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BULLETIN 170

GEOLOGY AND GEOMAGNETISM OF THE BOUNTY REGION EAST OF THE SOUTH ISLAND, NEW ZEALAND

by
DALE C. KRAUSE

**New Zealand Oceanographic Institute
Memoir No. 30**

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Photo, E. J. Thornley

MV *Taranui* in Wellington Harbour.

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FOREWORD

Over the past few years there has been a notable increase in the amount of magnetic data from measurements of the earth's field in the New Zealand region. Much of this has arisen from work carried out by Geophysics Division, D.S.I.R., comprising individual traverses in the near-shore region from ships operating with towed magnetometers.

The study reported represents the first occasion on which a close survey of a relatively extensive oceanic area in the vicinity of New Zealand has been carried out using this technique. The results, as well as throwing light on the near-surface physical properties of the earth's crust in this region, give an indication of the results likely to be expected from extensions of this technique to other areas around our coasts.

In this memoir Dr Krause has considered the correlations between the magnetic data and the sea-floor morphology and structure in an area that is of fundamental interest in problems of New Zealand structural geology.

The manuscript for this memoir has been prepared for publication by Mrs P. M. Cullen.

J. W. Brodie, Director,
New Zealand Oceanographic Institute, Wellington.

GEOLOGY AND GEOMAGNETISM OF THE BOUNTY REGION, EAST OF THE SOUTH ISLAND, NEW ZEALAND

ABSTRACT

THE ocean floor east of South Island, New Zealand, is a sub-continental region of predominantly east-west trend dominated by the Chatham Rise on the north and the Bounty Trough, which lies between the rise and the Campbell Plateau to the south. At least three banks exist on the rise. A system of submarine channels arises at the head of the Bounty Trough mainly as submarine canyons in the continental shelf and slope of south-east South Island. These channels coalesce to form a single channel that runs the length of the trough. At least three moderate-sized submarine canyons occur off the west coast of South Island. A geanticline trending north constricts the trough and is marked by the Mernoo Bank on the rise. The distribution pattern of earthquake epicentres shows northerly and easterly trends superimposed on the regional north-easterly structural trend of New Zealand for the north and north-west part of the area where information is available.

A magnetometer survey of part of the Bounty Trough revealed three features: (1) an intense, long arcuate magnetic anomaly with associated anomalies in the western part of the trough, (2) a low but persistent negative anomaly trending east in the eastern part of the trough, associated with local, intense anomalies and (3) widespread, low, ill-defined anomalies. The arcuate anomaly can be caused by a deep-seated highly magnetic intrusion piercing the lower levels of the crust. East-trending faults can be associated with this intrusion. The eastern anomaly can be caused by basement faulting with some local intrusions. The widespread, ill defined anomalies were too small to be adequately defined by the survey.

Magnetic profiles around New Zealand reveal several geomagnetic provinces in the sea floor: the Bounty Trough; the deep ocean floor characterised by large broad anomalies; the Macquarie Ridge characterised by intense, highly variable anomalies; the Campbell Plateau with numerous anomalies ranging from very large and extensive to intense but local; and lastly, the following with no or very local anomalies – Chatham Rise, the sea floor immediately flanking most of South Island and some of the Campbell Plateau, and Lord Howe Rise. The last two regions are probably areas of very thick sediments. The areas with widespread anomalies may be composed of relatively shallow, structurally complex crystalline basement rocks and of igneous intrusions.

Large changes in depth in the Bounty Region have occurred, probably mostly in Mesozoic time. The Chatham Rise and the Bounty Islands were uplifted near or above sea level, leaving the Bounty Trough as a relatively depressed region. Late Cenozoic movements have continued the trend. The ages of most of the faults, folds, and intrusions are unknown, but probably many formed in the earlier deformation and were reactivated in late Cenozoic time. Although the channels and certain other bathymetric features indicate recent geological changes and deformation, the area is thought to have been stable (relative to continental New Zealand) through most of Tertiary time.

INTRODUCTION

From 23 January to 7 February 1962, a bathymetric-geomagnetic survey was made of the Bounty Trough (bathymetric chart in pocket) on the New Zealand Oceanographic Institute cruise, Magnet I aboard the chartered vessel MV *Taranui*. The cruise was undertaken by the New Zealand Oceanographic Institute and the Geophysical Survey of the New Zealand Department of Scientific and Industrial Research. Scientific personnel consisted of: D. C. Krause, N. M. Ridgway, and A. Langford of N.Z. Oceanographic Institute; N. L. Roberts and R. B. Williams of Geophysical Survey.

The cruise grew out of discussions regarding the importance and necessity of undertaking detailed geomagnetic surveys of the sea floor off New Zealand. Joint investigations had been agreed upon and thus the stage was set to undertake the study when the author joined the New Zealand Oceanographic Institute for a year under a post-doctoral fellowship of the U.S. National Science Foundation in 1961.

The objectives of the cruise were threefold:

1. To survey a major geological feature using the proton magnetometer.
2. To obtain soundings over this relatively unknown area.
3. To test the existence of a possible east trending, geological structure in the south Pacific (Menard, 1958).

The time and facilities available dictated the scope of the investigation. The survey was set up to detect and elucidate the geomagnetic pattern of a large area and not to work out the details of a small area intimately. It was known that geomagnetic anomalies were common around New Zealand, but before this cruise nothing was known about their trends and pattern in the off-shore area.

Scientific exploration of the area began with Captain James Cook in the HMS *Endeavour* in 1769. Most of the information has been gathered since 1945, and most of the important geologic interpretations have appeared since 1950. Fleming and Reed (1951) discussed Mernoo Bank. Wellman (1956) extrapolated New Zealand tectonics into the region and made paleogeographic reconstructions. Knox (1957) again discussed Mernoo Bank and, briefly, the Chatham Rise. Brodie and Hatherton (1958) investigated the Hikurangi Trench. Brodie (1958) discussed the tectonic setting of the region. Fleming (1962) has reviewed the paleontological data and reevaluated the paleogeography. Norris (1964) studied the sediment distribution of the Chatham Rise, and Hikurangi Trench. Brodie (1964) produced bathymetric charts of the sea floor around New Zealand and discussed the tectonics and sedimentation of the region. The present study goes into greater detail in the Bounty region and contains new bathymetric and geomagnetic data. Readers are referred to Brodie (1964) and Norris (1964) for sediment distribution in the Bounty region. Smaller-scale bathymetric charts (U.S. Naval Oceanographic Office charts 6710 and 15254) show less accurate versions of the bathymetry of the Bounty region.

The first published geomagnetic data of the region were two geomagnetic profiles obtained by a magnetometer towed by an airplane from Christchurch to the Mernoo Bank and back (Gerard and Lawrie, 1955). In recent years a number of New Zealand and other ships have recorded profiles around New Zealand. Adams and Christoffel (1962) discussed three magnetic profiles between New Zealand and Antarctica. Heirtzler (1961) presented a profile taken in 1960 by the RV *Vema* of the Lamont Geological Observatory. The RV *Argo* of the Scripps Institution of Oceanography made a reconnaissance study of the region in 1961, and the magnetic information was furnished to the New Zealand Oceanographic Institute. Cullington and Hanley (1963) presented the results of a reconnaissance study of the New Zealand coastal waters to detect local variations of the compass.

The existence of the Bounty Channels was first brought to the writer's attention by H. W. Menard who investigated the channels in early 1961 with the RV *Argo* on the Monsoon Expedition. The study of the channels in this report grew out of the compilation of existing information in the records of the New Zealand Oceanographic Institute and of the soundings collected from *Taranui* during the present magnetic survey.

The proton magnetometer used was built by Geophysical Survey, D.S.I.R., and operated at a sensitivity of 30 gammas per count.

The echo sounder used was an ELAC Atair (Electroacustic Gymbau, Hamburg), which functioned well to a depth of 2,500 metres and occasionally to a depth of 2,900 metres.

BATHYMETRY – SOURCES OF INFORMATION

The sounding information for the area mapped has come from many sources (table 1) and was obtained by a variety of means ranging from surveys of the N.Z.O.I. and the Royal New Zealand Navy and traverses by many local and foreign ships to the very old wire soundings. The U.S. Navy furnished a large amount of data obtained in connection with recent Antarctic operations. The information ranges in quality from excellent (surveys of the HMNZS *Lachlan*) to poor. The N.Z.O.I. has a continuing programme for the compilation and analysis of the data on charts of various scales. The accompanying bathymetric chart (in pocket) represents the first of a series of compilations around New Zealand at a scale of 1 : 1,000,000.

The soundings have been analysed and incorrect ones eliminated. Poorly positioned tracks have been repositioned or eliminated if necessary. The chart shows the location of the soundings actually used. The basis for elimination of soundings was:

1. Compatibility with reliable tracks.
2. Density of soundings.
3. Logic of the bathymetric contouring.

The inaccuracies in the greater part of the charts are those associated with astronomical ship navigation, and it is not possible to eliminate these inaccuracies using present techniques of sextant navigation: there are additional inaccuracies because of the varying quality of the navigation from the ships. A better chart must await detailed surveys using precision methods such as used by the HMNZS *Lachlan* in her coastal surveys. Although such surveys would improve the details, the main features of the bathymetry are well defined by the present methods, except in the south-eastern part of the area (south of the Bounty Trough) where very little information exists.

Table 1. Source of Soundings

HMNZS *Tutira*	Nov–Dec 1949	New Zealand
HMNZS *Pukaki*	April 1950	New Zealand
HMS *Veryan Bay*	September 1950	United Kingdom
RRS *Discovery II*	November 1950	United Kingdom
HMNZS *Lachlan*	1951–55	New Zealand
HDMS *Galathea*	December 1951	Denmark
RNZFA *Tui*	August 1956	New Zealand
MV *Hertford*	..	United Kingdom
MV *Viti*	Nov 1960–May 1961	New Zealand
RV *Vema*	April 1960	United States
HMNZS *Kaniere*	Nov 1960	New Zealand
MV *Taranui*	Jan–Feb 1962	New Zealand
Various ships	All or part of 47 tracks on collector charts from ..	United States Naval Oceanographic Office
BA Charts 788, 1212, 3634		British Admiralty

REGIONAL DESCRIPTION

The accompanying bathymetric chart (in pocket) covers a part of the two-sheet bathymetric chart of New Zealand (Brodie, 1964) and represents more recent data. Features shown on the chart, figures 1 and 2, and table 2 are discussed below.

Hikurangi Trench

The Hikurangi Trench is shallow (3,000 m in depth), with a flat floor in which is incised a prominent deep-sea channel (Brodie, 1964); two major submarine canyons, Kaikoura Canyon and Pegasus Canyon, and other smaller ones, lead into the trough. Heezen (1963) reported 2 kilometres of sediment in the trench. The basement of the trench beneath the sediment therefore has a more trench-like profile.

The sea floor between the Chatham Rise and the trench is abnormally shallow (2,500 m) for a feature that would seem to be continuous with the deep-sea basin floor of the south-west Pacific Ocean. This sea floor has a few gentle hills.

North Chatham Slope

The North Chatham Slope morphologically is a continental slope. It has probably been steepened in late geological time both on the west at the trench and on the east at the extremity of the area mapped as judged by the presence of a trough at its foot. Numerous gullies are incised in the slope and at least one channel leads from its foot. A trough-like depression near 43°S lat., 178°E long., is interpreted as a graben.

