# MARINE GEOPHYSICS OF THE SCOTIA RIDGE AND SCOTIA SEA

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THIS is a report of progress made with geophysical investigations in the Scotia Sea and over the Scotia Ridge. The work is being carried out by members of the geophysics section of the Department of Geology, University of Birmingham. It is financed by a grant from the Natural Environment Research Council but it is also strongly supported by the British Antarctic Survey, which provides ship time and other valuable assistance. H.M.S. *Protector* also makes an important contribution to the programme.

The Scotia Ridge is the name given to the great arc of islands and submarine ridges which apparently forms a structural connection between South America and the narrow mountainous Antarctic Peninsula of western Antarctica. The geology of these islands is now quite well known but the origin of the arc is not understood, though several possible explanations have been advanced to explain it. It has been suggested (Hawkes, 1962) that the older islands may be fragments of a former land bridge between the two continents which was disrupted in Mesozoic times as a result of continental drift, there being a relative easterly drift of the fragments into their present positions. An alternative theory (Matthews, 1959) has implied that in former times a much larger landmass existed in this region, of which the islands and ridges are a remnant. Neither idea is very convincing. The South Sandwich Islands region of the arc is, of course, relatively young and has much in common with other active volcanic island arcs in various parts of the world but no satisfactory explanation of these structures has yet been given. Clearly, any advance beyond the stage of speculation is not possible without a knowledge of the nature and structure of the crust, both of the islands and the submarine ridges, and beneath the floor of the Scotia Sea. To increase this knowledge is the purpose of the present investigations.

The work started in the 1959–60 season and it has continued each year since. During the first few seasons, ship time for specific surveys was limited and so investigations were mainly of a reconnaissance nature. Latterly, resources have increased, more ship time has been made available and it has become possible to concentrate to some extent on particular areas. In the first few years only magnetic measurements were made at sea, though a Worden gravimeter was carried for making gravity measurements wherever suitable landing places could be found. In the 1961–62 season, arrangements were made to co-operate with H.M.S. *Protector* and a programme of two-ship seismic work (in which somewhat primitive equipment was used) was begun. This has now become an annual programme. Because H.M.S. *Protector* was able to spare only a limited time for geophysical work, single-ship seismic work in the Bransfield Strait area, using R.R.S. *Shackleton*, was also started. At first the technique used was to set up conventional land stations at two points on opposite sides of the Strait in succession and fire a line of charges between them using the ship. This method was successful but of limited application since it depended on the use of shore stations. For purely marine work with one ship only, Messrs G. & E. Bradley Ltd., London, were asked to design a 6-channel seismic telemetering system which could be installed in free-floating buoys. These buoys perform the function of a receiving ship and transmit seismic impulses by radio back to the firing ship, where they are recorded. This system was successfully developed by mutual co-operation and it was given trials in the 1963–64 season. It is now fully operational.

Sea-gravity measurements were added to the programme for the first time in the 1965–66 season, when the Askania instrument belonging to the Department of Geodesy and Geophysics, University of Cambridge, was borrowed and installed on board H.M.S. *Protector*.

Some details of the progress of the various surveys is given below, together with a discussion of future plans.

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*Br. Antarct. Surv. Bull.*, No. 12, 1967, p. 93-99.

## Magnetic Surveys

Most of the measurements have been made with a proton magnetometer designed and manufactured by Bruce Peebles Ltd., Edinburgh. This has a potentiometer recorder and a punched-tape digital output. Fig. 1 shows the tracks for which data are available. Position fixing remote from land is done by celestial navigation and dead-reckoning, the accuracy with which any point can be located thus being dependent on many factors such as the weather and length of passage. Cloud cover is mostly complete, so that sights of morning or evening stars are rare; a sun sight would provide a position line accurate to 2 nautical miles (3·7 km.), but in the middle of a long run made in bad weather there might be an uncertainty of 10 nautical miles (18·5 km.).

