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B. Jones

RECORD No. 1963/43

RESULTS OF SOUTH-WEST PACIFIC SUBMARINE GRAVITY SURVEY 1956

by

J. C. Dooley

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SUMMARY

Gravity observations in the south-west Pacific Ocean made in HM Submarine Telemachus and US Submarines Capitaine and Bergall indicate that in this area the broader geological features are very nearly isostatically compensated. Estimates of crustal thickness have been made for the broader features; these agree fairly well with estimates based on dispersion of seismic surface waves. Smaller features such as islands and trenches are not compensated. The crust near New Zealand appears to be similar to continental crusts. The crust under the Tasman Basin is presumably of oceanic type, but thicker than that under the South Pacific Basin.

1. INTRODUCTION

Gravity observations were made in the south-west Pacific in 1956 on a cruise of HM Submarine Telemachus, which was kindly made available by the Royal Navy, through the Royal Australian Navy. Equipment used was the Vening Meinesz pendulum apparatus of Lamont Geological Observatory, University of Columbia, New York; observations were made by H.M. Traphagen of Lamont Observatory and S. Gunson of the Australian Bureau of Mineral Resources.

The operational aspects of the survey and the methods of calculating and correcting the results to the stage of observed gravity values are described by Gunson (1963). The present Record describes briefly the interpretation of the results of the survey.

Earlier work had been done by the US Submarines Capitaine and Bergall, which made traverses from Brisbane through New Caledonia, New Hebrides, Solomon Islands, and New Guinea. The Telemachus cruise ran from Sydney to Wellington, thence zigzagged across the Kermadec and Tonga Trenches to Fiji, then returned to Sydney, passing near Norfolk Island and Lord Howe Island.

The course of the cruise covered most of the typical major topographic features found in the oceans, and the results illustrate (a) the typical crustal structures associated with these features and (b) the operation of isostasy. Although isostatic corrections have not been made for most of the stations, it is possible to study the extent to which the features are compensated by consideration of the free-air and Bouguer anomalies.

The Lamont Geological Observatory has reduced the results of the Telemachus cruise, and has kindly communicated full details of these to this Bureau.

Free-air anomalies have been communicated by Lamont for the Capitaine and Bergall cruises, but not the full data including depths to the sea floor for the observations; therefore no profiles have been prepared for these. For the Telemachus cruise, profiles have been prepared in the Bureau showing free-air and Bouguer anomalies for a density of 2.83 g/cm^3.

The part of the cruise covering the Kermadec and Tonga Trenches has been reported by Talwani, Worzel, and Ewing (1961). Reference is made to this area, but the main purpose of this Record is to discuss the results in the area between Australia, New Zealand, and Fiji.

2. PHYSIOGRAPHY OF THE AREA

The physiography of the area has been described by many authors, including Hess and Maxwell (1949) and Glaessner (1952). The principal features crossed during the Telemachus survey are shown on Plate 1, and include the Tasman Basin, Lord Howe Rise, New Caledonia Trough, Norfolk Ridge, Fiji Basin, New Zealand Shelf, Chatham Rise, South Pacific Basin, Kermadec-Tonga Ridge, Kermadec Trench, and Tonga Trench. The profiles of the sea-bottom for these features are shown on Plates 3 to 7. Rough depths of the main features are shown on Plate 1.

Standard (1961) has described in some detail the area bounded by latitudes 21°S and 37°S, the east coast of Australia, and longitude 165°E. He indicates that a number of guyots arise from the floor of the Tasman Basin in a north-south zone about longitudes 155°E to 156°E.

In the northern part of the area shown on Plate 2, the Capitaine and Bergall cruises crossed the Coral Sea Basin and the New Britain, Solomon, New Hebrides, and New Caledonia chains of islands and associated deeps. Approximate depths of these features are shown on Plate 1. In this area the deeps are located on the side of the island arcs away from the Pacific Basin, in contrast with the Pacific margins elsewhere.

3. PRINCIPLES USED IN INTERPRETATION

The observed gravity at each station was corrected:

(a) to sea-level from the depth of the submarine during the observation, and

(b) for theoretical gravity,

thus giving the free-air anomaly.

Bouguer anomalies were calculated without any orographic correction on the basis of a density of 2.83 g/cm^3 for the crust and 1.03 g/cm^3 for sea water. These corrections were made by the Lamont Geological Observatory.

Isostatic corrections on the Airy hypothesis with T = 30 km have been made for the stations in the Kermadec-Tongo area (Talwani et al., 1961), but they are not available for other parts of the survey. The principal of isostasy plays an important part in the interpretation of the gravity anomalies. However, the calculation of isostaic anomalies by the usual method is laborious. Although digital computers can be used to facilitate the calculations, it is first necessary to prepare maps showing mean heights or depths of selected areas. Such maps have not yet been prepared for the Australasian area.

However, we can consider the general operation of isostasy from a study of the free-air and Bouguer anomalies. In the case of features that are wide compared with the depth of compensation, free-air anomalies should be zero if these features are isostatically compensated. For a plateau, the Bouguer anomaly would be negative, and for an ocean basin it would be positive. If we assume an oceanic mean crustal density of 2.83 g/cm^3, and a mantle density of 3.27 g/cm^3 then for each kilometre of ocean depth there should be about four kilometres of mantle 'anti-root' for compensation on the Airy-Heiskanen hypothesis. A free-air anomaly of 18 mgal corresponds to a variation in depth to the mantle boundary of 1 km. It could also correspond to about 1 km of sediments of density about 2.4 g/cm^3 replacing the crustal material.