Chatham Rise

The Chatham Rise is separated from the South Island by a saddle termed the Pukaki Gap. Although the gap is not deep (500 m), it marks a

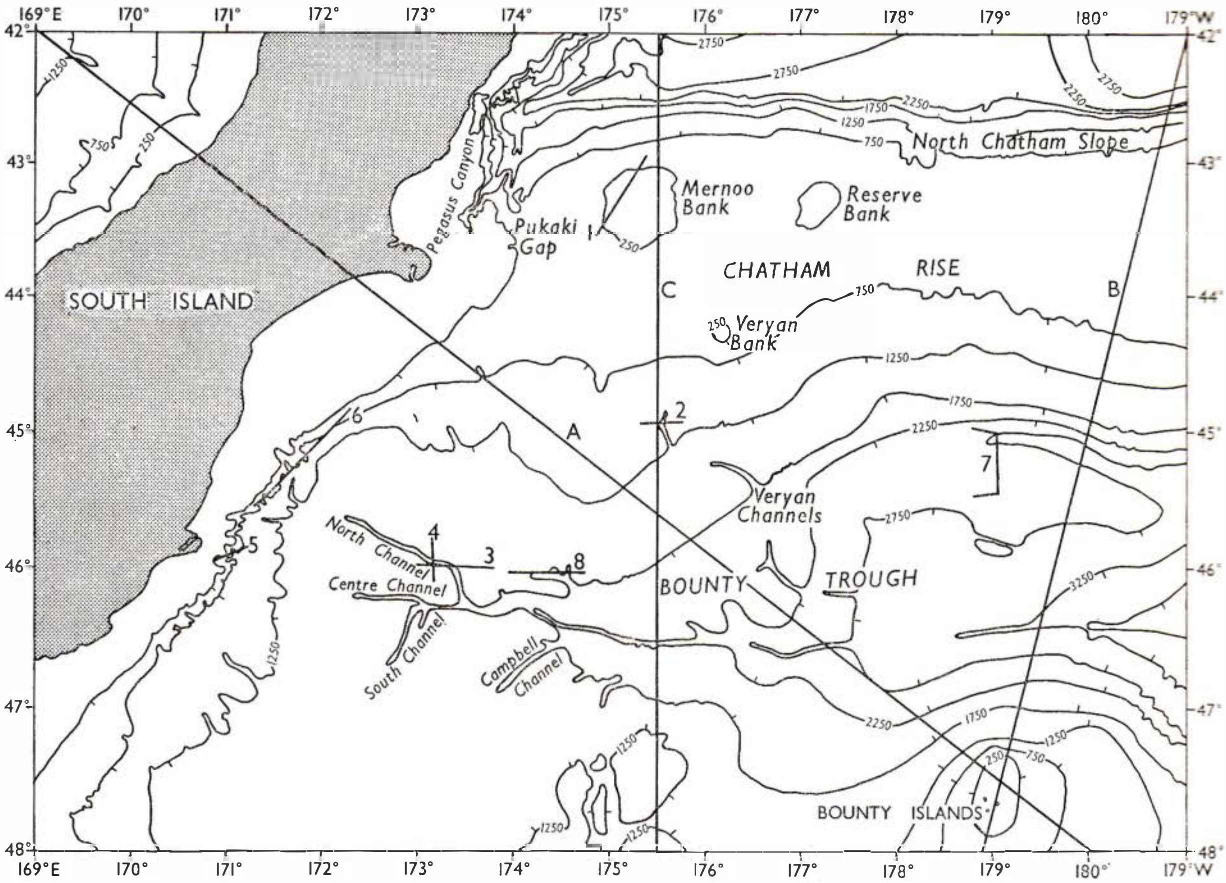

Fig. 1: Locations of bathymetric profiles across the Bounty Trough region. Depths in metres. (For profiles A, B, and C see Fig. 2; for profile 1, Fig. 3; profile 2, Fig. 4; profile 3, Fig. 7; profile 4, Fig. 8; profile 5, Fig. 5; profile 6, Fig. 6; profile 7, Fig. 9; profile 8, Fig. 11.)

Table 2. Details of Bathymetric Features

Feature	Width (km)	Length (km)	Slope (km/km)	Height (m)	Depth (m)
Hikurangi Trench	base 2–40	..	..	..	2,800
North Chatham Slope	50	550	0·2 max. 0·05 average	2,500	..
Chatham Rise	base 280	550	..	2,500	125–400
Mernoo Bank	60	75	..	..	125
South Slope of Chatham Rise	140	350	0·01–0·04	2,350	
Bounty Trough	300	750	0·004 average	..	1,250–4,000
Bounty Channel	2–4	800	0·004	400	1,250–4,000
Shelf west of South Island	35	..	..	..	..
Shelf east of South Island	average 50 range 1–90	..	0·001	..	..

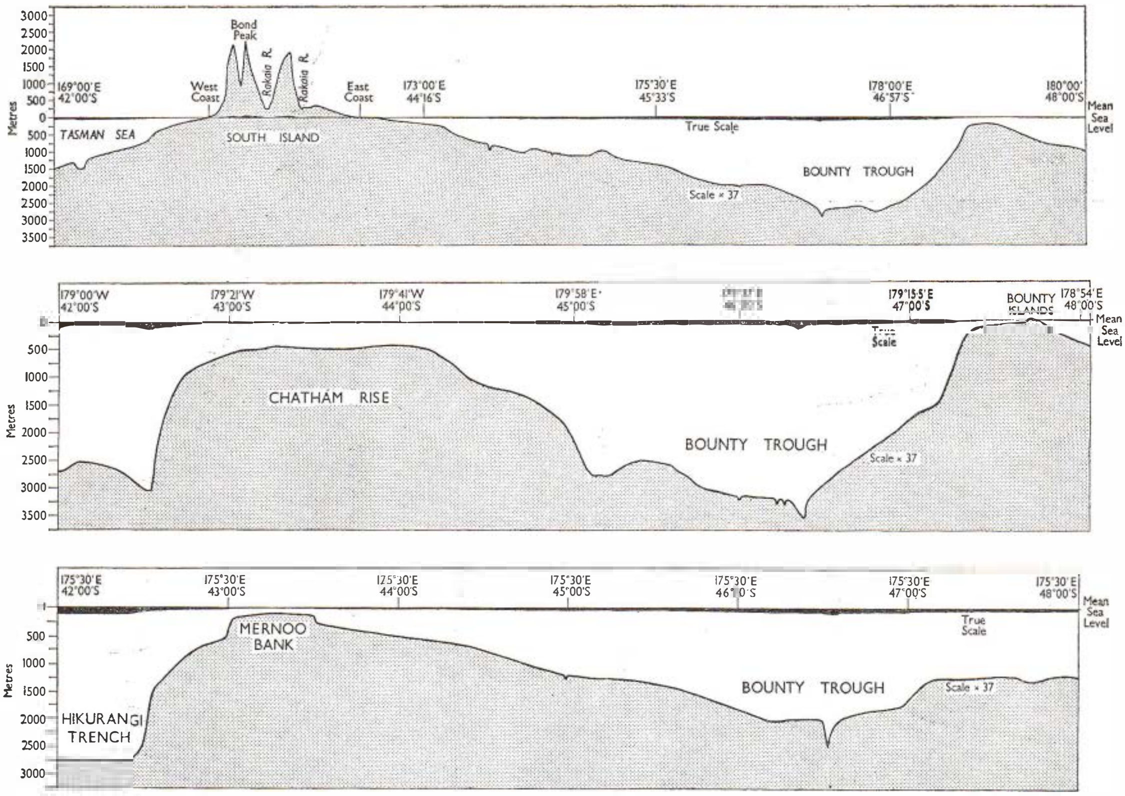

Fig. 2: Three profiles across the Bounty Trough region (Profiles A, B, C, fig. 1).

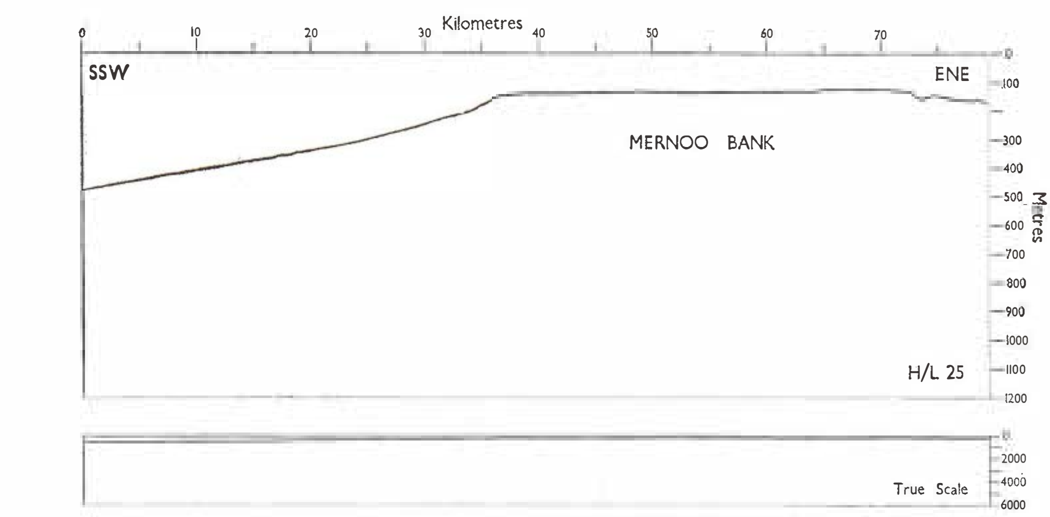

Fig. 3: Profile across Mernoo Bank (Profile 1, fig. 1).

distinct geological gap because the easterly trend of the Chatham Rise is not strongly marked in the geology of South Island.

Mernoo Bank (fig. 3) was at or above sea level during Pleistocene time and greywacke is found on its surface (Norris, 1964). Although Reserve Bank is only slightly above the general level of Chatham Rise, the occurrence of glauconite in the sediment is sufficiently affected for the bank to mark an area of maximum glauconite in the sediment (Norris, 1964); this is perhaps because of a slightly greater water current velocity over the bank and greater solution of the calcareous Foraminifera, the other main constituents of the

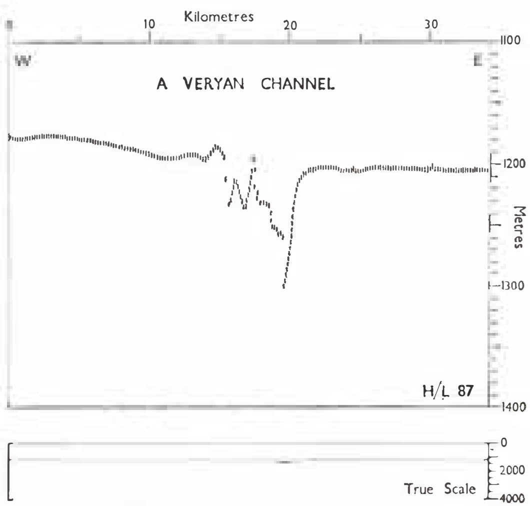

Fig. 4: Profile across a Veryan Channel (Profile 2, fig. 1).

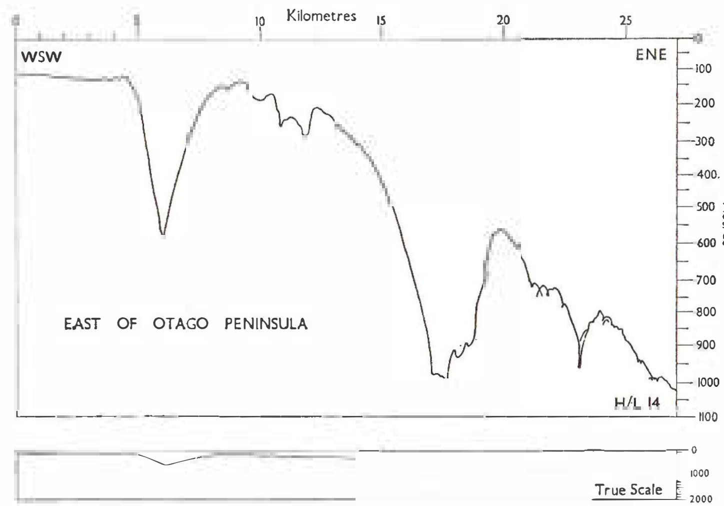

Fig. 5: Profile across submarine canyons east of Otago Peninsula (Profile 5, fig. 1).