Magnetic field values have been computed for 0·5 nautical mile (0·9 km.) intervals and they are currently being used to calculate a smooth regional field for the whole region and to derive residuals. In general, the ship's tracks are too far apart and navigation is not precise enough for magnetic anomalies to be contoured between profiles. The data cannot therefore be used for delineating complicated structural trends in the ocean floor. Had precise navigation been possible, parallel traverses could have been planned close enough to enable this to be done. The absence of navigational aids has also made it impossible so far to carry out detailed magnetic surveys in areas of interest in the deep ocean. However, offshore surveys using radar and visual position fixing, and with a line spacing close enough to permit contouring, have been made in Bransfield Strait and in the vicinity of Gibbs Island.

In an effort to obtain more information from the magnetic data a statistical analysis is being attempted. The method is a development of one already described by Griffiths and others (1964) in which the Scotia Sea was divided into areas on the basis of the correlation between the differences of two ratios of measurements made on successive magnetic anomalies. An extension of this method, which correlates a single ratio across running groups of four anomalies and contours the plotted values of the correlation coefficient, has seemed to give meaningful results in terms of the geological structure, but it has the problem of low statistical significance because of the limited number of anomalies. The present more rigorous study abstracts far more measures of anomaly shape and size from the data, and it attempts to cluster the anomalies by correlating them across the measures, using techniques first developed in numerical taxonomy. It is hoped that the clusters will have areal unity and that their geological significance can be deduced from the correlation of individual measures across the anomalies within a cluster.

## Gravity Surveys

A number of gravity base stations has been established, both on the Antarctic Peninsula and on the islands of the Scotia arc. The absolute values of these stations are dependent on the quality of the ties with the South American gravity network measured with Worden and La Coste gravimeters carried on board ship. The values assigned to these stations have been given by Griffiths and others (1964, table III). Later work is tending to confirm these values and it seems that they are correct to $\pm 1$ mgal.

On land there are still difficulties of height determination, ice thickness and station position to be overcome but progress is being made with these problems. Enough reliable secondary stations have now been occupied by both the University of Birmingham group and British Antarctic Survey land parties for a map to be drawn showing the main features of the gravity field over the South Shetland Islands and northern Graham Land.

The gravity traverses made at sea by H.M.S. *Protector* in the 1965–66 season are shown on Fig. 2. When these data have been reduced, enough information will be available for gravity profiles to be drawn across the arc in the Bransfield Strait area.

## Seismic Surveys

Seismic lines shot so far are shown in Fig 3. A number of these have been published and interpretation of the remainder has been virtually completed. Long seismic lines, such as are needed to give information on crustal thickness and upper mantle velocity, have been shot by

