BOUGUER ANOMALY MAP OF GRAHAM LAND

By F. J. DAVEY* *and* R. G. B. RENNER

ABSTRACT. Since 1959 gravity measurements have formed part of a geophysical survey of the Scotia Sea and Graham Land. The marine gravity survey has been operated from ships of the British Antarctic Survey and H.M.S. *Protector*, while field parties have completed land traverses on the peninsula and the Larsen Ice Shelf. Bouguer anomalies have been calculated and are presented as a contoured map.

GEOPHYSICAL investigations of the Scotia arc, including South Georgia, the South Sandwich Islands, South Orkney Islands, South Shetland Islands and Graham Land, were commenced in 1959 by the Sub-Department of Geophysics, Department of Geology, University of Birmingham, in collaboration with the British Antarctic Survey. The initial exploration of the region was conducted from the ships of the Survey, R.R.S. *John Biscoe* and R.R.S. *Shackleton*, using magnetic methods supplemented by land gravity measurements. Since its inception, a more extensive geophysical coverage has been achieved with the inclusion of both seismic reflection and refraction techniques. Results of this marine geophysical work have been published by Griffiths (1963), Cox (1964*b*), Griffiths and others (1964), Allen (1966*b*) and Griffiths and Barker (1967).

Also in 1959, geophysical surveys on land were commenced by the British Antarctic Survey from the station at Hope Bay (Ashley, 1962; Cox, 1964*a*; Allen, 1966*a*). These surveys, which initially involved magnetic measurements, not only link up with the marine work in the Scotia Sea but also form the basis of a much wider geophysical investigation of the Antarctic Peninsula. Since 1962 (at Hope Bay) and since 1963 (at Stonington Island) these land surveys have been extended to include gravity measurements.

The present paper deals with the gravity aspect of these surveys and it includes the results obtained from both the marine and land measurements.

ABSOLUTE VALUE OF GRAVITY

One major difficulty in the establishment of a gravity survey on the Antarctic Peninsula is linking the network of base stations to those of the international gravity system. This arises from the extreme distance of the Antarctic Peninsula from the nearest international gravity base station at Punta Arenas in South America, which is in excess of 1,300 km. and involves a sea voyage of several days. The early links between South America and the Antarctic, using a Worden gravimeter (Griffiths and others, 1964), were made from Montevideo to Deception Island via Stanley (Falkland Islands). This involved the accurate measurement of two gravity differences: one of about 1,480 mgal and the other of about 980 mgal, and in both cases a sea voyage of several days. The mean of several links gave a value for gravity at the Deception Island base of 982·2254 cm. sec.$^{-2}$ with an estimated standard error of $\pm 1\cdot 9$ mgal. During the 1964–65 Antarctic summer, Kennett (1965*a*), using a LaCoste and Romberg geodetic gravimeter, established a more accurate link through a closed loop between Punta Arenas, Stanley, Montevideo and Deception Island, obtaining a value of 982·2223 cm. sec.$^{-2}$ for absolute gravity at Deception Island. In view of the low and consistent drift of the LaCoste and Romberg gravimeter and the proximity of the survey area to Punta Arenas, compared with Montevideo, it was decided to adopt the value of 982·2223 cm. sec.$^{-2}$ at Deception Island and to relate all Graham Land measurements to this value. Confirmation of this value for Deception Island was provided in 1966 by F. J. Davey, who obtained an absolute value of 982·2224 cm. sec.$^{-2}$ with a Worden gravimeter by way of a closed loop through Deception Island, Punta Arenas and Stanley.

THE GRAVITY SURVEY

The ship-based gravity programmes have been carried out during October to April, the Antarctic summer season, and have consisted of small landing parties operating from R.R.S.

* Sub-Department of Geophysics, Department of Geology, University of Birmingham, Birmingham 15.