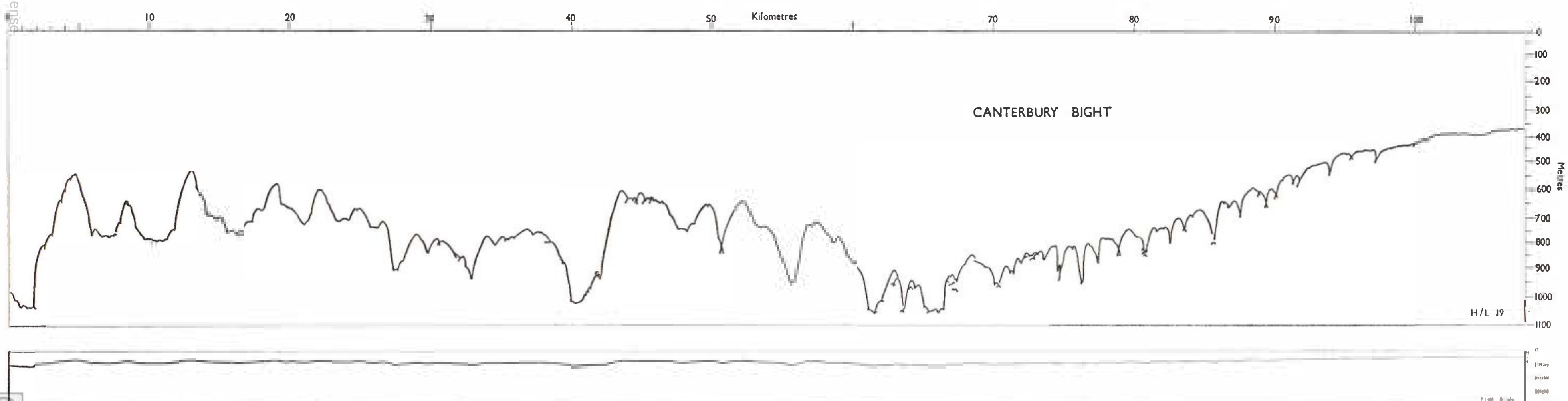

Fig. 6: Profile across canyons of the Canterbury Bight (Profile 6, fig. 1)

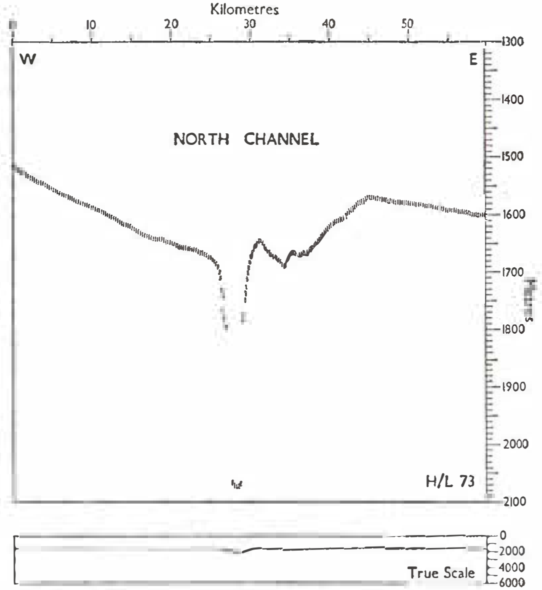

Fig. 7: Profile across North Channel (Profile 3, fig. 1).

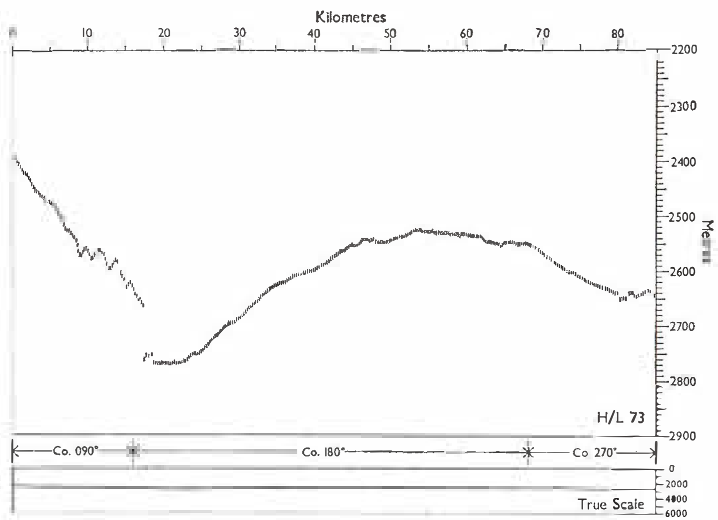

Fig. 9: Profile across the northern part of eastern end of the Bounty Trough (Profile 7, fig. 1).

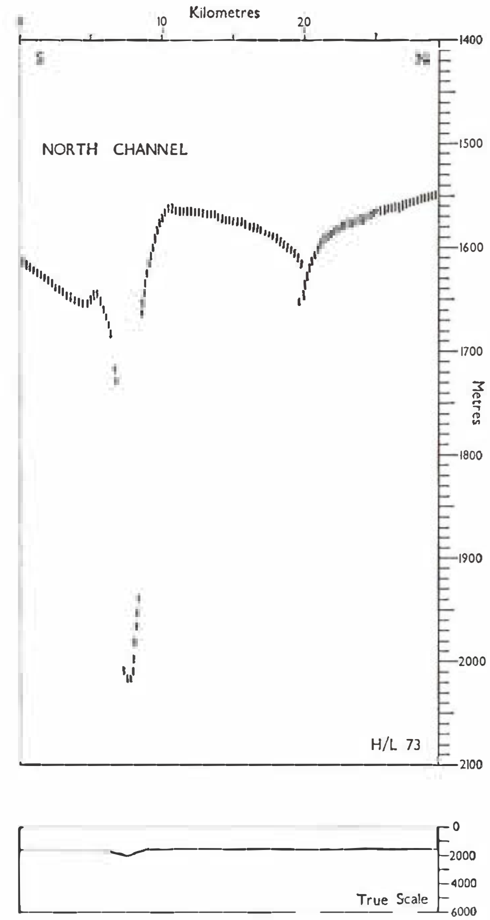

Fig. 8: Profile across North Channel (Profile 4, fig. 1).

sediment. Veryan Bank has been eroded flat and was also at or near sea level during Pleistocene time. It is covered by calcareous sand and shell, as is most of Mernoo Bank.

Many gullies and several channels (such as the Veryan Channels, fig. 4) cross the southern slope of the Chatham Rise. The Veryan Channels may consist of several channels although only two are shown because the area is not thoroughly surveyed.

A north-south cross structure, the Mernoo anticline, along the 175th meridian modifies the bathymetry considerably. In the north, it begins with the Mernoo Bank, continues south to constrict the Bounty Trough and appears as a mass of irregular hills in the southern part of the area (see bathymetric chart).

Urry Bank

Urry (1949, p. 262) reported a depth of 199 m at 45°S lat., 174° 18′E long., based on an American source. Subsequently other ships have passed near the location without finding this depth and the N.Z.O.I. has twice made cursory searches for it without avail. Therefore, it has not been included in this compilation. However, as the sea floor is quite irregular here and there are high points nearby, the bank may exist although not necessarily in its reported position.

Bounty Trough

The Bounty Trough may be divided into the following regions from west (shallow water) to east (the deeper Pacific):

Boundary: Shore line

1. Continental shelf (Canterbury Bight) 0–250 m

Boundary: Inner continental slope

2. Upper platform 1,250–1,750 m

Boundary: Geanticlinal cross elevation

3. Lower platform 2,750 m

Boundary: Steep slope

4. Deep trough 3,000 m

The Bounty Trough is a bathymetrically complex depression between the Chatham Rise and the Campbell Plateau. The western terminus of the trough is the shelf area of the Canterbury Bight, the coastal embayment of South Island between Christchurch and Dunedin. The water depth at the shelf edge drops to about 1,250 m by way of a complex slope that cannot properly be called a "continental slope". In many regions in the world, the typical "continental slope" as a single feature does not exist. Instead, the slope is divided into two or more segments with a broad zone of intermediate depth between them. Because the existing nomenclature does not properly fit such a region, two new terms are proposed: the "inner slope" and the "outer slope". The inner slope is defined as the slope that is bordered at the top by the continental shelf. The outer slope is defined as the slope bordered at the bottom by the deep-sea floor.

Dissection of the inner slope gives it a complex character off Otago (fig. 5), and half way northward along the shelf edge of the Canterbury Bight (fig. 6). The shelf edge is deeply cut by submarine canyons that in some cases extend far up the shelf. At 45°S lat., the slope is cut by gullies, but northwards the gullies diminish in number.

The upper platform is a very flat plain sloping gently at 1 : 1000 eastwards, in which submarine channels up to 400 m deep (figs. 7 and 8) are incised. The trough is more or less constricted by the Mernoo anticline which appears in the north as Mernoo Bank. Southward of Mernoo Bank are submarine hills and a broad, gently plunging elevation. South of the trough an irregular elevation marks the southerly continuation of the anticline. The exact configuration of the anticline is not known but it consists of a gentle rise that is somewhat undulating and is cut by several submarine channels.

Eastwards of the 175th meridian, the trough drops to a local bench at 2,100 m depth, which is cut by channels.

The lower platform at 2,750 m depth is a region of gentle relief occupying the northern half of the lower part of the trough in the area under discussion. The longitudinal profile of one submarine channel near 46°S lat., 179°E long. shows a reversal of slope. The platform drops off to the south-east in a series of two or more steps to the deep medial channel of the trough.

Channels of the Bounty Trough

The submarine channel system (figs. 7, 8, 9) is a prominent feature of the Bounty Trough and has been briefly described by Brodie (1964).

North Channel, Centre Channel, and South Channel obviously have their origin near the coastline, as they merge into the system of submarine canyons of the continental shelf between the Clutha River in the south and the Waitaki River in the north. Several other channels cross the upper platform but none are as deep nor as continuous as the three mentioned above, cross sections of which show them to be up to 400 m deep and $3\frac{1}{2}$ km wide near 173°E long. (figs. 7 and 8).

Apparently one or more channels of appreciable

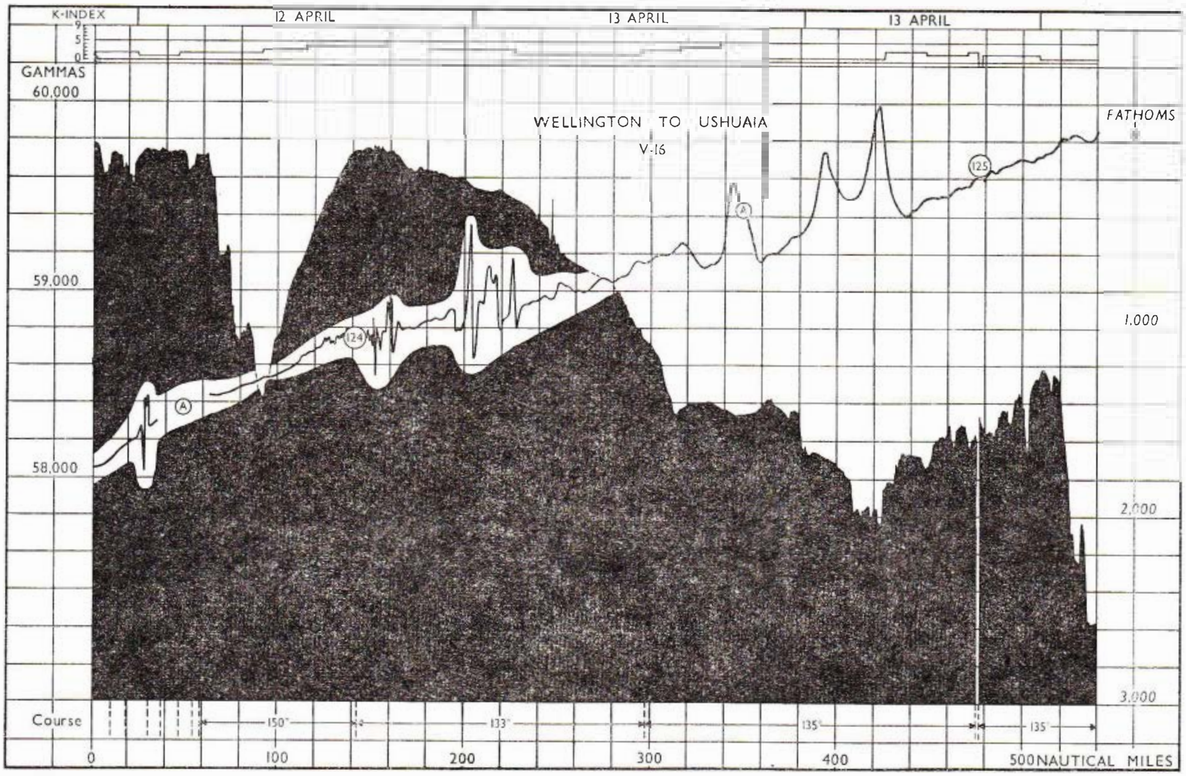

Fig. 10: Bathymetric and magnetic profiles taken by RV *Vema*.

size occurs on the north slope of the trough near 173°E longitude, but the evidence is not clear. A channel seems to be present at the position (45°S lat., 174° 20′E long.) previously given for Urry Bank, but little evidence of it is found immediately to the south. Channels of several ages may exist, the older ones being partly buried by later sedimentation, but surveys in much more detail are needed to give a definitive answer.