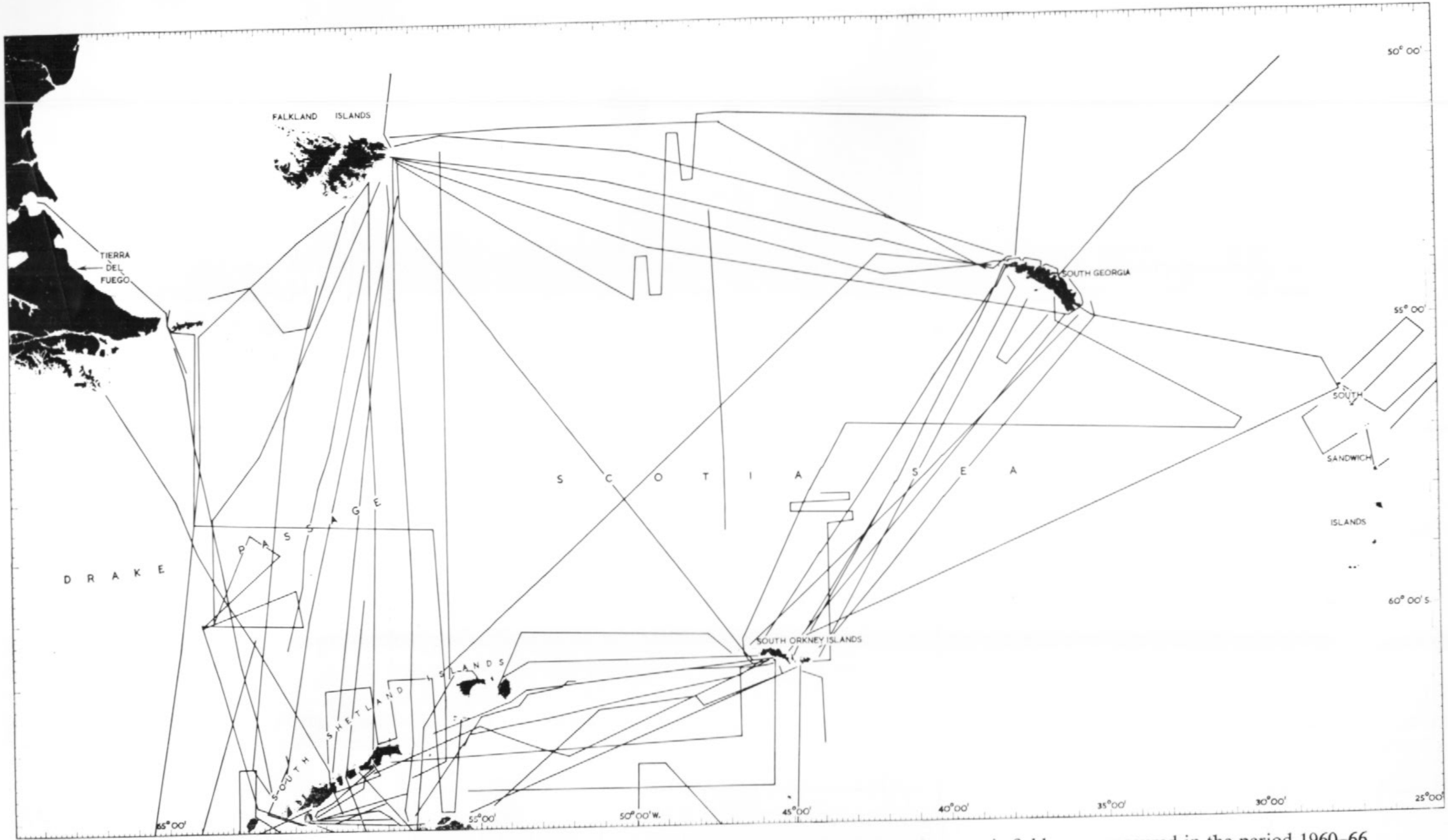


Fig. 1. Map of Drake Passage and the Scotia Sea, showing the tracks along which bathymetry and total magnetic field were measured in the period 1960–66.