Assuming a normal crustal thickness of about 35 km, crustal thickness under the various features can be estimated roughly. The choice of 35 km for the normal thickness is somewhat arbitrary, but it will be seen that this gives results in fair agreement with the surface-wave estimates.

Thus if it is assumed that the oceanic crust has a constant mean density, its thickness, T(km), under broad features can be calculated from the formula

$$T = T_o - H(D_m - D_w)/(D_m - D_c) - G/\left[2\pi k\ 10^8 (D_m - D_c)\right]$$

where T_o = normal or sea-level thickness (35km)

H = ocean depth (km)

D_c = density of crust (2.83 g/cm^3)

D_w = density of water (1.03 g/cm^3)

D_m = density of mantle (3.27 g/cm^3)

k = gravitational constant (c.g.s. units)

G = free-air anomaly (mgal)

Using the values in brackets for T_o and the densities, we get

$$T = 35 - 5.1\ H - 0.054G.$$

The actual composition of the crust will undoubtedly be more complex than assumed above. However, the available data do not enable a more sophisticated interpretation, *e.g.* involving two or three layers. The use of this formula should be regarded as a first approximation, which can indicate the type of variations to be expected. More refined interpretations can be made as other data become available; seismic refraction measurements would be very useful in this respect.

At the other extreme, very local variations in topography are generally not compensated. In this case the free-air anomaly correlates with the topography, while the Bouguer anomaly is independent of topography if the correct density is used.

The situation is more complicated near continental margins, major topographic changes, or features of intermediate dimensions. Even if local compensation were to occur, the gravity anomalies from the compensating feature would be spread over a larger area than the visible topography; if regional compensation occurs, the area of spread will be greater still. The results of this effect for typical cases is shown on Plate 1.

4. DISCUSSION OF RESULTS

Plate 2 shows free-air anomalies for the Telemachus stations, and also for parts of the Bergall and Capitaine cruises. Plates 3 to 7 show profiles of Bouguer and free-air anomalies and ocean depths for the Telemachus observations. As topographic details are not available for the other cruises, no profiles have been prepared for them.

Spacing of stations was limited by capabilities of the submarine and was generally 50 miles, or 100 miles in the later part of the Telemachus cruise. Closer readings were taken over trenches. Note that free-air anomalies are mostly near zero (i.e. within about 20 mgal), the principal departures being over, or near, the ocean deeps. Strong negative anomalies appear over the trenches themselves, generally with a positive anomaly on the island or ridge side.

Examples of such anomalies are:

(a) -230 mgal, south of New Britain

(b) -248 mgal, west of Solomon Islands,

(c) -278 mgal, north of New Hebrides, and

(d) -136 mgal, at southern end of the New Hebrides Trench

The associated positive anomalies are generally about 60 to 100 mgal. The general features are in accordance with the free-air anomaly curve C in Plate 1. Positive anomalies occur on both sides of the New Hebrides Trench. This area is very interesting, being near the change in direction of the active seismic zone, and with the trenches located on the side of the island arcs away from the Pacific Basin. More detail is required to interpret this area properly.

Plate 3 shows a high positive Bouguer anomaly over the Tasman Basin, with the free-air anomaly close to zero. By using the formula in the previous section, a crustal thickness of 10 km has been calculated for this area. Estimates of crustal thickness for the various features by this method are shown in Table 1, Column A.

Officer (1955) made estimates of the crustal thickness for these features on the basis of dispersion of seismic surface waves. His estimates are also shown in Table 1. The gravity estimates agree fairly well with these.

The free-air anomalies over the Lord Howe Rise are slightly positive, and correlate with some local features, indicating that these are not compensated. The crustal thickness apparently increases considerably towards New Zealand. Negative anomalies in Cook Strait are believed to be related to troughs of sediments.

Negative free-air anomalies show that the Kermadec Trench is not compensated. Positive anomalies east of this may indicate local over-compensation. However, the change from land to ocean is broadly compensated, and the rise in the Bouguer anomaly is associated with this change. For an uncompensated Trench the Bouguer profile should rise smoothly as in curve C in Plate 1; the hump over the trench probably results from two negative anomalies due to lighter material on the flanks of the trenches.

TABLE 1

Estimates of crustal thickness

Features	Depth (km)	Free-air anomaly (mgal)	Crustal thickness (km)		
			Seismic	Gravity	
				A	B
South Pacific Basin	6	+15	5-10	4	5
Tasman Basin	5	-10	5-10	10	10
Fiji Basin	4	+30	15	13	13
New Caledonia Trough	4	0	15-20	15	14
Kermadec-Tonga Ridge	2	+80	25	20	19
Lord Howe Rise	1.5	0	20	27	24
New Zealand Shelf	0	+50	20-30*	32	28

* Based on travel-times of earthquakes. Other figures in this column are based on surface-wave dispersion.

Plate 4 shows the profile across the northern part of the Tasman Basin, which is similar to the southern part. The Lord Howe Rise appears completely compensated, with a thickness of up to 27 km as shown in Table 1. The thickness for this and the New Zealand shelf appear excessive compared with the seismic estimates; a better agreement might be obtained with T_o = 30 km. A higher mantle density or lower crustal density would need to be used then to keep the calculated thinner oceanic crusts at a reasonable figure. Column B of Table 1 shows estimates of the thickness based on T_o = 30 km, D_m = 3.40 g/cm^3, D_c = 2.80 g/cm^3. The formula corresponding to this is

$$T = 30 - 4.0H - 0.04G$$

These figures generally agree better with the seismic data than those of Column A, though the changes are not large.