Campbell Channel runs north parallel to the coast in the subdued trough between South Island and the main part of the Campbell Plateau. A number of small subsidiary channels lead into it, but nowhere does it emerge on the continental shelf to trap sediment dumped on the shelf. Although the channel is well developed, its gradient is very small.

The above-mentioned channels all coalesce west of the 175th meridian to form the main Bounty Channel, which is not well surveyed in its lower reaches. It is well established east to 176°E long., and the writer believes it has been crossed near 180° long. by the RV *Vema* (Heirtzler, 1961). A few spot soundings between 176°E and 180°E long. indicate continuity.

Although the "Veryan Channels" have been mapped as a single major channel because of the limited survey data, more than one channel is probably present. One or more of these originates north of the Veryan Bank.

Bounty Islands

The Bounty Islands consist of coarse-grained granite on the crest of a poorly surveyed, broad elevation. Small gullies mark the north-west side of the elevation where one ship (RV *Vema*) has crossed it (fig. 10). Wasserburg, *et al.* (1963) determined the age of the granite to be 189×10^6 years B.P. by means of the potassium-argon and strontium-rubidium methods.

Tasman Sea (West Coast)

Part of the Tasman Sea floor lies within the area of the bathymetric chart accompanying this bulletin and is briefly described here. The continental slope west of the continental shelf is relatively gentle (1 : 100) and marks the intersection of the Lord Howe Rise with South Island.

Three large submarine channels cut the slope and seem to correlate with Cook, Whataroa, and Hokitika Rivers. Grey River and Teremakau River may also have contributed sediment to Hokitika Canyon.

INTERPRETATION OF THE BATHYMETRY

Implications of the Channels

During the Pleistocene lowering of sea level, the rivers Clutha, Taieri, and Waitaki and minor rivers between them dumped their sediment loads directly into the submarine canyons that are incised into the continental shelf. The large canyons east of Otago Peninsula do not correspond with any adjacent large rivers, but may correspond with former positions of the mouth of the Taieri River and may be localised by the presence and erosion of the Otago Peninsula. Between the Waitaki River and Banks Peninsula, canyons do not cut the slope although large rivers such as the Rangitata and the Rakaia enter the sea in this sector. Evidently their large sediment load was all dumped on the shelf or else actively built it out.

The sediment flowed down the submarine canyons and out on to the upper terrace of the Bounty Trough. There it flowed in small channels, which joined to form the three large channels: North, Centre, and South Channels.

A certain amount of coarse material (boulders, gravel, and some sand) must have been deposited at the base of the slope (1,250 m depth), but a large part of the sand, silt, and clay continued down the channels and eventually was deposited on the deep-sea floor far to the east of the charted area. The evidence for this is as follows:

1. The channels do not have pronounced, strictly marginal levees, which suggests that the sand and coarse silt of turbidity currents did not overtop their edges.
2. Any submarine fans that exist at the bottom of the slope have been incised by the channels.
3. No evidence of accumulation of sediment has been found anywhere along the length of the main system of channels.

Although these channels superficially seem the youngest bathymetric feature visible, they seem to be at grade with the sea floor (west of 175°E long.). This implies a genetic relationship whereby the coarse sediment flowed down the channels, while silt and clay overtopped the channels and built up the surrounding plain. Thus, the channels could be both eroded and nondepositional features. Verification of this must await future work.

The coalescing of all of the channels west of 175°E long. indicates that the north-south Mernoo anticline predates the channel formation. The broad, gently sloping expanse of the sea floor west of the geanticline implies that the geanticline has acted as a dam to the spread of sedimentation until relatively recent times.

Campbell Channel and the Veryan Channels are unusual in that they arise, not on the continental shelf, but in submarine areas, and have been doing so for a long time. This implies either that (a) the source area was once at sea level and that the channels are very old (less so for Veryan Channel, which would receive some sediment from the erosion of Mernoo and Veryan Banks) or that (b) there is a submarine source for turbidity currents.

If a submarine source has existed then either the submarine sediment has moved out from the shore as a sheet, accumulated, and gained momentum in the centre of the trough (perhaps the origin of Campbell Channel), or a true source of removable submarine sediment exists such as submarine slumping of pelagic sediment. A choice cannot be made because of the paucity of data.

It is questionable whether a Veryan Channel once crossed the Mernoo anticline and thus predated it.

Interpretation of the Lower Platform of the Bounty Trough

The writer suggests that the lower platform was previously flat and has since been deformed into a gentle east-west anticline that still carries portions of the original flat floor.

A submarine channel at 45° 45′ S lat., 179° 00′ E long., with deep water both upstream and down stream, could have been beheaded by deformation. (The poorly surveyed platform of 2,100 m depth may be either a fan formed by turbidity currents dropping coarse sediment at the east edge of the Mernoo anticline or an uplifted portion of the lower platform.)

Several features characterise the lower platform:

(a) The low relief with broad, flat, or gently dipping expanses;
(b) The broad, gentle, east-west rise;
(c) The beheaded channel;
(d) The relatively steep southern flank of the Chatham Rise where it meets the platform (fig. 9). A small fault lies just at the foot of that slope – a dip-slip throw of at least tens of metres is indicated. Also at the foot of the slope is a shallow depression;
(e) The steep slope to the south-east into the deeper portion of the Bounty Trough.

A geologic history of the relatively recent deformation may be reconstructed from the above information:

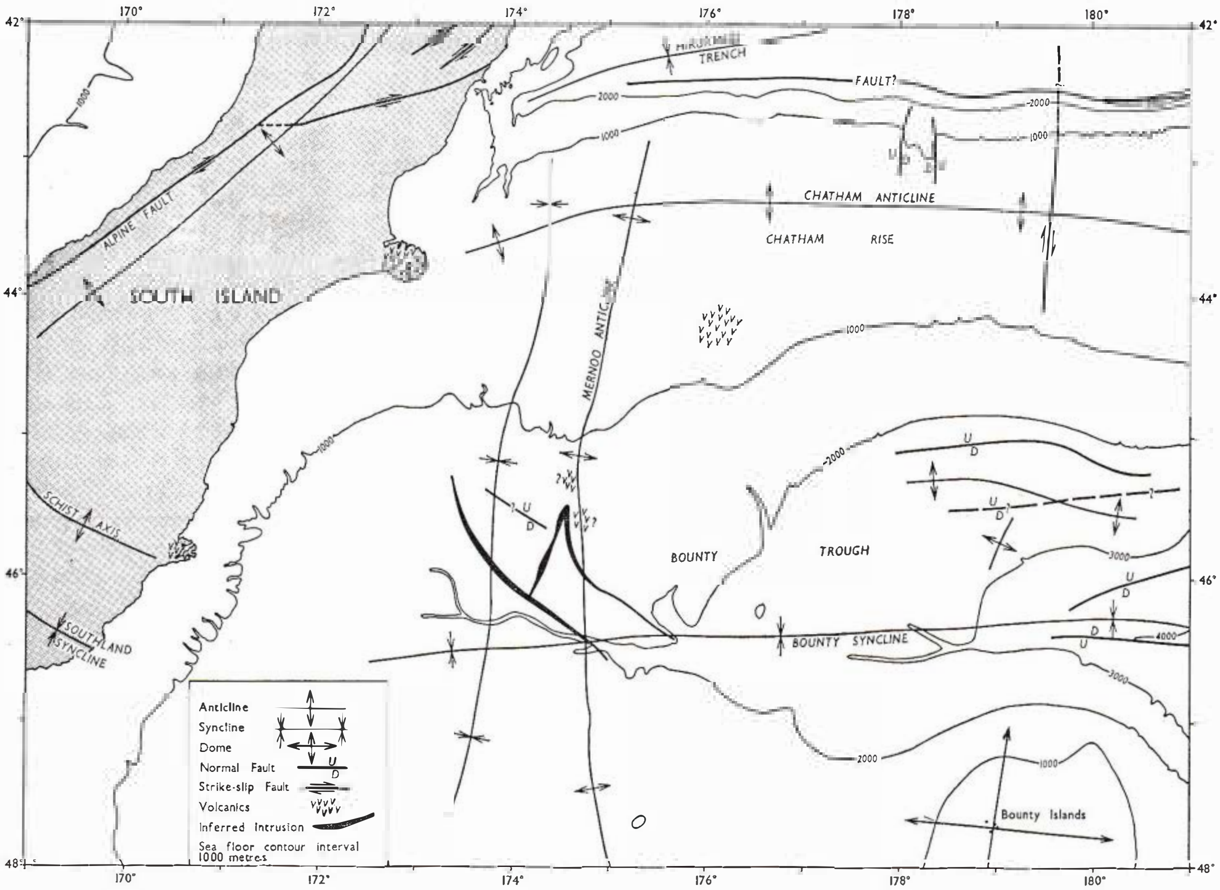

Fig. 11: Structural interpretation of the Bounty Trough.

1. On to a previously existing sea floor formed in part by the south limb of the Chatham Rise, sedimentation built up a flat sea floor stretching right across the trough and for an indefinite distance to the east, considerably farther than the margin of the area charted. (A topographic high to the east would have facilitated this sediment accumulation.)

2. A submarine channel was established across this gently sloping sea floor.

3. Deformation of the sea floor by the rise of an east-west anticline-domed up the sea floor across the course of the channel, thereby beheading it. (If an alternative explanation of the beheading of the channel is sought in slumping then a volume of 800 km^3 would have had to be removed by this means.)

4. The Bounty Trough to the south-east of the platform has been down-dropped relative to the platform by 1,000 metres. A crossing of the area by the RV *Vema* (fig. 10) (Heirtzler, 1961) illustrates the graben-like nature of the discontinuity between the two areas.

Geologic Structure

The geologic structure of the Bounty region may be discussed under three categories: (1) primary structures (obvious, dominating), (2) secondary structures superimposed on the primary structures but large, and (3) minor structures superimposed on the first two patterns. Both primary and secondary features and a few minor features pertinent to the discussion are shown in fig. 11.

Primary structures are the Chatham anticline, the South Island anticline, the Bounty syncline, and the syncline of the Hikurangi Trench. These may be termed geanticlines and geosynclines because of their size.

Secondary structures are the Mernoo anticline, the less well defined syncline to the west of it, the dome of the Bounty Islands, and the major escarpment, the North Chatham Slope. In scale these equate with the terrestrial features of the Alpine Fault, the schist axis (Wellman, 1952) and the Southland Syncline of South Island.

Minor structures include faults on the Chatham Rise, the faults and folds of the eastern Bounty

Trough, the few scattered volcanoes and the lesser structures of South Island (not included here).

There is little obvious correlation between the exposed portion of South Island and the sea floor to the east of South Island. The apparent discontinuity may reflect one or more of the following situations:

1. Similar structures in both areas, displaced laterally by faulting near the edge of the continental shelf;
2. Similar structures distinguished by a sharp change in strike at the edge of the shelf;
3. Totally different structures marked by a change of tectonic facies and/or crustal structure near the edge of the shelf.

Various authors (see Fleming, 1962) have proposed structures for the discontinuity. This study neither confirms nor rejects any of these, but rather favours the last two situations listed above.