John Biscoe and R.R.S. *Shackleton*. Landings on the mainland and offshore islands can be extremely difficult due to inaccessibility, adverse sea and weather conditions, and the pressing commitments of the ships whose time is primarily governed by the relief and resupply of the British Antarctic Survey's stations. Despite these factors, about 150 stations have been occupied using Worden gravimeters. The majority of these measurements are concentrated along the west coast of the Antarctic Peninsula, north of the Survey's station on Galindez Island (lat. 65°14·6′S., long. 64°16′W.). Marine geophysical programmes have continued each year, and during the 1964–65 season a LaCoste and Romberg geodetic gravimeter was kindly loaned for this work by the United States Oceanographic Office. The instrument, based on R.R.S. *Shackleton*, was used to strengthen the gravity link between the Antarctic Peninsula and the international network in South America (Kennett, 1965*a*). During 1965–66, F. J. Davey used a Graf-Askania Gss2 sea gravimeter, installed in H.M.S. *Protector*, to complete 8,300 km. of marine gravity traverses between the Falkland Islands and Marguerite Bay. Part of these data were useful in extending the otherwise limited gravity measurements on the west coast of Graham Land.

The first land-based gravity survey started from Hope Bay in 1963–64 when J. Mansfield, using a Norgaard gravimeter, occupied about 60 stations on Tabarin Peninsula and on the fast ice of Duse Bay. During the same period P. Kennett, working in conjunction with geological field parties and using a Worden gravimeter, commenced a gravity survey from Stonington Island. The latter survey included local traverses on the west coast of Graham Land (Kennett, 1965*b*), while the main summer programme achieved a traverse of the peninsula to the east coast where further measurements were taken northwards to Cape Disappointment (lat. 65°33·5′S., long. 61°43′W.) (Kennett, 1965*c*, 1966*a*, *b*). In the following season, 1964–65, R. G. B. Renner continued the gravity survey from Stonington Island, the Survey's station at Hope Bay having closed down in the meantime. Traverses were made on the east coast as far north as Hope Bay thus enabling the survey to be tied in with previously occupied gravity stations, including several of those originally established by the ship landing parties. In all there are over 600 stations on the east coast of Graham Land between lat. 68°35′S. (Mobiloil Inlet) and 63°24′S. (Hope Bay).

Land gravity survey

Due to the present state of exploration within this region and because a full topographic survey has not yet been completed, any land gravity survey over Graham Land is subject to inaccuracies not normally encountered to such an extent in surveys elsewhere. The gravity base-station network has still to be enlarged and improved; there are appreciable errors in station positioning and height determinations, and sea depths beneath the Larsen Ice Shelf are largely unknown while the terrain itself restricts the areas where traverses are possible. Despite the shortcomings explained below, the overall errors in the Bouguer anomalies are comparable with the ±20 mgal attributed to the majority of gravity surveys in Antarctica (Bentley, 1964). Although the absolute errors may appear to be large, the relative errors between neighbouring stations are much smaller.

Apart from two stations occupied from aircraft landings, the land gravity survey on the east coast has been carried out using dog-sledge transport from the Survey's stations at Hope Bay and Stonington Island. Station positions have been obtained by sledge wheel and compass, the traverses being tied to known trigonometrical points, while station heights have been calculated using aneroid barometers (Kennett, 1965*c*). The lack of suitable topographic maps has prevented systematic terrain corrections from being made, though where severe terrain irregularities are present corrections have been applied using the information available. The majority of the gravity stations are, however, situated on the Larsen Ice Shelf well away from any features requiring terrain correction. Throughout the reduction of the results, density values of 2·67 g. cm.$^{-3}$ have been used for rock, 0·9 g. cm.$^{-3}$ for ice and 1·03 g. cm.$^{-3}$ for sea-water. By far the greatest factor contributing to the errors has been the absence of data on the thickness of the Larsen Ice Shelf and the depth to bedrock beneath. This was partly overcome in the 1966–67 summer when several ice-thickness profiles were obtained using an airborne radio echo-sounding technique (Renner, 1969). Using these data, and by extrapolation, estimates were obtained for thicknesses of the ice shelf. Together with the available bathy-