The estimate for the New Zealand shelf is based on the area near Auckland. The Bouguer anomaly map of New Zealand (Robertson and Reilly, 1958) shows positive anomalies in the north-western part of North Island; as the topography is fairly low in this area, free-air anomalies will be a little higher than the Bouguer anomalies, and of the same order as the off-shore anomalies; thus the estimate could be representative of a moderately large area. Eiby (1957) estimated a thickness of about 18 km from a seismic refraction profile near Wellington; an estimate from the above formulae for the vicinity of Wellington would not be justified because of the locally-varying gravity anomalies. There is no reason to suppose that the Wellington results are applicable to the northern shelf area, as Eiby (1958) has shown that major structural changes occur between these places.

Thomson and Evison (1962) estimated a crustal thickness of 30 to 40 km for New Zealand from a study of group-velocity and phase-velocity dispersion of earthquake waves. Reilly (1962) estimated a normal crustal thickness of between 29 and 34 km for New Zealand, based on average Bouguer gravity anomalies on land. These figures appear to be consistent with the estimates made here from the gravity observations on the shelf.

A gravity measurement made on Lord Howe Island by the BMR shows that this island is not compensated. The positive departure from the smooth Bouguer profile (Plate 4) suggests that the density of the rocks forming it may be less than 2.83 g/cm^3; 2.6 g/cm^3 would give a smoother curve. One reading (Station 128) was made a few miles from the edge of the Derwent Hunter Guyot reported by Standard (1961); as the submarine's echo sounder was not working well in deep seas it was usually switched off; thus apparently the submarine passed right over the guyot without the observers being aware of it. At Station 128 the calculated effect of the guyot would be only about 6 mgal, which is negligible. Over the guyot, if uncompensated, the free-air anomaly might reach 250 to 300 mgal.

The Norfolk Ridge and Fiji appear to be partly compensated, as shown by the opposite trends in the Bouguer and free-air anomaly curves.

The results for the Kermadec-Tonga area have been reported in detail by Talwani et al. (1961). However, the profiles are discussed briefly here.

Plate 5 shows the profile off the east coast of North Island; this profile crosses the Trench obliquely twice. The negative free-air anomalies indicate that the Trench is not completely compensated. Negative correlation of Bouguer anomalies and topography indicate partial compensation or sediments flanking the Trench. Use in the Bouguer correction of a density lower than the true density would give a similar effect, but the effect appears to be too large on some profiles to be explained in this way.

The profiles on Plate 6 are more typical, with the overall change from ridge to ocean basin as the dominant feature in the Bouguer anomaly, and the negative free-air anomaly of some 200 mgal over the Kermadec Trench. The free-air anomaly over the Ridge reaches about +100 mgal. Again there is negative correlation with the Bouguer anomalies.

Plate 6 shows two profiles across the Tonga Trench, which are generally similar to those over the Kermadec Trench. The northernmost profile was discussed in detail by Talwani et al.(1961).

Raitt, Fisher, and Mason (1955) made seismic refraction measurements in the northern part of the Tonga Trench. Their traverse was located near the Telemachus gravity stations 97 to 105*, and this provides some control for interpretation of the gravity results. Talwani et al. (op. cit.) improved on the profile of Raitt et al.(1955) by postulating a thicker lower crustal layer(velocity 7.6 km/sec, density 3.2 g/cm^3) to make a total crustal thickness of 37 km west of the Trench. They also suggested that this layer continues under the Trench, but was not revealed by the seismic work, being masked by the layers above and below it. A still better fit with the gravity results was obtained by assuming a tongue of mantle material (density 3.4 g/cm^3) intruding into the lower layer beneath the west flank of the Trench.

* Note on Talwani et al. (1961): The station numbers in Figure 4 and Figure 7 appear to be one less than the corresponding observations in Table 2 and Figure 3. The numbers used in this Record correspond to those of Table 2.

The crustal thickness deduced thus under the Kermadec - Tonga Ridge is more than that found by Officer (1955). One explanation for this offered by Talwani et al (op.cit.) is that the material under the Ridge has a Poisson's ratio of 0.34 instead of 0.25 to 0.28 as usually assumed for igneous rocks.

The mean density of the crust calculated from the profile of Talwani et al. (op. cit.) is 3.04 g/cm^3 under the Ridge, 2.96 g/cm^3 under the Trench, and 2.80 g/cm^3 under the South Pacific Basin. They used a density of 3.4 g/cm^3 for the mantle. These values for the densities are supported to some extent by correlation with seismic velocities. From this it can be seen that there are variations in mean density, and these variations would affect the estimates of crustal thickness in Table 1. However, without further seismic refraction measurements it is impossible to allow for this with any certainty.

5. CONCLUSIONS

The broader orographic features of the Tasman and Coral Seas appear to be very nearly isostatically compensated. Estimates made for the thickness of the crust under various features are approximate, especially as density variations may occur. However, in general, changes of more than about 5 km in the estimates would involve assumptions about the density of rocks that would appear unlikely from results of seismic and gravity measurements in other parts of the oceans, and from consideration of the types of rock to be expected in the crust.

