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TIME-TERM ANALYSIS OF NEW BRITAIN/NEW IRELAND ISLAND ARC STRUCTURES

by

D.M. Finlayson and J.P. Cull

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SUMMARY

Seismic data from the New Britain/New Ireland region are interpreted by the time-term method to give depths to four refractors: (a) the near-surface refractor in the area of the Rabaul Caldera; (b) the basement refractor under the Gazelle Peninsula/southern New Ireland area; (c) the intra-crustal refractor; and (d) the Moho refractor under New Britain, New Ireland, and surrounding waters. The respective least-squares velocities are 4.64 ± 0.08 km/s, 6.11 ± 0.02 km/s, 6.84 ± 0.03 km/s, and 7.92 ± 0.05 km/s, with the residuals indicating that there is a wider divergence of structure at the Moho boundary than at the upper three refractors.

INTRODUCTION

The combined distribution of shots and recording stations for seismic refraction surveys conducted during 1967 and 1969 in the New Britain/New Ireland region of Melanesia (Brooks, 1971; Finlayson, 1972; Finlayson et al., 1972; Finlayson & Cull, in press) provides an opportunity for applying the time-term interpretation techniques of Scheidegger & Willmore (1957) to an island arc structure (Fig. 1). The tectonic complexity of the Bismarck and Solomon Sea region has made it the focus of a number of geophysical investigations in recent years (Rose, Woollard & Malahoff, 1968; Furumoto et al., 1970; Denham, 1969, 1973; Johnson & Molnar, 1972; Krause, in press; Willcox, in prep.) and the seismic refraction interpretation presented in this paper gives a structural basis for some of that work. The interpretations published so far from the refraction data (Finlayson et al., 1972; Finlayson & Cull, in press; Wiebenga, 1973) do not provide the overall picture of crustal structure obtained by using the time-term technique.

DATA AND ANALYSIS

The data from the 1967 and 1969 seismic refraction surveys conducted by the Bureau of Mineral Resources, Geology & Geophysics (BMR) and co-operating universities are listed in various reports (Brooks, op. cit.; Finlayson, op. cit.) and are sufficient to provide the sound statistical basis essential for the time-term interpretation method. A description of the surveys and the methods used is given by Finlayson et al. (op. cit.). Briefly, 44 marine shots were recorded in 1967 on 17 sets of land based recording equipment and 54 marine shots were recorded in 1969 on 24 sets of equipment. The equipment was relocated during various stages of the survey, to provide readings at 28 sites in 1967 and 48 sites in 1969. Altogether, 1074 seismic first arrivals were recorded at distances less than 100 km and 396 at distances greater than 100 km; all arrivals were allotted a subjective 'quality' and an 'accuracy' for use in subsequent weighting of the data.

The distribution of shots and stations (Fig. 1) largely satisfies the criteria that should be incorporated in any survey using the time-term interpretation method (Scheidegger & Willmore, 1957; Willmore & Bancroft, 1960), namely:

1. Shot and station locations must form extended patterns to provide adequate determination of the velocity in the marker layer.
2. Where the most accurate interpretation is required (which in this case is the Rabaul area) there must be an adequate number of stations and shots connected to other survey points in several directions.
3. Recording stations should not be moved too frequently, so that a statistically significant quantity of data is recorded at each station.

4. To determine a unique solution it is important to have several locations at which shots and stations are near-coincident.

The method has been applied to crustal investigations in a number of areas: the Lake Superior survey (Berry & West, 1966; Smith, Steinhart & Aldrich, 1966), various Australian surveys (Finlayson, 1968; Underwood, 1969), and the Continental Margin Refraction Experiment (Bamford, 1971). Unfortunately these surveys were not really designed with time-term interpretation in mind, as is evident from the linear arrangements of shots and stations, and the weaknesses of applying a time-term analysis to such experiments have been described by O'Brien (1968).

The mathematical method used for the interpretation of data in this paper is that of Berry & West (op. cit.) and is described only in outline here.