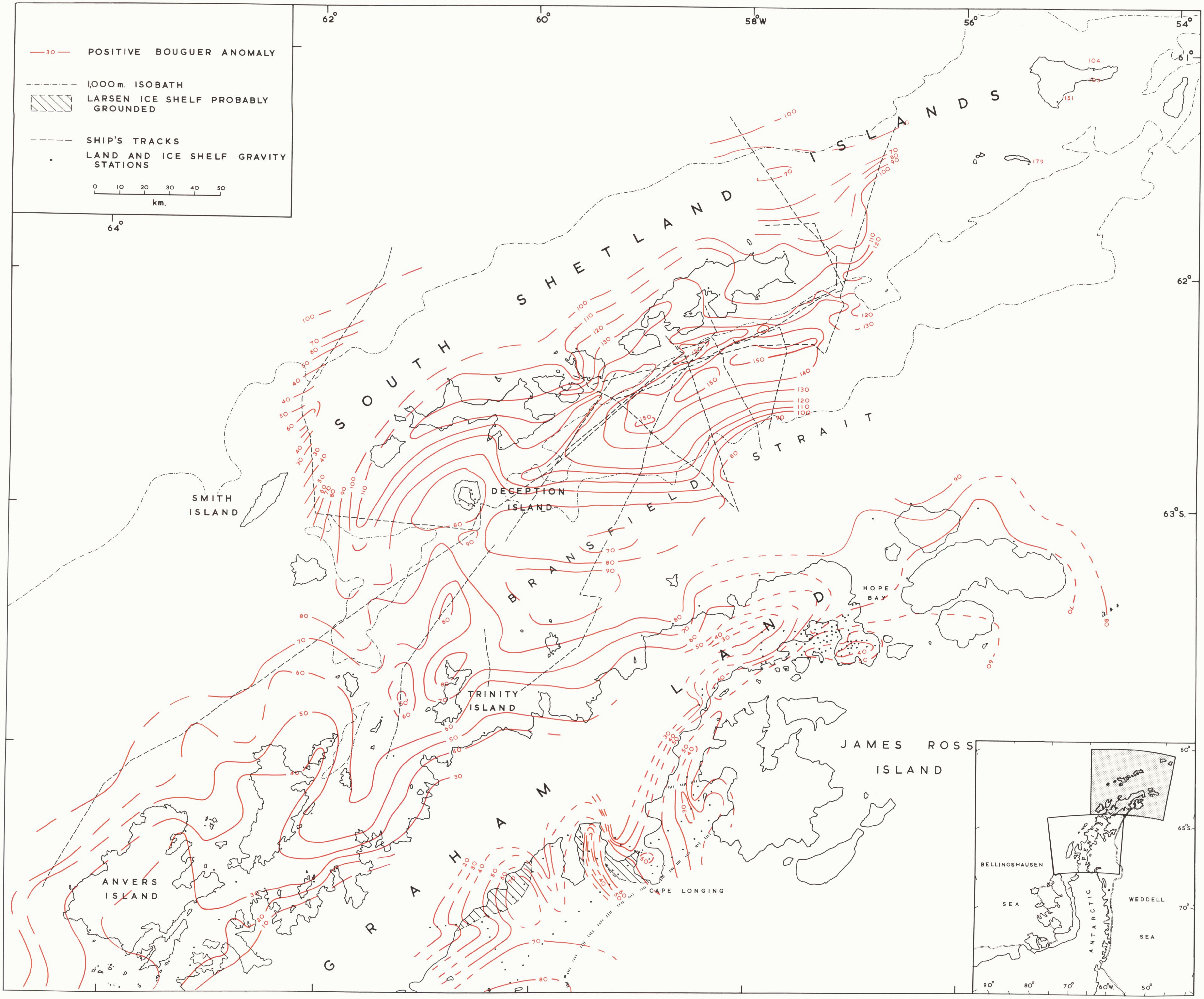

Fig. 1. Bouguer anomaly map of northern Graham Land. Contours at 10 mgal intervals.