Localized features, such as Lord Howe Island and the Kermadec and Tonga Trenches and other ocean deeps, are not compensated. The ridges associated with trenches generally show positive free-air anomalies. Intermediate features, such as Norfolk Ridge and the Fiji Islands, appear to be partly compensated.

The main discrepancies between estimates of crustal thickness from gravity and seismic (Officer, 1955) measurements are for the Kermadec-Tonga Ridge, Lord Howe Rise, and New Zealand. For New Zealand, the gravity estimates agree better with later estimates by Thomson and Evison (1962). It is doubtful whether the ocean depth or gravity anomalies over the Kermadec-Tonga Ridge are nearly constant over a sufficient width for the simple method used here to be accurate; the calculations of Talwani et al. (1961) suggest further that the mean crustal density is greater than normal under the Ridge.

Many authors have stated that the crust of the Tasman Basin is the same as that of the South Pacific Basin; this is based on estimates by Officer (1955). However, the Tasman crust appears somewhat different from the western edge of the South Pacific crust, insomuch as both are nearly isostatically compensated, but the Tasman Basin is about 1 km shallower. This shows as a difference of about 5 km in thickness in Table 1, but does not disagree seriously with Officer's estimates of 5 to 10 km for both crusts. Both crusts could be of about the same thickness with a lighter Tasman crust. As Talwani et al.(1961) obtain a density of 2.80 g/cm^3 for the South Pacific crust, the Tasman crust would need to have a density about 2.4 g/cm^3, which seems very improbable.

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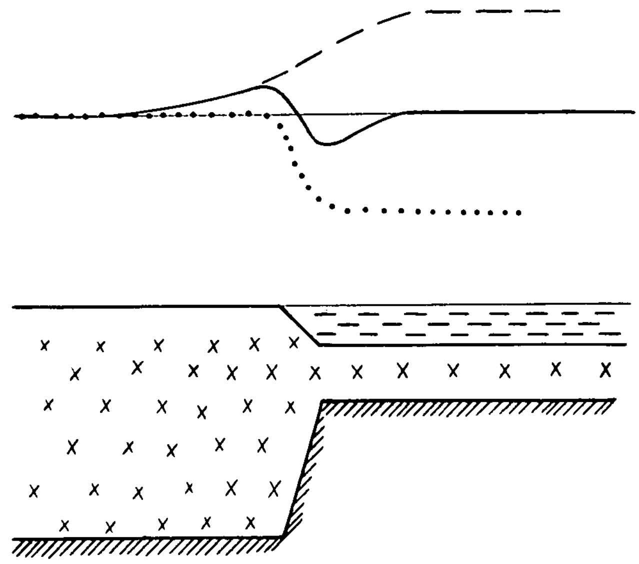
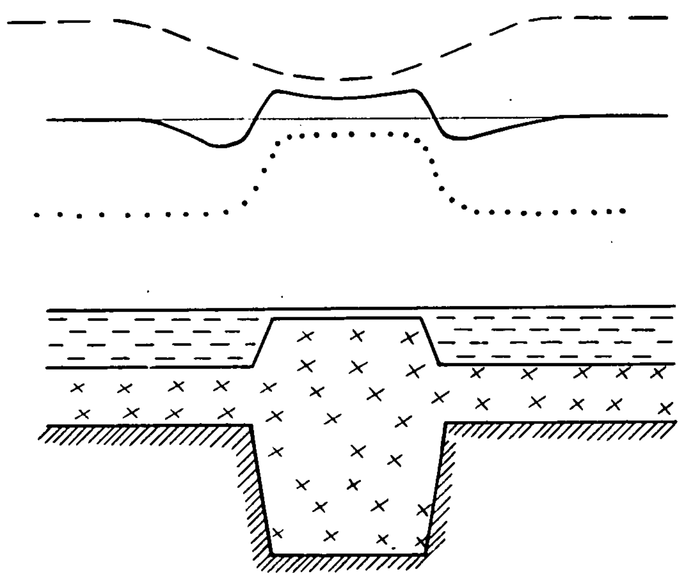
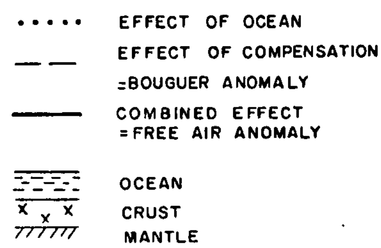
PLATE I