Assuming that there is a refracting boundary with seismic velocity V_1 above and V_2 below, the theoretical travel-time for the critically refracted head wave between sites i and j can be written

$$t_{ij} = D_{ij}/V_2 + a_i + a_j \qquad \text{.......... (1)}$$

where D_{ij} = distance separating the ith and jth sites

a_i and a_j = time-term at the ith and jth sites (i.e. at the shot-point and recording station).

If T_{ij} = observed travel-time for head wave, the residual difference between the theoretical and observed travel times can be written

$$R_{ij} = T_{ij} - t_{ij} \qquad \text{.......... (2)}$$

$$= X_{ij} - a_i - a_j \qquad \text{.......... (3)}$$

where $X_{ij} = T_{ij} - D_{ij}/V_2$ .... (4)

Assuming that the sites i and j are from a total of N shot and recording stations sites, there should therefore be, at most, a total of N(N-1) equations of the form (3) if there were both a shot and a station at each site. There will, however, be only N + 1 unknowns - the N time-terms and the refractor velocity V_2. The ststistical criterion taken to giyen the best-fit solution is that the sum of the squares of the residuals (R_{ij}^2) shall be a minimum.

Berry & West (op. cit.) give details of the method used to derive the set of linear equations in the unknown time-terms a_r (where r = 1 ..... N) and velocity V_2, which can be solved by matrix methods readily available at computer centres. They also describe the data handling method in the practical situation where there are not shots and stations at each site. The authors adapted the method for use on a CDC 3600 computer. In practical survey operations it is often impossible to satisfy the condition of coincident shots and stations, and therefore a set of time-terms can only be determined subject to the value of a constant (α) which is of opposite sign for shot and station sites. In the present interpretation a unique solution is achieved by using values of the constant α determined from several pairs of near-coincident shots and stations. (see Table 5).

In a multi-layer model, time-terms can be determined for successive refractors, and the depths to these refractors can be written

$$H_n = \sum_{p=1}^{n} h_p$$
$$= \sum_{p=1}^{n} \left(\left(a_p - \sum_{p=1}^{p-1} h_q / K(V_{p+1}, V_q) \right) K(V_{p+1}, V_p) \right) \qquad \text{.........} (5)$$

where n = number of layers above bottom refractor

H_n = total depth to critical refractor

h_p = thickness of layer with velocity V_p

a_p = time-term to critical refractor V_{p+1}

and $$K(V_{p+1}, V_p) = \frac{V_{p+1} V_p}{(V_{p+1}^2 - V_p^2)^{1/2}} \qquad \text{etc.}$$

The standard deviation of the residuals R_{ij} is used to derive a measure of the statistical uncertainty of the time-terms and of the velocity determined by the time-term method.

The identification of the refractors in the New Britain/New Ireland region to which time-term analyses could be applied has been described by Finlayson et al. (1972). The data used in the least-squares analyses in that paper provide the basis for data selection for the time-term analysis of four refractors: (a) the near-surface refractor in the region of the Rabaul volcanic caldera; (b) the basement refractor in the Gazelle Peninsula/southern New Ireland region; (c) the intra-crustal refractor; and (d) the Moho refractor over the whole survey area. The refractor velocities are illustrated in the example of a reduced time-distance plot shown in Figure 2.

The allocation of data to a particular refractor is necessarily a subjective process, especially at distances in the cross-over regions of time-distance plots. Thus some data may well be included in the analyses of two refractors if there is no geophysical justification for limiting them to one refractor or another. All the time-term analyses finally adopted are the result of an iterative process in which the residuals from each individual observation were examined at each cycle and those rejected which were thought to be grossly distorting the solution.

LOCAL STRUCTURES IN THE RABAUL CALDERA

A total of 131 seismic first-arrival data points at distances out to 16 km are used to determine the time-terms at 30 locations (16 shots and 14 recording stations) in the vicinity of the Rabaul caldera (Fig. 3). In a preliminary study of the caldera in 1966, Cifali, D'Addario, Polak & Wiebenga (1969) established near-surface velocities of approximately 2.5 km/s from refraction results. Therefore in the present interpretation around the Rabaul caldera, corrections are applied to the observed travel times by replacing the depth of water at the shot-points with a pseudo-layer with velocity 2.5 km/s for the purpose of the analysis.