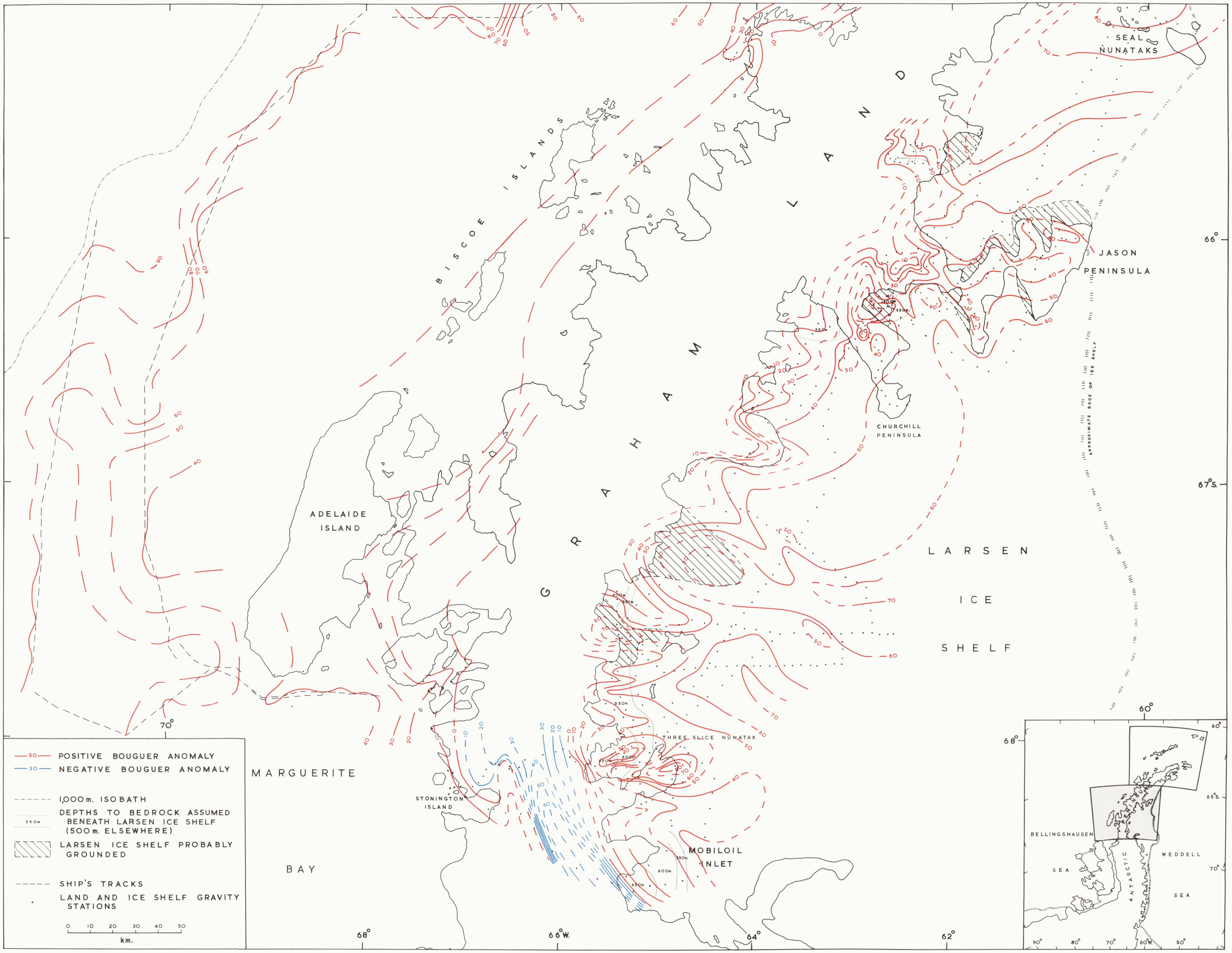

Fig. 2. Bouguer anomaly map of southern Graham Land. Contours at 10 mgal intervals.

metric data, this allowed limiting values to be placed on depths to bedrock which compared favourably with values measured beneath other Antarctic ice shelves, and with depths to the continental shelf surrounding Antarctica. Beneath much of the ice shelf a depth to bedrock of 500 m. has been used in the reduction of the data (Figs. 1 and 2); indications as to other depth values incorporated are shown in Fig. 2. The anomalies on the ice shelf could therefore be due to variations in bedrock topography and not to density differences within the bedrock itself. This is particularly so in some of the inlets where glacial overdeepening is the probable cause of gravity "lows".