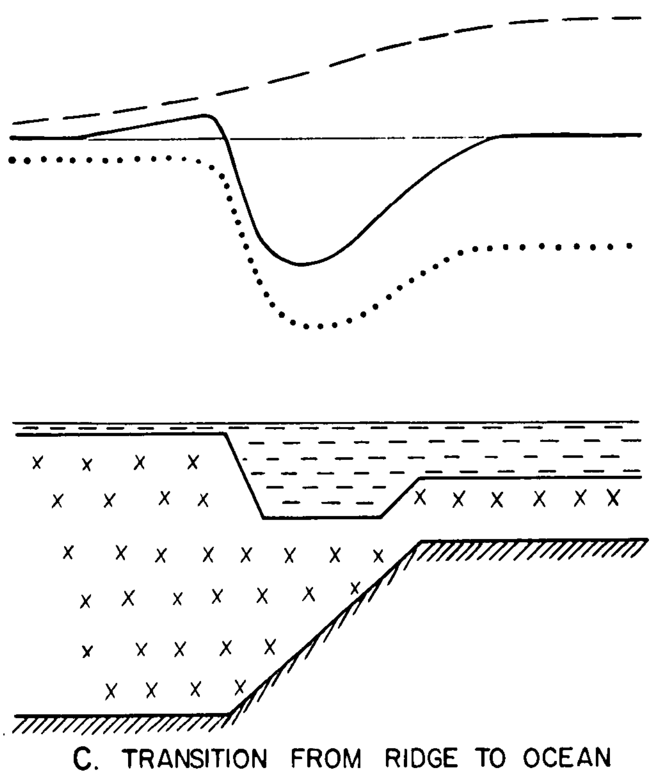


A. CONTINENTAL MARGIN
(COMPENSATED)



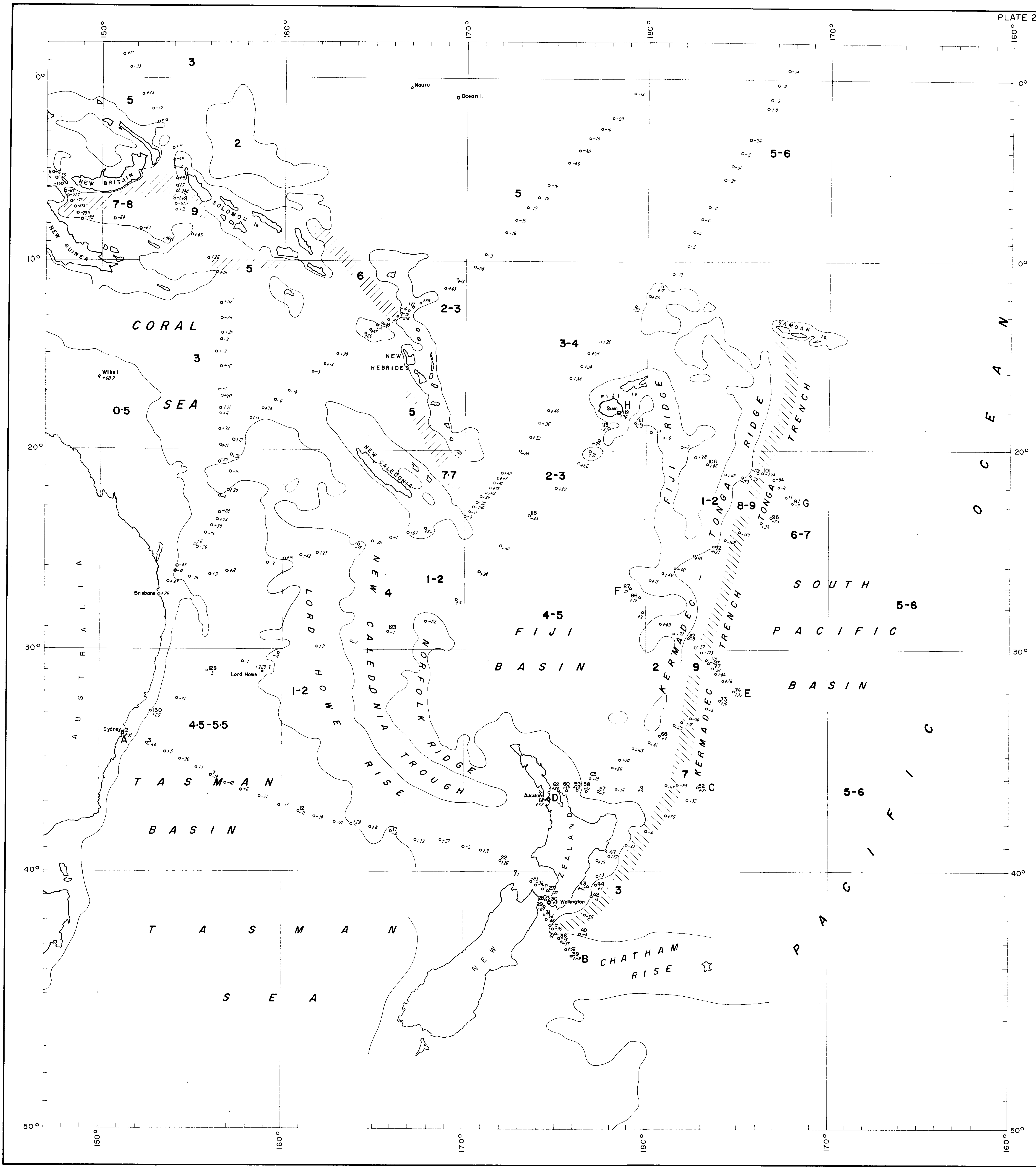
B. OCEANIC RIDGE
(COMPENSATED)





C. TRANSITION FROM RIDGE TO OCEAN
(COMPENSATED) WITH UNCOMPENSATED TRENCH

TYPICAL GRAVITY EFFECTS FOR CRUSTAL FEATURES



LEGEND

- 1000 fathom line
- Ocean deep
- o 39 Submarine gravity station
- +59 Free-air anomaly (milligals)
- **6** Representative depth of oceanic feature in kilometres

SUBMARINE GRAVITY SURVEY (1956)
S-W PACIFIC OCEAN

FREE-AIR ANOMALIES

MERCATOR'S PROJECTION
EQUATORIAL SCALE 240 MILES TO 1 INCH (APPROX)

COMPILED SEPTEMBER 1961

GEOPHYSICAL BRANCH, BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS G 231-17