The time-term computations give a velocity of 4.64 $\pm$ 0.08 km/s for the material in the critically refracting layer, and the resultant time-terms for the various sites are listed in Table 1. Depths to the refractor are determined using equation (5) in a one-layer model with 2.5 km/s material overlying 4.64 km/s material, and these are contoured in Figure 3. The distribution of residuals is illustrated in Figure 4 with those for other refractors; the standard deviation of the residuals is 0.12 s, giving an uncertainty in depth of $\pm$ 0.4 km using the velocity model determined above.

From Heming's geological description (in prep.), the 2.5 km/s refractor probably contains rocks consisting of lava flows, tuff, tuffite, coral limestone, and volcanic ash while the 4.64 km/s refractor contains older metamorphosed sedimentary rocks, lava flows, and intrusions; consequently the velocity transition is probably complex. It is also evident that the dense rocks (presumably of high velocity) expected near the surface by Laudon (1968) on the basis of his graviy work are not apparent in the seismic results. However, dense surface rocks can have low seismic velocity because of weathering and fracturing (Lort & Mathews, 1972), and thus the low velocity does not necessarily prove the non-existence of dense rocks.

BASEMENT STRUCTURE

The presence of a refractor with velocity of approximately 6.1 km/s in the Gazelle Peninsula/southern New Ireland area is evident from preliminary examination of the data (Finlayson et al., 1972). This refractor (defined as basement) is interpreted as the upper boundary of a thick pile of volcanic, pyroclastic, and intrusive rocks formed by lower and middle Tertiary island arc magmatism. These rocks are exposed in some parts of the Gazelle Peninsula and New Ireland but are generally overlain by younger, less consolidated rocks.

Most of the first-arrival data at distances less than 100 km were recorded in this area, and they are well suited to time-term analysis. Data from 736 seismic arrivals are compiled to give time-terms at a total of 118 shot-points, and recording stations. For interpreting basement structure and deeper refractors, a water correction velocity of 4.0 km/s is adopted, based on the meagre information available from the Rabaul caldera and engineering refraction surveys in the Gazelle Peninsula (Cifali, Milson & Polak, 1968; Cifali et al., 1969).

The velocity for the basement refractor determined from the analysis is 6.11 $\pm$ 0.02 km/s. The time-terms computed using this velocity are listed in Table 2 together with the depths computed using a single-layer model with 4.0 km/s rock overlying a 6.11 km/s basement. The results are contoured in Figure 5. The residual distribution is shown in Figure 4 and the standard deviation is 0.22 s, giving an uncertainty of 1.16 km from the model adopted for the depth computations.

Some of the features of structure are illustrated in an east-west section through Rabaul (Fig. 6). The following features of the interpretation deserve special mention:

1. The shallow basement in the northwest of the Gazelle Peninsula.
2. The rapid increase in depth at a point half-way along the north coast of the Gazelle Peninsula.
3. The deep basement under the eastern St Georges Channel.
4. The much shallower basement under central than under southern New Ireland.
5. The deep basement east of New Ireland.

INTRA-CRUSTAL STRUCTURE

The difficulties of identifying any structure within the crust above the Moho are many, and it may be that the interpretation here, representing a step in velocity from 6.11 km/s to between 6.8 and 6.9 km/s, is an over-simplification of the variation of velocity with depth. However, careful examination of first-arrival data in the range 80 to 150 km seems to indicate clearly the presence of a refractor, and with the added evidence from subsequent arrivals outside this range the case for the refractor improves.

The refractor is most easily identified in the Bismarck Sea, where there is clear evidence that the first velocity identified is 6.78 km/s and there is little evidence of a velocity near 6.1 km/s.