It is notable that while the structures of the sea floor seem to be oriented generally east-west or north-south and those of the mainland of New Zealand are oriented north-east to south-west, yet the distribution of earthquake epicentres on South Island correlates better with the sea-floor trends than with the geologic structure of South Island (see section on Earthquakes).

Geologic History

The history of the Hikurangi Trench is complex because of the influence of the deformation undergone by the emergent portions of New Zealand and the lateral migration of sites of deposition. Despite this complexity the geologic and bathymetric evidence suggests that the present bathymetry was established in the late Tertiary and Quaternary.

The history of the Bounty region is largely unknown, but is presumably long. Very few geologic samples other than Recent sediments have been obtained from this region, the only bedrock samples being greywacke from the Mernoo Bank and granite from the Bounty Islands. A sequence in the Chatham Islands east of the charted area provides more information.

These data and the foregoing bathymetric information suggest the following history. The Mernoo greywacke and the Chatham schist indicate that the Chatham Rise was a site of deposition in the Mesozoic and that probably large volumes of sediment were deposited. According to Reed (1958, p. 55), 15,000 ft of sediment would be necessary for the production of a schist such as the Chatham schist if the metamorphism is a simple load metamorphism. This, of course, also implies 15,000 ft of erosion at the Chatham Islands to remove that same overburden. A large amount of overburden was eroded off the site of the Bounty Islands to expose the granite and a lesser amount was probably eroded off Mernoo Bank. At the time of the greywacke deposition, the Rise must have been as deep or deeper than the Bounty Trough and the Hikurangi Trench, so that the present bottom topography must be of late Mesozoic or younger age. By Oligocene time, the schist was exposed at the Chatham Islands, and the geologic conditions have not changed appreciably at the islands since that time. By extrapolation, therefore, the bottom topography of adjacent areas had probably been established by Oligocene time.

The Bounty Trough therefore probably came into existence during Mesozoic or early Tertiary time. The area has been only slowly undergoing transformation since then although its recent development may have been more rapid. The comparatively subdued regional bathymetry attests to the quiet geologic history from post Eocene to Pliocene times. The deep channels, the beheaded channel, the suspended lower terrace of the trough and the graben-like nature of the deeper part of the eastern part of the trough all attest to a late deformation and a break in the sedimentation regime.

EARTHQUAKES

The distribution of earthquake epicentres over the Bounty region (fig. 12) reveals a distinct pattern, some of which is real and some of which is due to the distribution of seismographs in New Zealand. The epicentres plotted are those of shocks recorded in the 21-year period from 1941–61 (Hayes, 1942–59, Anonymous, 1960–61, and data from the New Zealand Seismological Observatory) and are of varying reliability. The epicentres for the first 10 years were published without magnitude information (these are given the conservative value of 3–4 magnitude in fig. 13) and the instrumental coverage was only fair (pers. comm., Director, Seismological Observatory). The instrumentation was somewhat better for the next five years, and the present instrumentation

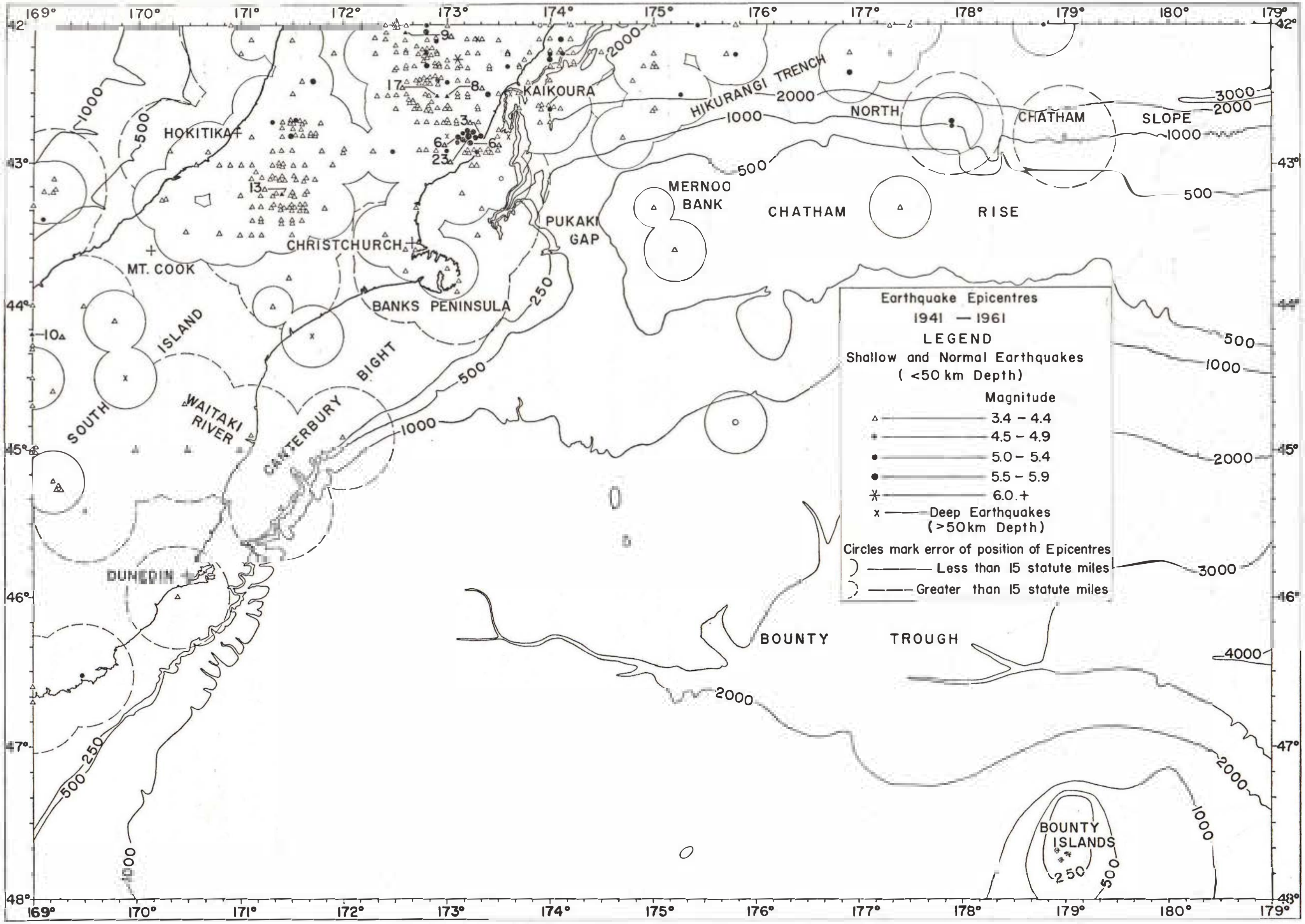

Fig. 12: Distribution of earthquake epicentres in the Bounty region.

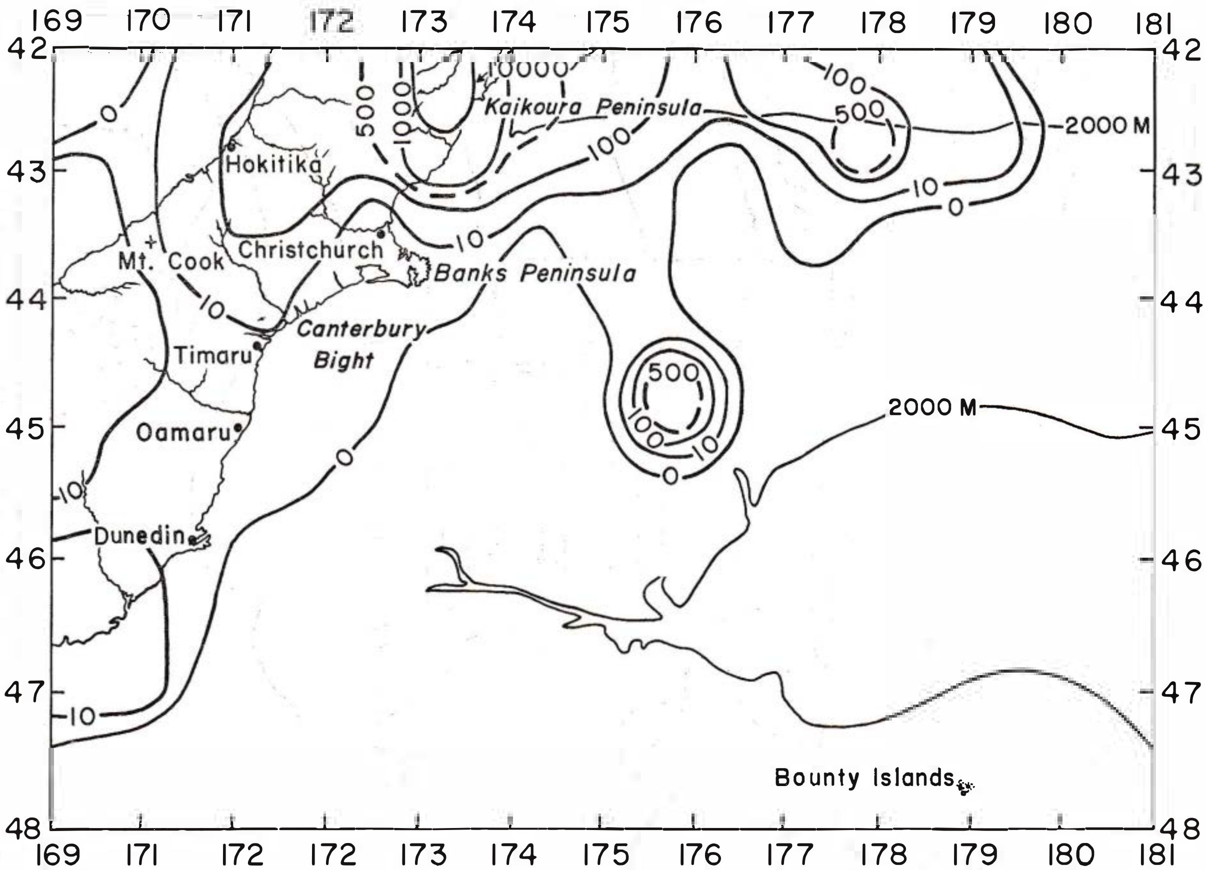

Fig. 13: Distribution of earthquake energy in the Bounty region.

is quite good, but coverage is still limited. No earthquakes of a lesser magnitude than about 5 would be located if they occurred in the south-eastern corner of the chart area (data from the Seismological Observatory). A magnitude 4 earthquake probably would not be recorded if it occurred in the whole south-eastern half of the chart area. A magnitude 3 earthquake might or might not be recorded if it occurred off shore.

The chart of energy released by earthquakes (fig. 13) was prepared from fig. 12 by assigning the earthquakes the energy computed by the formula (Richter, 1958):

$$\log E = 11 \cdot 4 + 1 \cdot 5 M$$

where E is the energy in ergs and M is the assigned magnitude. These energies were then summed over a degree of latitude and longitude and contoured as multiples of a magnitude 3·5 earthquake.

Magnitude	Energy (ergs)
3·5	$10^{16 \cdot 65}$
4·5	$32 \times 10^{16 \cdot 65}$
5·5	$1000 \times 10^{16 \cdot 65}$
6·5	$32{,}000 \times 10^{16 \cdot 65}$

The assumed values of the earthquakes prior to 1951 may give slightly low energies to the regions around Otago and Hokitika River but this will not affect the overall pattern.

An inspection of figs. 12 and 13 shows that the zero contour of energy release approximately follows the instrumental limit for locating the epicentres of small earthquakes with two notable exceptions – Pukaki Gap and the area east of Mernoo Bank. It is not known whether small earthquakes occur in and around the Bounty Trough. A relatively aseismic region extends across South Island from the Tasman Sea through Mt. Cook to the Canterbury Bight. Another such "corridor" separates the Hokitika area from the highly seismic region west of Kaikoura. This latter seismic region is very active and has a northerly trend (fig. 12) in contrast to the regional fault structure which trends north-east. Such a situation suggests an *en echelon* structure. A broad seismic zone extends south of the Hikurangi Trench to include the North Chatham Slope, indicating a certain unity of structure.