TO ACCOMPANY RECORD No. 1963/43

G 231-17

FREE-AIR AND BOUGUER ANOMALY AND TOPOGRAPHY PROFILES SYDNEY TO CHATHAM RISE

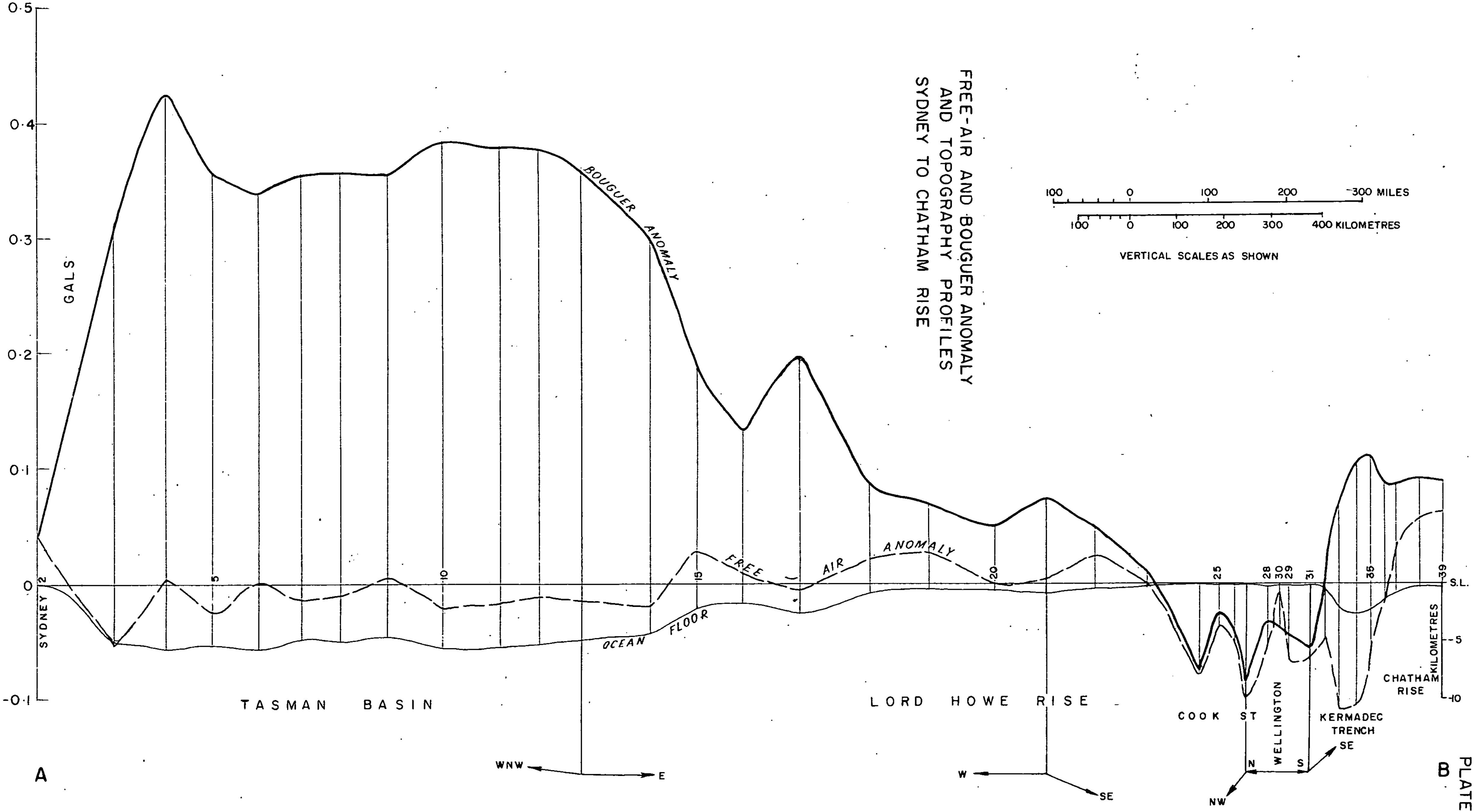
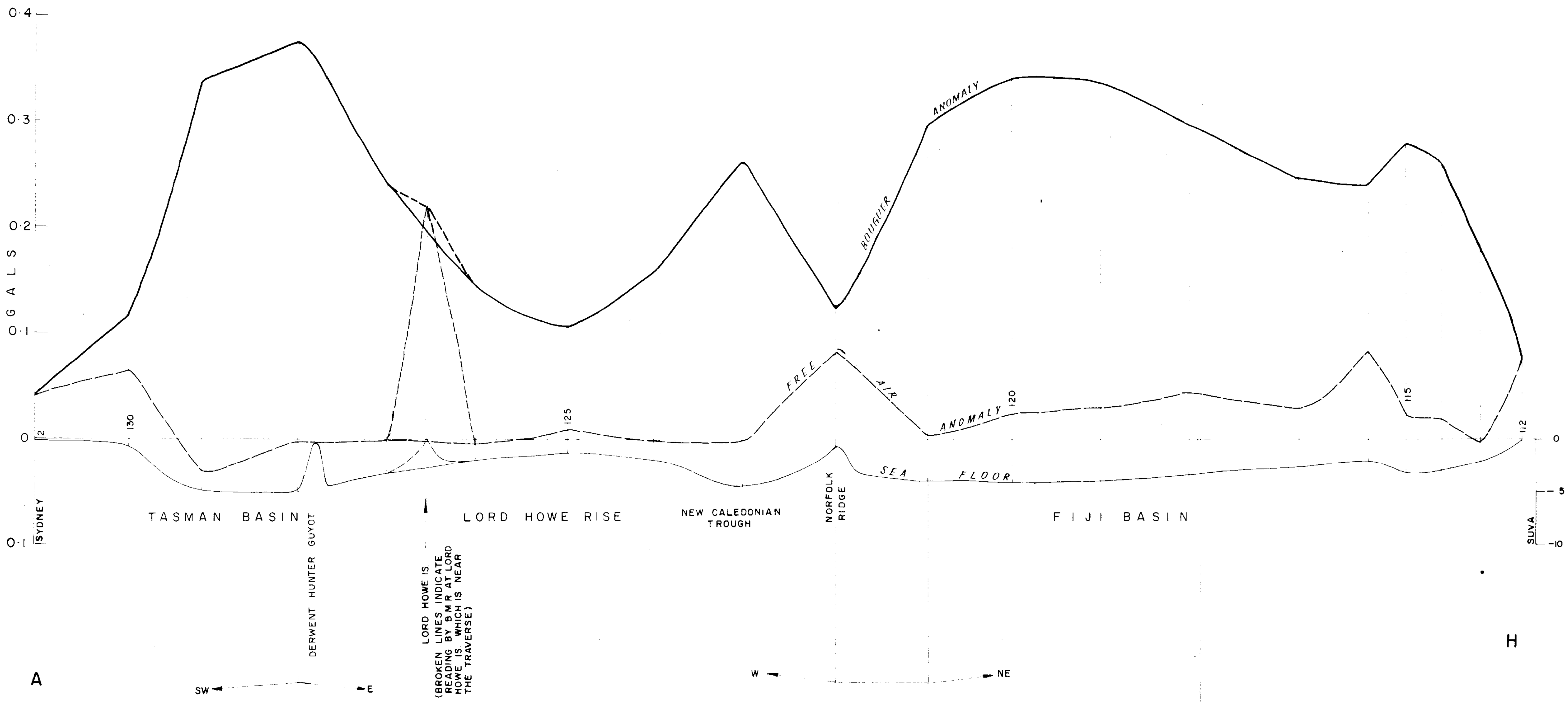