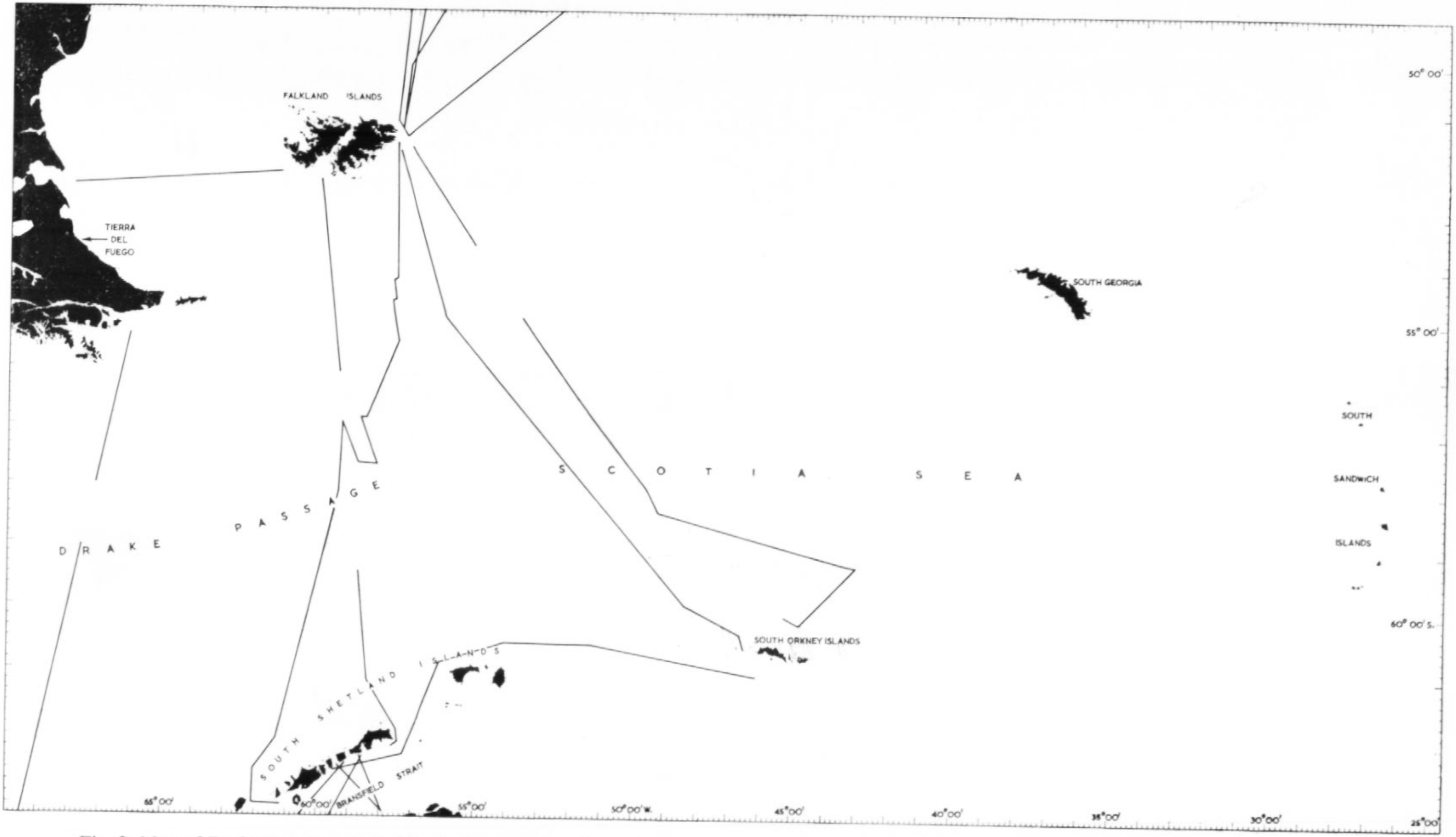


Fig. 2. Map of Drake Passage and the Scotia Sea, showing the tracks along which bathymetry and the gravity field were measured in the period 1965–66.


Fig. 3. Map of Drake Passage and the Scotia Sea, showing seismic refraction profiles shot in the period 1962–66. Unreversed profiles are indicated by dashed lines.

H.M.S. *Protector* with R.R.S. *Shackleton* acting as recording ship. In a normal year the 10-day two-ship programme yields perhaps six reversed lines or about 250 nautical miles (460 km.) of profile. A conventional 8-channel seismic refraction amplifier system with high- and low-cut filters and outputs at two levels is used, together with an ultra-violet oscillograph for recording. Facilities for recording on magnetic tape for subsequent processing are being added. It is not possible to obtain an entirely quiet ship, but by using a 1,500 ft. (450 m.) cable and by paying careful attention to hydrophone suspension, line lengths of 70 nautical miles (130 km.) have been obtained in calm weather with a maximum charge size of 300 lb. (136 kg.). Line lengths of 40 nautical miles (75 km.) are more usual, these being sufficient in many instances to define crustal thickness and to give mantle velocities.

So far the seismic sonobuoys have been used mainly to fill in details of the upper crustal and sedimentary layers on the long two-ship lines. Depth penetration is limited by the maximum transmission range which is 20 nautical miles (37 km.) at the frequency used (27 Mc./sec.). To achieve greater ranges it will be necessary to install direct-recording equipment in the buoys. At present a reflection seismic profiler is being constructed. This instrument is similar in principle to an echo sounder but, being of lower frequency and higher power, it is capable of penetrating beneath the sea floor and, it is hoped, of providing a continuous record of the structure and thickness of the unconsolidated sedimentary layer down to a depth of up to 1·5 km.

## Bathymetry

It has been usual for R.R.S. *Shackleton* to keep her echo sounder running while on passage, particularly when the magnetometer has been streamed, and to send details of sounding lines which are relatively well-fixed to the Hydrographic Department for plotting on the 1 : 1,000,000 Ocean Plotting Sheets. In addition, the bathymetric data are being used at Birmingham for the construction of contour charts of interesting areas and they are also of great help in the detailed interpretation of magnetic, seismic and gravity measurements.