Errors in measured gravity due to the calibration and drift of the instruments were estimated to be less than ±1·4 and ±1·5 mgal, respectively. The gravimeters were calibrated in the United Kingdom both before and after the surveys, whilst during each survey the drift rate was carefully recorded as a travelling and static drift, the latter including the overnight drift and that during periods when conditions did not permit travel.

In the estimate of the overall standard error for the land-based gravity stations, it is convenient to subdivide these stations so that the errors in each may be evaluated:

i. For stations at sea-level, the error in Bouguer anomaly is ±1·5 mgal.
ii. For stations on the Antarctic Peninsula, assuming all rock beneath the station, the error is ±6 mgal, and assuming all ice beneath the station, the error is ±8 mgal.

The majority of gravity stations occupied, especially on the traverses across the peninsula from Stonington Island to the east coast, were situated on a relatively unknown thickness of ice overlying bedrock. The difficulty in calculating the Bouguer anomaly for such stations was partly overcome by first calculating the Bouguer reductions for the station assuming all-ice and all-rock columns then comparing these values with a Bouguer reduction based on an estimated ice–rock distribution. This latter ratio was determined from field observations at the plateau edge, where ice-cap sections were exposed, and also from ice thicknesses measured during the radio echo-sounding survey carried out by Dr. C. W. M. Swithinbank (personal communication). Glacier thicknesses could only have limiting values placed on them. Although the errors involved in ice-thickness estimates could be considerable, it was found that even allowing for maximum discrepancies the general west–east anomaly pattern across the peninsula remained unaltered.

For stations on the Larsen Ice Shelf, considerable errors may be introduced by using incorrect ice thicknesses and depths to bedrock, a 50 m. depth variation causing a difference of 3·4 mgal. In the inlets along the east coast, sea depths may vary considerably, but farther east on the Larsen Ice Shelf the bottom topography appears to be more regular and hence the errors are smaller. Because of the unsystematic variation in bottom topography, free-air anomaly errors are given:

i. In relatively flat areas of surface topography the error is ±3 mgal.
ii. In areas of extreme undulation the error is ±9 mgal.

At several localities on the Larsen Ice Shelf adjacent to the mainland, and often in association with disturbed ice-shelf relief, the calculated Bouguer anomalies were far in excess of those in the immediate vicinity. These anomalies are unlikely to be the result of density variations in the bedrock but to areas where the ice shelf is grounded and where an incorrect bedrock depth has been used in the Bouguer reduction. Gravity values at these localities have been adjusted accordingly and the areas of possible ice-shelf grounding are shown on the maps.

Most of the land gravity readings on the west coast of the peninsula have already been published (Griffiths and others, 1964) and they have been supplemented with additional readings by one of the authors (F.J.D.). The latter readings were also made using a Worden gravimeter and they have been tied in to the British Antarctic Survey gravity base stations at Admiralty Bay, Deception Island and Signy Island. The heights of these stations were as near sea-level as possible, usually within 1 m. vertically. An estimate of the terrain correction has been made for stations falling within the Bransfield Strait area delineated on p. 80. However, as Griffiths and others (1964) found, difficulties arise from the lack of suitably detailed topography; therefore, no terrain corrections have been made outside this area. Griffiths and others considered that this correction would not exceed 3 mgal at most stations and the recent calculations tend to confirm this. Therefore, land gravity values on the west coast may be up to 3 mgal low.