The general seismic pattern in the area is, therefore, a north-to-south, east-to-west distribution of epicentres superimposed on the north-east-trending structures of South Island. There is a notable lack of information south-east of South Island. Although large earthquakes do not generally take place there, a single epicentre near 45°S, 176°E indicates that earthquake energy is released; smaller earthquakes thus probably occur.

The distribution of earthquakes is far from uniform from year to year, so trends might be modified by future outbursts of activity in areas that are at present relatively aseismic.

GEOMAGNETIC RESULTS

The earth's magnetic field as recorded by the magnetometer is converted to gammas by the following equation:

$$H = \frac{2\pi}{\gamma_p} \cdot N \cdot f/R$$

where H = field value in gammas

p = ·267513 gamma^{-1}. sec.$^{-1}$, the proton geomagnetic constant (Driscoll and Bender, 1958).

N = precession count cycles (500 or 1000).

f = frequency of crystal (10,000 cps).

R = indicated count of instrument (cycles of crystal per N).

The survey was corrected for diurnal variation and magnetic storms from Amberley Observatory magnetograms furnished by A. Cullington of the Magnetic Survey, Christchurch. The corrections were necessary for only a few short periods and never amounted to more than one count (30 gamma units).

The magnetic survey was plotted both on a track chart which was contoured (see chart in pocket at end of bulletin) and as profiles (fig. 14) The earth's smoothed field was determined as follows. Through each of the profiles, a straight line was drawn by eye to represent the earth's smoothed field. The magnetic intercepts of these lines with longitudinal meridians were plotted, and a straight line was drawn by eye through the intercepts for each meridian. The intercepts of these lines at the position of each profile were plotted. A new straight line for each profile was fitted by eye to these intercepts to give a better approximation of the earth's field. Thus an equation was obtained for the earth's smooth field over the area:

$$F = (S-45°)\ [4{\cdot}43(E-174°) + 374{\cdot}5] - 182\ (E-174°) + 59810$$

where F = total magnetic field in gammas at a position (S, E) where S = south latitude in degrees and E = east longitude in degrees. The resultant

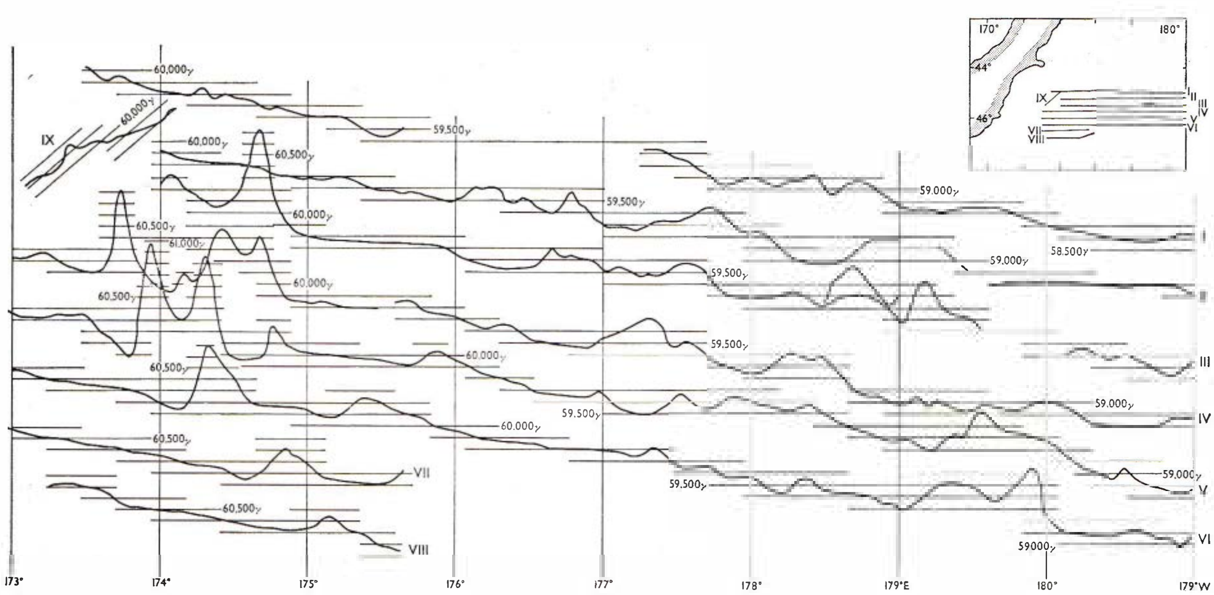

Fig. 14: Magnetic profiles of the Bounty Trough.

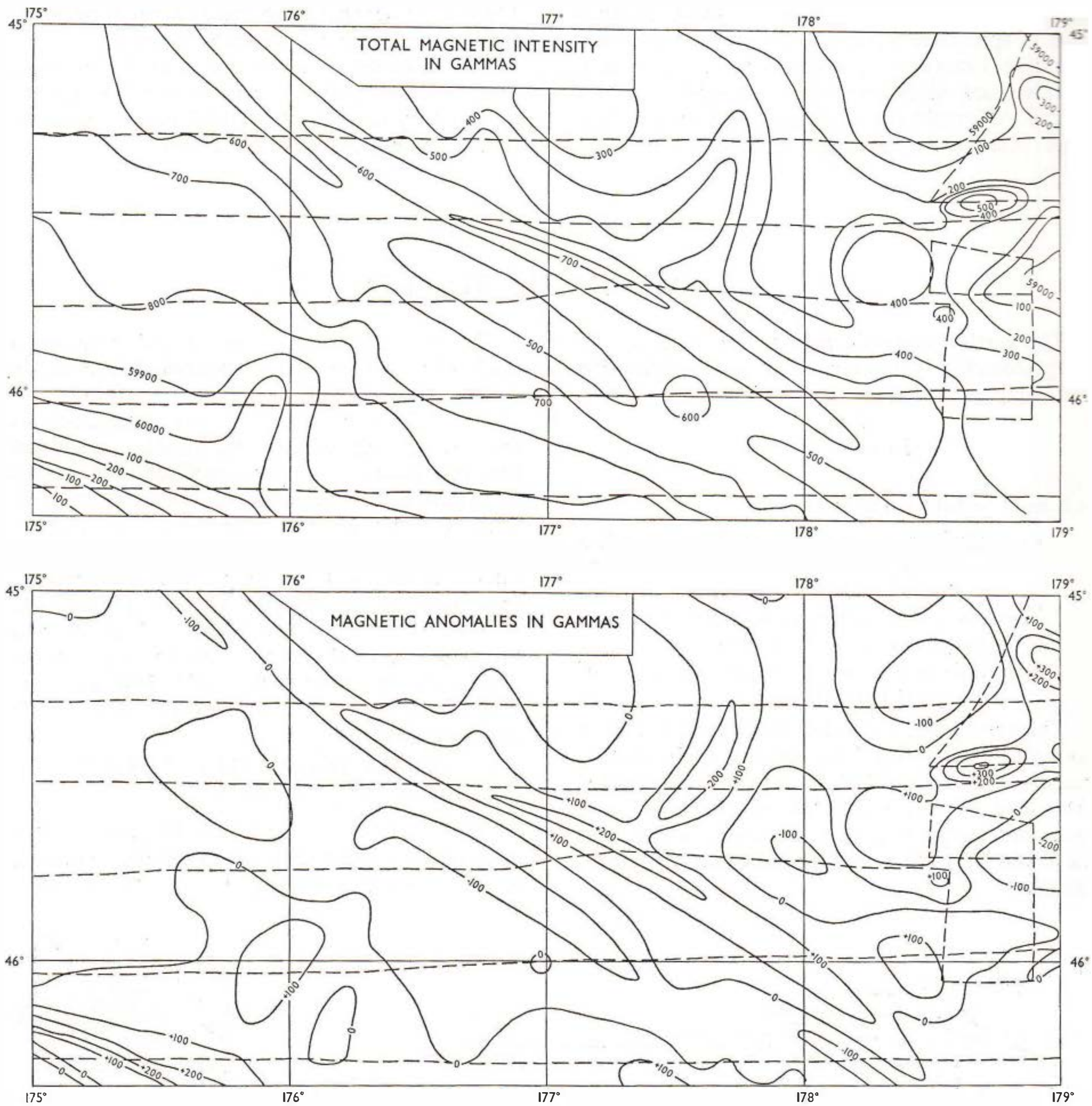

Fig. 15: Alternative magnetic contours of the central Bounty Trough.

field (see chart) curves slightly over the area from north to south.

Any errors in the regional value of the total field will not change the interpretation of the anomaly chart and the conclusions drawn from it.

The anomaly chart was produced from the contoured total magnetic field by subtracting the smoothed earth's field from the total field.

The anomalies fall into three natural groups:

1. An intense positive, arcuate anomaly marking the west end of the Bounty Trough and associated minor anomalies:

This intense arcuate anomaly associated with other anomalies in the eastern quarter of the area is the most distinctive feature in the region. The arcuate anomaly was well-defined by the survey. It is 200 km long, 14 km wide, and of 900 gammas

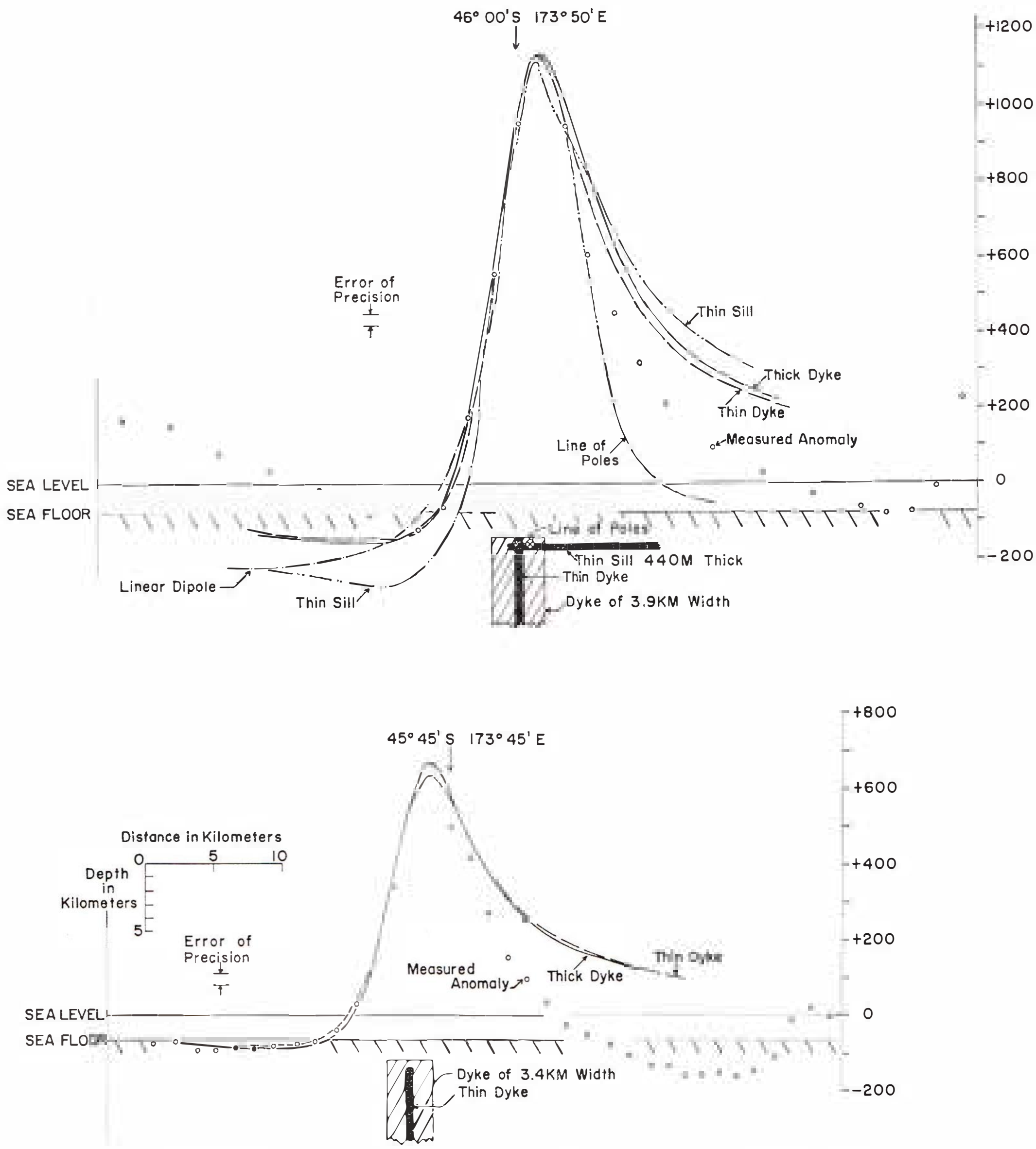

Fig. 16: Theoretical anomaly of a dyke and the recorded magnetic anomaly.

relief (700 gammas positive plus 200 gammas negative).