The present echo sounder, a dry-paper Kelvin Hughes MS26J machine, replaced a less powerful wet-paper machine in 1963.

## Results and Future Programme

A survey of progress indicates that the present is the right time for an appraisal of the results obtained so far and for a consideration of how the work should be planned over the next few years.

As far as magnetic survey is concerned, as explained already, the immediate need is for a navigation system which will make detailed magnetic surveys possible. If an area can be contoured, structural trends and geological boundaries can be determined, and on this basis further geophysical work can be planned. The magnetic data collected so far have been useful in many ways and the statistical studies being carried out on them may prove to be of practical value, but it is clear that there is little point in continuing to collect data on long sea passages unless more precise position fixing can be done.

Apart from magnetic measurements in the Scotia Sea, most other work has been done in Bransfield Strait and some distance to the east, though a programme of measurements has been started in the vicinity of the South Orkney Islands. A generalized interpretation of the crustal structure has been made and it is known that in Bransfield Strait and under the South Shetland Islands the main crustal layer is of oceanic type. The mantle has a slightly lower than normal velocity and it is at 15 km. depth under the Strait but it is about 5 km. deeper to the north of the South Shetland Islands. There is no reason for believing that there is any thick crustal root beneath these islands. This region of the ridge appears to be different from that some distance to the north-east though the main crustal layer has the same velocity. Here the mantle is also at a depth of 15 km. but it has an anomalously low velocity.

The results of a seismic traverse across the Scotia Sea from the South Orkney Islands to South Georgia have already been reported by Allen (1966). This report includes the results of seismic lines shot in the vicinity of the South Orkney Islands which, taken together with the results of lines shot in the 1965–66 season, provide preliminary information on this sector of the arc. It is proposed to concentrate on a study of this quite considerable continental block and the trench to the north in the 1966–67 season. In the following year, bathymetric, magnetic and seismic measurements will be extended westwards to link these surveys with those already completed in Bransfield Strait. In the interim it should also prove possible to carry out surveys of areas of interest in deep water with the magnetometer and seismic profiler, provided navigational equipment is forthcoming.

For a number of reasons, progress is necessarily slow. Time is limited and the available working days are often further curtailed by bad weather and by unforeseen but necessary changes to the ships' programmes. However, the British Antarctic Survey is making every effort to support the work and the situation is improving steadily. The University of Birmingham group at present consists of four scientists, devoting their full time to these investigations, and a Technical Officer in charge of maintenance and development of equipment. With a group of this size full use can be made of available ship time at any time in the Antarctic summer season.

Apart from the seismic profiler, no new major developments in geophysical technique are planned for the near future. Instead, effort will be concentrated on improvements in navigation. The possibility of installing a V.L.F. system is being examined and it is hoped that in the next few years a satellite navigation system will become available. More sea-gravity measurements are required and it is possible that in due course money will become available for the purchase of a suitable gravimeter. Recent developments in these instruments have made it practicable to consider installing one in a ship the size of R.R.S. *Shackleton*.

Finally, in discussing the marine work, it should not be forgotten that British Antarctic Survey geophysicists are carrying out systematic magnetic and gravity measurements on the Antarctic Peninsula. This is an important contribution; no real understanding of the structure of the Scotia arc will be reached unless the land work progresses simultaneously with that being done at sea. Even when the programme outlined for the next few years has been completed, it will leave very large areas unvisited, but nevertheless it ought to provide answers to a number of questions concerning the nature of the southern part of the ridge and perhaps the origin of the arc as a whole. If it does, the expenditure of time and money will have been well justified, as these are matters of major scientific importance.

## Acknowledgements

The continuing programme of geophysical investigation described above would not have been possible without the extensive facilities provided by the British Antarctic Survey, for which the authors would like to thank its Director, Sir Vivian Fuchs. The helpful co-operation of Capt. D. Turnbull, of R.R.S. *Shackleton*, of successive Commanding Officers of H.M.S. *Protector* and of all Survey and ships' personnel is gratefully acknowledged. Dr. R. J. Adie has given helpful advice on geological aspects and the presentation of information, and Professor F. W. Shotton has provided laboratory facilities in the Department of Geology, University of Birmingham.

*MS. received 16 June 1966*

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