PLATE 3

TO ACCOMPANY RECORD No.1963/43. GEOPHYSICAL BRANCH, BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS G231-12



FREE AIR AND BOUGUER ANOMALY
AND TOPOGRAPHY PROFILES
SYDNEY TO SUVA
VERTICAL SCALES AS SHOWN

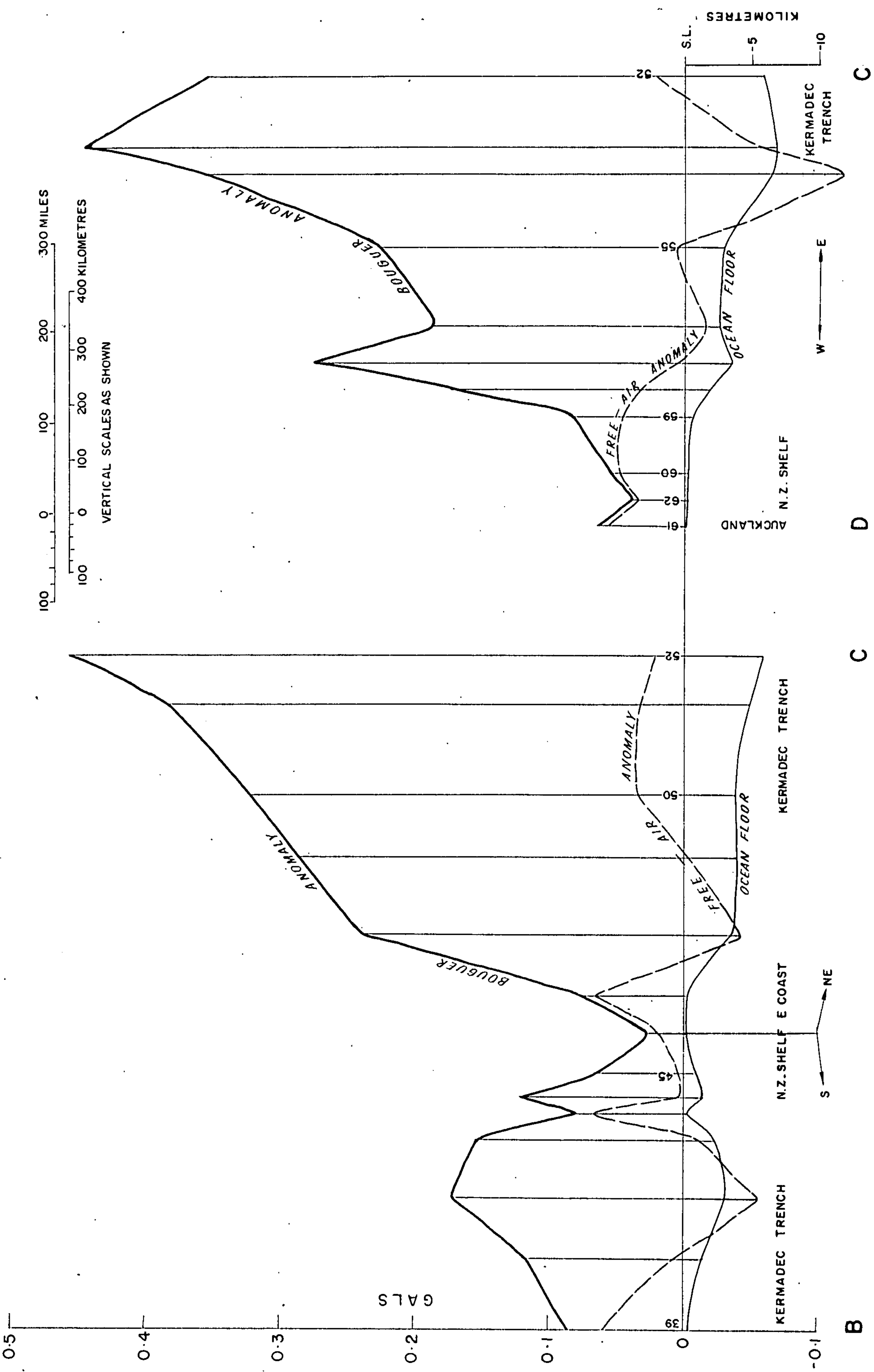
100 0 100 200 300 MILES

100 0 100 200 300 400 KM