An essentially parallel feature lies to the north. More or less at right angles to the trend of the first two anomalies is a third area of intense anomaly.

2. A broad, negative, tongue-like anomaly in the deeper part of the Bounty Trough lying north of its axis.
3. Low, poorly defined anomalies of various orientations.

The first two groups are well defined by the survey. Anomalies of the third group are poorly defined because their size is similar to that of the spacing of the survey lines (28 km) and their intensities are quite low (100 gammas). This leads to ambiguities in contouring the data. An alternative solution (fig. 15) of part of the anomaly chart (in pocket) is considered to be less likely as it involves a more subjective interpretation than the solution given on the chart, but it is illustrative of the uncertainty involved.

INTERPRETATION OF GEOMAGNETIC DATA

The magnetic anomalies represent changes of the earth's magnetic field caused by local changes in properties of the magnetic rocks of the earth's crust and upper mantle. These changes may be brought about by a variety of geological or physical factors (Nagata, 1961).

Two crossings of the large arcuate anomaly were compared with theoretical anomalies produced by dykes, sills, and dipoles (fig. 16). The measured anomaly best approximated the theoretical anomaly of dykes. For the large anomaly the properties of the "dyke" could lie between the reasonable limits of those of (1) a "dyke" of 3·9 km depth below sea level, 3·9 km width with an apparent susceptibility of 0·0056 and (2) a "dyke" of 3·9 km depth, 0·39 km width, with an apparent susceptibility of 0·056. For the smaller anomaly, the properties of the dyke could lie between those of (1) a "dyke" of 3·4 km depth, 3·4 km width, with a susceptibility of 0·0034 and (2) a "dyke" of 3·9 km depth, 0·39 km thickness, with a susceptibility of 0·034.

Although the match between the south side of the measured anomaly and the theoretical curve of the dyke is excellent, the match between the north side and the theoretical curve is poor. The north side of the measured anomaly is too low and falls in position between that of the dyke and that of a line of dipoles. The south side of the measured anomaly does not follow that of the line of dipoles. The causative geophysical feature may be (1) a dyke that expands upward so that its north wall dips at almost the same angle as the magnetic field (70°S) or (2) a vertical dyke, combined with a normal fault to the north in which the basement block to the north has been moved upwards. The fault would lie to the north of the dyke anomaly.

The anomaly for the thin sill is similar to that for thick sills and does not represent the measured anomaly closely enough to be preferred to the dyke hypothesis. The anomalies for sills are based on derivations of V. Vacquier (pers. comm.). The anomalies for the dykes were taken from calculations by R. D. Adams (pers. comm.) based on a formula for the total magnetic anomaly produced by an infinite line of magnetic poles (Henderson and Zietz, 1948).

In summary, the intrusive rock is at least 3½ km deep. If it is a few hundred metres wide, the rock is very highly magnetic. If it is a few kilometres wide, the rock has a magnetic susceptibility characteristic of rock such as continental basalt.

The simplest interpretation of the *Vema* magnetic profile of the Bounty Trough (fig. 10) (assuming uniform intensity and direction of magnetisation) is that the three large anomalies represent dyke or pipe-like intrusions. Combined with these are three faults that would explain the negative anomalies at milages: 330, 370, and 440 naut. miles. Each would be normal with downthrow to the south. The faults could have a transcurrent component, which would be undetectable by the magnetic survey. One fault bounds the floor of the Bounty Trough at naut. mile 330. Another occurs at the northern positive anomaly. The upward trend of the general field south of the last southern anomaly can represent the gradual rise of the basement to the south.

The tongue-like negative anomaly trending east-west in the lower part of the trough is apparently associated with the central fault mentioned above. The present survey did not extend far enough south to examine the southern fault. (An alternative, less credible, hypothesis is to postulate the presence of reversely polarised lava flows or a metamorphic alteration of the bedrock, which has destroyed the magnetic minerals.)

The low, poorly defined anomalies are indicative of the grain of the basement but are too conjectural to interpret reliably.

The basic interpretation of the magnetic survey (chart and fig. 15) is that a basement of medium magnetic properties has been faulted east-west to form a trough down-thrown relative to the Chatham Rise to the north. Highly magnetic rock has been intruded along some of the fractures.

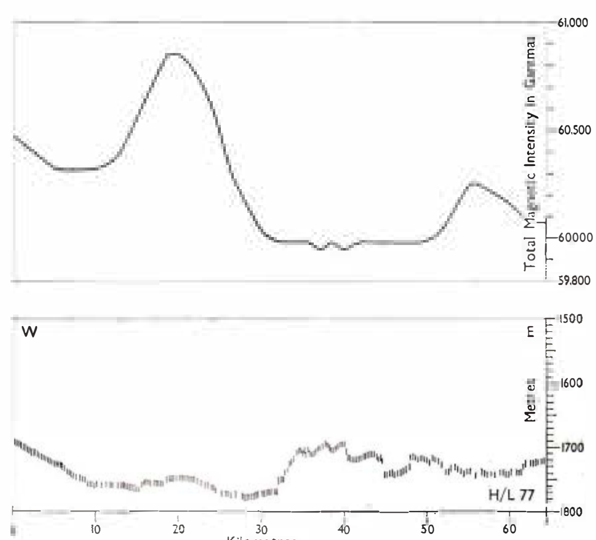

Fig. 17: Magnetic and bathymetric profiles showing spatial correlation over a part of the Mernoo anticline (Profile 8, fig. 1).

If the intrusions are simple in shape they can (for the same anomaly) vary from a thin dyke whose top is 4·0 km below sea level to a dyke 3·4 km wide and 3·4 km deep. The intrusion is deep within the earth's crust and must extend to the mantle. This implies a rock of mantle composition or at least derived from mantle rock. The intrusive material has replaced the crustal rock either by moving it aside or forcing it upward. The dyke-like nature of the inferred body indicates that the walls moved apart.

In general, little correlation exists between the magnetic anomaly and the bathymetry, but in one place (fig. 17) the correlation is good. This structure could form in many ways: it could be a direct expression of deformation, differential compaction, chemical alterations of the sediment or the exhumation of older structures by slumping.

REGIONAL GEOMAGNETIC PATTERN

The region can be divided into the following geomagnetic provinces (fig. 18) based on the types of anomalies recorded on various individual profiles crossing the region:
(O) oceanic, (P) Campbell Plateau, (M) Macquarie Ridge, (B) Bounty Trough, and (A) a collection of areas showing rare localised anomalies if any.

(O) The *oceanic province* is characterised by anomalies typical of the deep-sea basin such as have been well studied in the north-east Pacific (Mason, 1958; Raff and Mason, 1961; Vacquier, Raff, and Warren, 1961; Raff, 1962). No detailed work has been done off New Zealand in this province. However, the anomalies are typical in shape and a reconnaissance grid by the RV *Argo* (V. Vacquier, pers. comm.) indicates that they are elongate. Adams and Christoffel (1962) have proposed correlations between widely separated tracks in this area. Although the exact correlation may be debatable, the probability that correlation exists seems very good. The geologic origin of this type of anomaly is unknown Mason (1958). These anomalies also occur in the Tasman Sea.

(P) The *Campbell Plateau* is a region of numerous but diverse magnetic anomalies. The anomalies range from small to large and from very narrow, intense local anomalies to very broad, deep-seated anomalies. The complexity of the provincial character does not allow correlations from track to track (fig. 18).

On the other hand, a thorough geomagnetic survey of the province will greatly elucidate its tectonics. The anomalies apparently range from intense local deformation of the basement, perhaps with instrusions of igneous rock, to large deformations of the entire crust.

(M) The Macquarie Ridge is associated with local, intense anomalies, which are confined to the ridge and its flanks and are related to its basaltic composition.

(B) The anomalies of the Bounty Trough differ from those of the Campbell Plateau in that the low anomalies are more subdued and the high anomalies are higher.

(A) The areas of no anomaly or of local anomalies are of diverse physiography. Basically, they can be divided into two groups: marginal regions and rises. The marginal regions consist of such areas as the deep-sea floor adjacent to the Campbell Plateau and the area immediately east of South Island. The rise region consists of the Chatham Rise, western Cook Strait, and the Lord Howe Rise. In the last, oceanic-type anomalies seem to extend some distance up the southern flank of the rise. Local anomalies occur in the relatively smooth field and may represent igneous bodies of basaltic composition (such as Banks Peninsula). Both the marginal regions and the rises seem to be areas of very thick sediments. The smooth magnetic field is interpreted as representing a thick body of nonmagnetic sediment, which overlies a depressed basement that is nonmagnetic either because the temperature of the basement exceeds the Curie temperature or because the iron has been metamorphically recombined into nonmagnetic silicates.

ORIGIN OF THE BOUNTY TROUGH

The Bounty Trough is an anomalous feature because in very few other places in the world is the transition from the shoreline to oceanic depths known to extend over such a long distance. An analysis of its formation can shed light on the general question of crustal deformation and evolution.