Marine gravity survey

The marine gravity measurements were made using the Graf Askania sea gravimeter Gss2 No. 11, which was installed in H.M.S. *Protector*, the Royal Navy's ice patrol ship of 3,450 tons displacement. The gravimeter was installed just aft of amidships at about the level of the waterline where acceleration due to roll and pitch may be expected to be minimal. The measurements were undertaken whilst the ship was assisting in hydrographic work and therefore the tracks followed were not necessarily the best from a geophysical viewpoint.

The survey was linked to the international gravity network via the British Antarctic Survey's gravity base station at Stanley, Falkland Islands, and station WH 1019 (Woollard, 1963, p. 62, 119) at Punta Arenas, Chile. The drift of the gravimeter for the survey was somewhat variable, reaching a maximum of +20 mgal/month. The survey was completed at intervals over a period of 2 months with base-station links at intervals of 16 days or more. For most of the survey the sea conditions were good with the ship operating in calm or sheltered water. Although no cross-coupling computer was installed with the equipment, errors due to cross-coupling and platform off-levelling may be expected to be low. Navigation was by means of radar and terrestrial fixes with occasional star sights where the ship was outside radar range of the peninsula or the offshore islands. These fixes were plotted on the relevant Admiralty charts at a scale of 1 : 500,000 from which the position data were taken. The accuracy of the fixes was within ±1 km., whereas the star sights were accurate to about ±4 km. Unfortunately, not all Antarctic charts are completely reliable and the error in position of some islands may be as much as 4 km., leading to a maximum error in gravity of about 2 mgal. A large error could be introduced in the Eötvos correction when changing from fixing on a correctly positioned island to one incorrectly fixed. However, this is usually easy to determine and the inconsistent fixing point can either be allowed for or the discontinuous part smoothed over. Free-air anomalies were calculated at 10 min. intervals of time, in general corresponding to about 3·7 km. intervals. Two sections of track, a total length of about 75 km., were adjusted in position by about 2 km. on the basis of bathymetry and this improved their fit with the other gravity data.

A useful estimate of the accuracy, or self-consistency, of the survey can be obtained from considering the discrepancies in measured gravity at track intersections. Eleven intersections gave a r.m.s. error of 6 mgal before adjustment. The gravity gradient at the intersections had a maximum value of 3·8 mgal/km. and thus navigational inaccuracies could contribute significantly to these discrepancies. Gravity measurements with the ship at anchor near the position of land readings provide checks on the calibration figures for the gravimeter; this procedure is especially useful as the gravity value at the base station for the marine survey (Stanley) is at least 700 mgal lower than that found in the region of the survey. One such reading is:

	Bouguer anomaly (mgal)		*Separation* (km.)
	Ship	*Land*	
Whalers Bay, Deception Island	77·8	72·1	0·6
		75·6	1·3

In view of the errors likely to be introduced in the marine values by variations in drift rate and the Bouguer correction, lateral gravity variations in the region and the possible error in the land value, the agreement between the two gravity values is quite good.

Bouguer corrections have been made using a constant density of 2·67 g. cm.$^{-3}$ for all rocks. The simple Bouguer slab correction has been made to the majority of the gravity data. However, in Bransfield Strait and to the north of the South Shetland Islands, where the bathymetry is known to be two-dimensional in structure, a two-dimensional terrain correction has been applied. This area is limited in the east by long. 57°W. and in the west by a line passing from Trinity Island through Deception Island to Smith Island.

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APPENDIX

The volcanic eruption at Deception Island on 21 February 1969 occurred close to the British Antarctic Survey scientific station and this resulted in the gravity base station, which had been used as the base for this survey, being covered by about 1 m. of ash. Values for other gravity base stations in this area are given below and details of their positions have been given by Griffiths and others (1964).

The value for the station at Signy Island was obtained by Kennett (1965*a*) during his revision of the South America–Antarctic Peninsula gravity link. The other values are based on the revised value for Deception Island, using the station differences given by Griffiths and others (1964).

Gravity station	*Gravity value* (cm. sec.$^{-2}$)
Signy Island, South Orkney Islands	982·1394
Admiralty Bay, King George Island	982·1930
Galindez Island, Argentine Islands	982·3392
Stonington Island, Marguerite Bay	982·5094