and Sonar Doppler

1. Punch up sets of time segments over which each system is to be used. Segments for position may differ from segments for Eotvos Correction.

* Note that this method can only be used if the time segments run from fixed node to fixed node. If any part of the run is suspect, the whole node-node run must be replaced. Around free nodes, the values out to fixed nodes on each link must be replaced. The alternative is to replace only the suspect parts, and re-run the Least Square Program, a more costly method.

2. (a) Read in sets of time segments

   (b) Read in listings from VLF and Sonar Doppler reductions

   (c) Merge between fixed nodes, correcting gravity for Eotvos Correction

3. Output listing of station number, time, latitude, longitude, water depth and corrected gravity (raw gravity - Eotvos Correction).

4. Input resultant listing into program for preparation of data for least squares for the gravity results.

Preparation of Data and Least Squares

As before.

Bouguer Anomaly Reduction

1. Input densitites to be used (0.0, 1.9, 2.2, 2.67 gms/cc)

2. Compute and print out Bouguer anomaly values plus principle facts for all of these densitites, and also Free Air Anomalies at the points

3. Save principle facts plus Bouguer anomaly for 2.2 gms/cc for plotting and contouring program.

Station Plot and Countouring

1. Input principle facts plus B.A. for 2.2 gms/cc.

2. Plot maps at 1:250,000 scale using Transverse Mercator Projection on Clarke 1858 spheroid.

3. Plot station positions, B.A. values, water depth, and some of the station numbers (each hour on the hour and node points).

4. Contour at 5 mgal intervals, either on the computer or by hand.

Magnetic Reductions

1. Punch up cards for shore monitor at one minute intervals

* This could be done by trace following of the analogue records.

2. (a) Input shore data

(b) Input station listing with latitudes and longitudes, at 10 minute intervals.

(c) Input ship magnetic data, either from original digital tape or from saved document from Sonar Doppler input.

(d) Input regional values at one degree squares.

3. (a) Compute regional values at positions of each 10 minute point

(b) Interpolate regional at one minute points linearly.

4. (a) Plot Ship value - Regional

(b) Plot Ship - Regional - Shore

(c) Plot Shore

Vertical scale 200 gammas/inch

Horizontal scale to correspond to 1:250,000 scale

* It would be advantageous to plot the results at map scale for use in later profile plotting. However, it should be possible to produce the profile maps by computer. If so, a larger horizontal scale would be better at it could then be used for analysis.

The stumbling block in complete automation is determination of the base lines, the direction in which they run and the value to use. These could be defined by the BMR and fed into the computer. The minimum anomaly on each segment could be determined and used as the base line value (see notes on Magnetic Reduction).

WORK FLOW CHART FOR PRESENTATION OF MARINE SURVEY 1:250,000 MAPS

1. B.M.R. OPERATION

Preparation of pre-survey material
Scribing of 1:250.000 scale Base Maps
Allocation of B.M.R. Geophysical Drawing Office file numbers to Base Maps

2. B.M.R. TO CONTRACTOR

Two (2) "Ozaloff" transparencies of each Base Map (Item 1) to be used as working sheets andregistration of overlays

3. SURVEY OPERATIONS

4 CONTRACTOR TO B.M.R.

Computer produced plot of traverses with Bouguer Anomalies depths and contours at intervals as determined by station density, indicated in standard map 1099-1 for inspection and smoothing of contours

5. B.M.R. OPERATION

Inspection of computer produced sheets, smoothing of contours

6. B.M.R. TO CONTRACTOR

Inspected computer produced sheets for fair drawing

7. CONTRACTOR OPERATION

Fair drawing of the following computer produced results incorporating all amendments indicated by B.M.R. (Item 5)

a) one (1) overlay of "Cronaclear" 0.004"or similar stable, clear,drafting film for each 1:250.000 map area showing traverses and station numbers

b) one (1) overlay of "Cronaclear" 0.004" or similar stable, clear,drafting film for each 1:250.000 scale map area showing Bouguer Anomalies, depths and contours

NOTE: Each overlay should be registered precisely with the appropriate Base Map transparency as supplied by B.M.R. under Item 2. In addition, each overlay should bear the north point and the appropriate name or reference number of the map area. (Refer to standard sample (B.M.R drawing No.1099-1) for gravity data overlay)

8. CONTRACTOR TO B.M.R.

For detailed edit:

a) Overlays as per item 7a
b) Overlays as per item 7b
c) Relevant checking material for 8a and 8b

9. B.M.R OPERATION

Detailed checking of overlays as per item 8
Allocation of B.M.R. Geophysical Drawing Office file numbers to overlays (items 7a and 7b)

10. B.M.R. TO CONTRACTOR

Overlays for amendments

11. CONTRACTOR OPERATION

Amendments to overlays

12. CONTRACTOR TO B.M.R.

Amended overlays

13. B.M.R. OPERATION

Production of Gravity Maps.
Each map being a composite transparency of:-

a) Base Map (original)
b) Traverse and station numbers (overlay 7a)
c) Gravity data (overlay 7b)
d) Standard reference panel
Allocation of B.M.R. Geophysical Drawing Office file numbers

14. B.M.R. OPERATION

Production of transparencies for magnetic data Each transparency being a composite of:-

a) Base Map (original)
b) Traverse and station numbers (overlay 7a)

The positions of magnetic baseline for the traverses will be indicated on the composite transparency.

NOTE: One transparent copy with indicated baselines to be retained by B.M.R. office for positioning of seismic results

15. B.M.R. TO CONTRACTOR

Composite transparency for each of the 1:250.000 scale map areas as produced in item 14

16. CONTRACTOR OPERATION

Fair drawing of Magnetic Profiles overlays on "Cronaclear" 0.004 or similar, stable, clear drafting film for each 1:250.000 scale map area

NOTE: Each overlay should be registered precisely with the appropriate Base Map transparency as supplied by B.M.R to the contractor under item 2. In addition, each overlay should bear the north point and the appropriate name or reference number of the map area. (Refer to standard sample for magnetic profiles overlay)

17. CONTRACTOR TO B.M.R.

Magnetic Profiles overlays as per item 16

18. B.M.R. OPERATION

Production of Magnetic Profile maps.
Each map being a composite transparency of:-

a) Base Map (original)
b) Traverse and station numbers (overlay 7a)
c) Magnetic Profiles (overlay 16)
Allocation of B.M.R. Geophysical Drawing Office number to Magnetic Profiles overlays.
d) Standard reference panel
Allocation of B.M.R. Geophysical Drawing Office file numbers to the composite transparencies

19. B.M.R. TO CONTRACTOR

Magnetic Profile maps (transparencies, item 18) for printing and compilation of report.

20. B.M.R. TO CONTRACTOR

Bouguer Anomaly Maps (transparencies item 13) for printing and compilation of report.

21. CONTRACTOR OPERATION

Printing of Bouguer Anomaly maps
Printing of Magnetic Profiles maps
Collation of Survey Report

22. CONTRACTOR TO B.M.R.

Report and all originals, survey data and other compilation material

G449-3

TO ACCOMPANY RECORD No. 1968/1