The trough is either a primary sedimentary

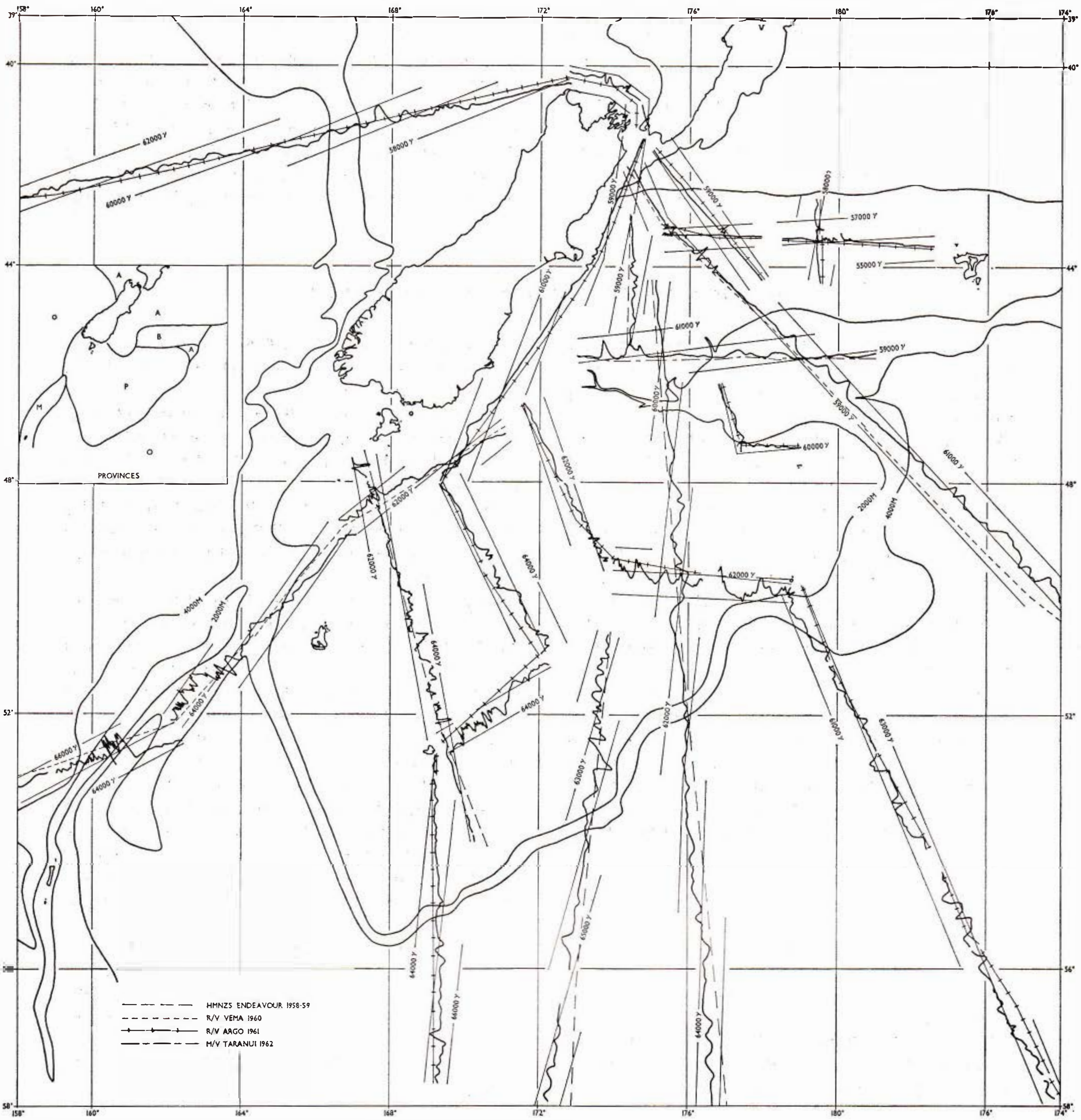

Fig. 18: Regional magnetic pattern around southern New Zealand. The geomagnetic provinces drawn on the inset map are as follows: O, oceanic; P, Campbell Plateau; M, Macquarrie Ridge; B, Bounty Trough; A, areas showing rare localised anomalies, if any.

feature or else has been created through crustal deformation and evolution. Evidence for late Mesozoic and early Tertiary evolution of the trough is scattered throughout this paper. The strongest evidence is the occurrence of greywackes in the Chatham Islands of similar composition to those of southern South Island (W. A. Watters, pers. comm). These greywackes require a source similar to that for the southern South Island, which is not available adjacent to the Chatham

Islands. Although the rocks composing the greater part of the Chatham Rise are unknown, the magnetic character of the rise implies a largely sedimentary origin for the near-surface rocks.

The greywacke sediments had to be transported to their present site at the Chatham Islands from a long distance away. They must either have crossed the present site of the Bounty Trough or travelled along the length of the Chatham Rise. In either case, the site of deposition at the Chatham Islands must have been at a greater depth than the sea floor in the position of the Bounty Trough, which would otherwise have trapped sediment entering it. The source area of the greywackes was either southern South Island or, more likely, the nearby Campbell Plateau, which, judged by its magnetic character, has a heterogeneous structure and rock type. For example, the exposure of the Bounty Islands granite and its subsequent erosion would certainly have furnished the sediments to form greywacke. The crust on either side of the Bounty Trough has thickened and become exposed above sea level. From the foregoing arguments, therefore, the Bounty Trough has been formed since mid-Mesozoic time.

In the process of formation, what has happened to the crust beneath the Bounty Trough? The surface of the Chatham Rise intersects the comparatively flat floor of the lower platform (2,750 metres) of the trough at a sharp angle. Judged from evidence at the Chatham Islands of stability since Oligocene time (Hay, Mutch, and Watters, in press), this rise surface is Oligocene or older. The platform floor, which shows good evidence of being deposited as a flat body, must have been in equilibrium with the deep-sea floor to the east unless a base level was created by a structural dam, for which there is no evidence. Because the platform was at equilibrium, it must have been at nearly the same depth as the deep-sea floor which implies a similar crustal thickness at that time. A continental apron flanks the Campbell Plateau to the east (Heirtzler, 1961) as shown by the *Vema* profile; the apron is composed of sediment brought down from the subaerial continent, and was formerly in equilibrium with the platform. The apron completely buries the abyssal hills at the outer slope and thus must represent deposition over a long period of time. The fact that the platform is now much higher than the deep-sea floor and apron implies either that the platform has risen or the deep-sea floor has recently sunk. Because of the relatively uniform depth of the deep-sea floor to the east and because the Chatham Rise and the Bounty Islands show clear evidence of uplift, the platform is considered to have risen. There is no reason to suspect that an isostatic anomaly exists here, so therefore the crust must have thickened under the platform. This could happen in three ways: the crust under the platform was thickened by thrust faulting, it was thickened by a mineralogic phase change to lighter minerals at the Mohorovicic Discontinuity, or light minerals were fractionated and deposited at the base of the crust. The first two mechanism are preferred.

Crustal thickening was possibly accompanied by crustal rifting, for the lower part of the Bounty Trough (fig. 11) resembles a graben. The trough may be due in part to erosion and slumping caused by turbidity currents, but its large size seems to call for a larger mechanism. The magnetic anomalies in the upper portion of the trough imply an emplacement of igneous dykes which would be consistent with rifting. These two events, rifting and emplacement, need not be of the same age although their association suggests it. The rifting and the crustal thickening seem to have occurred at about the same time. The forces involved are unknown but are perhaps related to the east-west structure in the south-east Pacific. Until heat flow is known and studies of the deep-sea floor to the east are made, suggestions of mechanisms for the deformation are premature.

In summary, north of the Campbell Plateau, then a land area, there formerly existed a sea floor of oceanic depth and thickness. Greywackes were deposited at the site of the Chatham Rise either in a trench-like depression or as a deep-sea fan over a continually subsiding area. Eventually, near the end of the Mesozoic perhaps, the process reversed. During post-Mesozoic time, the same type of deposition was probably going on in the head of the Bounty Trough and is still proceeding. Some uplift of the floor of the trough has taken place to form a transverse geanticline and to uplift the lower platform.

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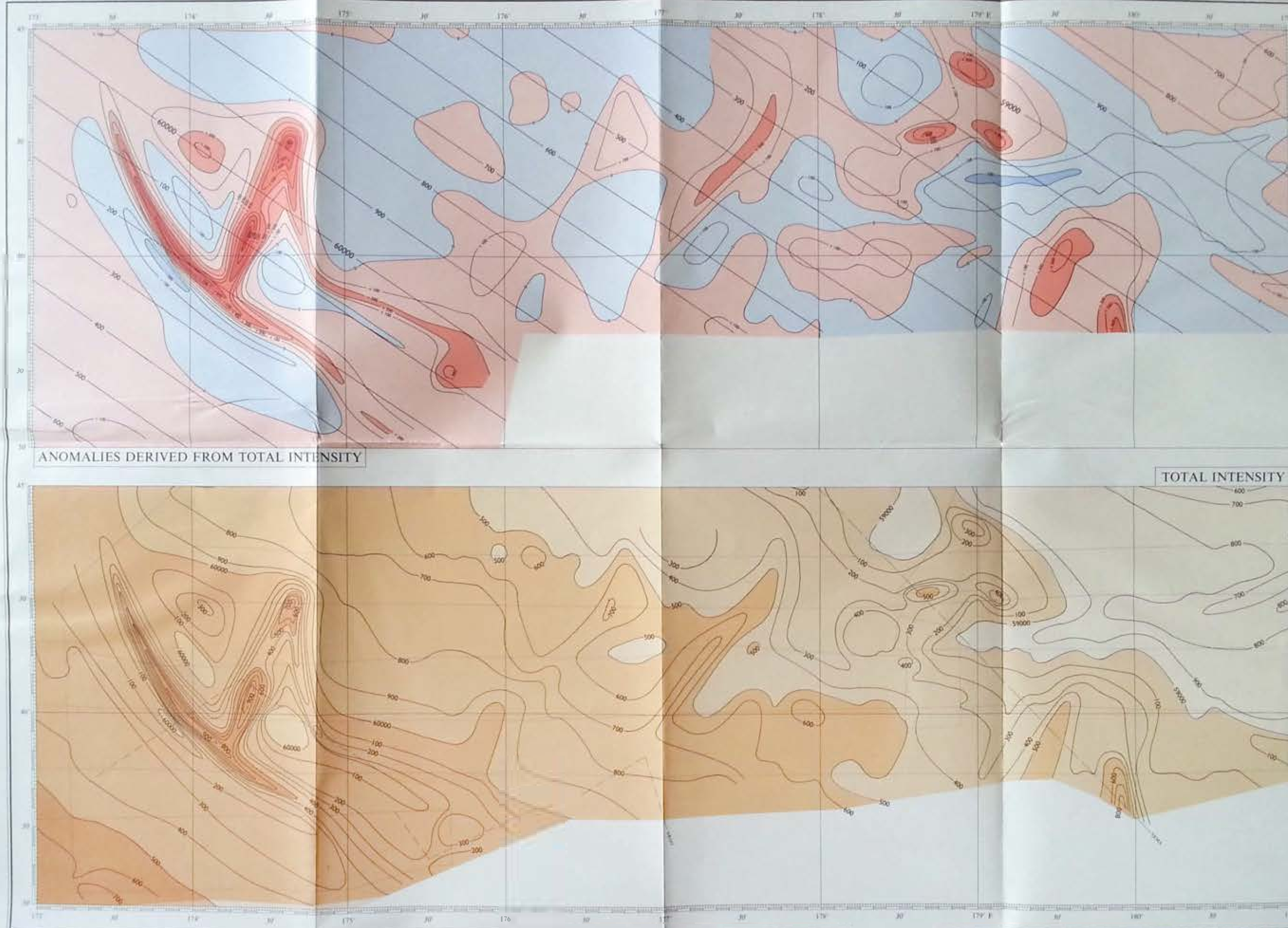
BOUNTY TROUGH

MAGNETIC FIELD–TOTAL INTENSITY AND ANOMALIES

SCALE 1:1,000,000 AT LAT 46° S

MISCELLANEOUS SERIES NO. 8



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Published by the Department of Scientific and Industrial Research, 1965

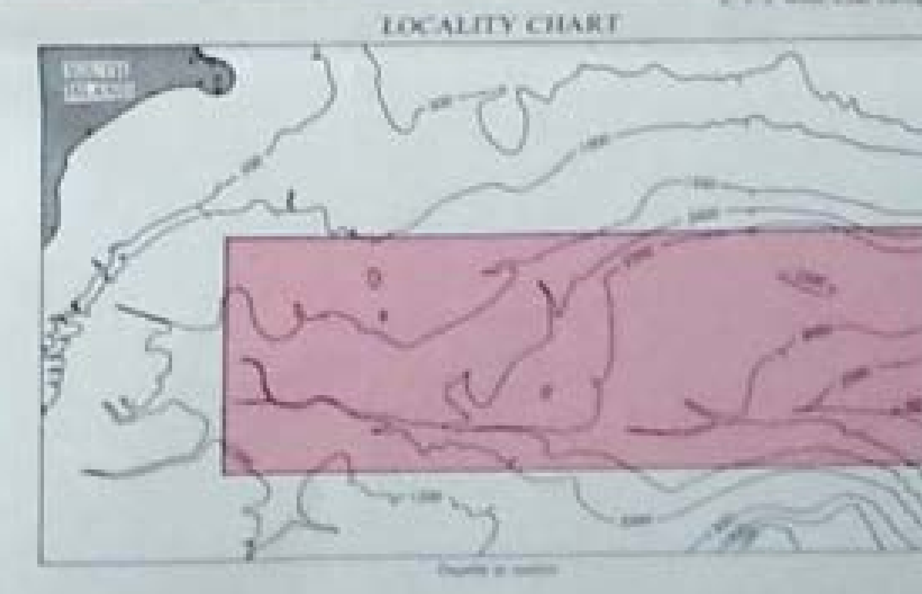
Isomagnetic lines

Regional anomaly

Intervals 100γ

Ships' tracks

LOCALITY CHART



OCEANIC SERIES

BOUNTY

SCALE 1 : 1,000,000 AT LAT. 46°

BATHYMETRY

NOT TO BE USED FOR NAVIGATIONAL PURPOSES

HYPSOMETRIC TINTS

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