GEOPHYSICAL BRANCH, BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS G231-16

TO ACCOMPANY RECORD No. 1963/43

FREE-AIR AND BOUGUER ANOMALY AND TOPOGRAPHY PROFILES SOUTH KERMADEC TRENCH AREA



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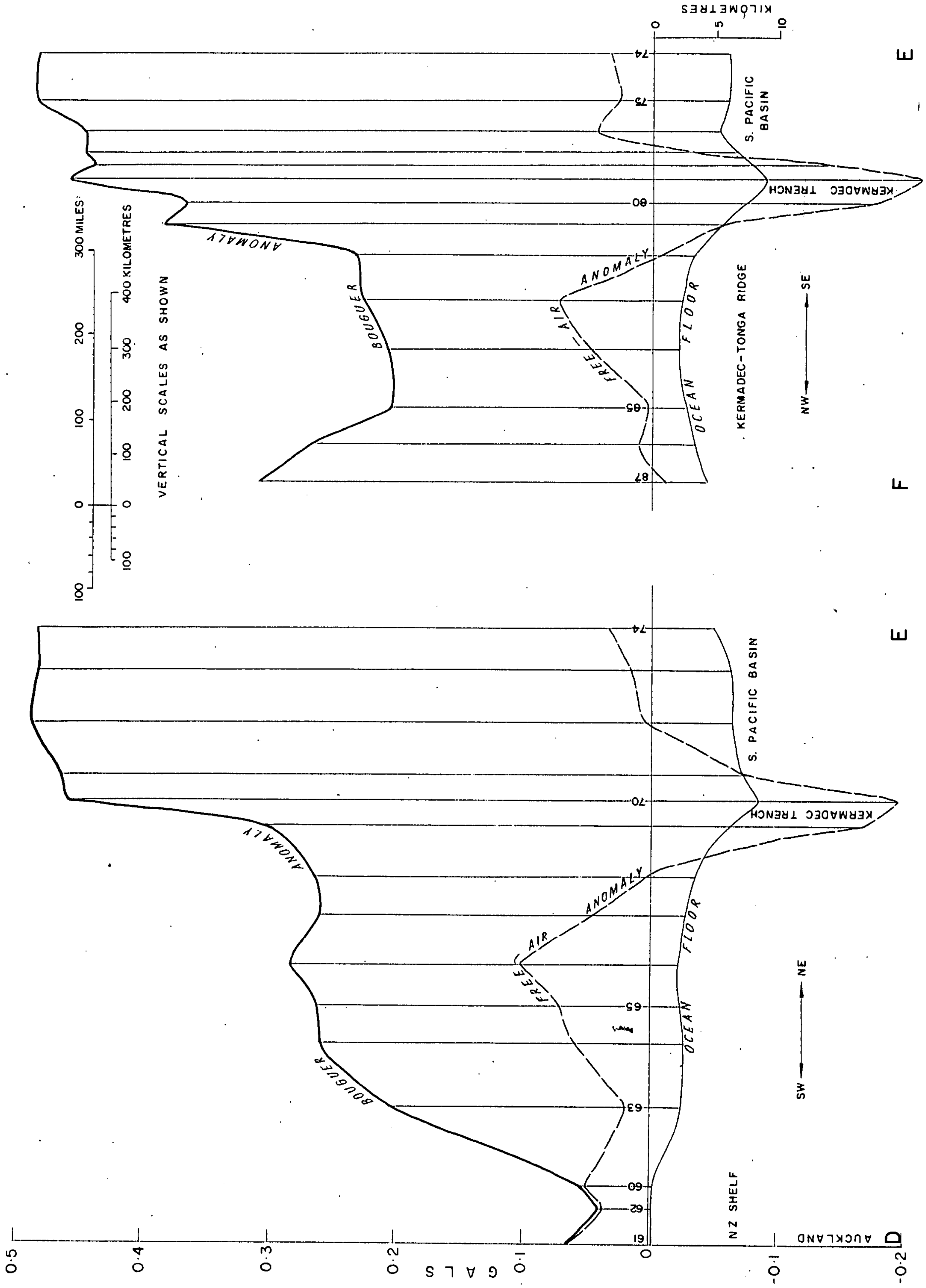

FREE-AIR AND BOUGUER ANOMALY AND TOPOGRAPHY PROFILES TONGA TRENCH AREA