For the time-term analysis, 191 data points are used to give time-terms at 64 places (25 recording stations and 39 shot-points). Iteration of the data analysis procedure to eliminate arrivals which were of doubtful interpretation indicates a velocity which does not deviate far from 6.8 km/s. The final solution adopted gives a velocity of 6.84 $\pm$ 0.03 km/s and the time-terms listed in Table 3. The distribution of residuals (Fig. 4) seems to substantiate the idea of a distinct intra-crustal refractor, since the number of data used represents a large percentage of those available for interpretation. The standard deviation of the residuals is 0.26 s.

The depth determinations are made using equation (5) and the data available from the time-term interpretation of the basement refractor. Where there are deficiencies in the information available for depth calculations, estimates have been made from the least-squares analysis of Finlayson et al. (1972). The depths are contoured in Figure 7, and the following features may be noted:

1. Depths in the Bismarck Sea are generally less than 5 km, and the 6.84 km/s refractor is the first detected below the sea bed.

2. Other depths range up to 25 km, with average depths of approximately 15 km in the Rabaul area.

3. In central New Britain there seems to be an area where the refractor shallows to less than 10 km corresponding with an area of high Bouguer gravity anomalies (Brooks, 1971).

4. The depths under central New Ireland (approximately 5 km) are much shallower than under the southern part of the island (10-15 km).

MOHO STRUCTURE

Most methods of interpreting seismic refraction data make various assumptions about the existence of refractors, continuity over a certain area near shot-points and recording stations, reversal of ray paths, lateral uniformity over a certain distance, and increasing velocity with depth, which are the logical extension of experience in sedimentary basins. In crustal investigations, especially in island arc areas, there must always be some doubt about making such assumptions when one considers that island arc tectonism involves large vertical movements, magmatism, metamorphism, phase changes, large-scale horizontal shear and consequent discontinuities and large boundary gradients.

The interpretation of Moho structure in an area such as New Britain/New Ireland is inevitably difficult and is not helped by the added complication that the seismic arrivals from the greater distances required for the interpretation contain a greater proportion of poor results. In the present time-term interpretation an attempt is made to include as many data as possible even though the scatter of residuals is high.

In all, 188 datum points have been used to determine the time-terms at 51 sites (28 shot-points and 23 recording stations). The velocity computed from the final analysis is 7.92 $\pm$ 0.05 km/s and in the iteration process, the most probable velocity for the region was always found to be approximately 7.9 km/s. The distribution of residuals (Fig. 4) clearly demonstrates that although 7.92 km/s is the most probable velocity for the region as a whole, there is likely to be a good deal of variation within the region. The standard deviation of the residuals is $\pm$ 0.44 s. The velocity determined is in agreement with the evidence from marine refraction work in the Solomon Sea Basin by Furumoto et al. (1970) of velocities ranging between 7.7 and 8.0 km/s.

The distribution of residuals is likely to be influenced also by anisotropy in the crustal layers and upper mantle. Christensen (1972) has summarized the argument for anisotropy in the oceanic layer 3, backed by laboratory evidence that velocities vary from 6.2 to 7.1 km/s along the different axes of rock samples. Keen & Barrett (1971) found 8 percent seismic anisotropy in the upper mantle from survey work in the Pacific Ocean Basin off British Columbia.

The time-terms and depths are listed in Table 4 and the depth contours illustrated in Figure 8. The depths under the Bismarck Sea generally increase from 10 to 20 km going from NW to SE, and a large increase in depth under the north New Britain coast indicates a major structural feature. The differences between the depths under the south coast of New Britain and the Solomon Sea margin are not nearly so great. The shallower depths in central New Britain probably reflect the similar structure in the intra-crustal depth contours. From the results of Furumoto et al. (1970), depth to Moho is 12 to 13 km under the Solomon Sea Basin.

The depths to the Moho under the Gazelle Peninsula are generally less than 25 km increasing to approximately 35 km in the Rabaul area. Southern New Ireland has a Moho depth in excess of 30 km except for the area in the southwest of the island. East of New Ireland the depths are consistently greater than 30 km, indicating that the structure in that area is not that of typical oceanic crust. Two representative crustal cross-sections in the region are illustrated in Figure 9.

DISCUSSION

Seismicity and earthquake focal mechanism studies have shown that Rabaul lies at a triple junction of lithospheric plates: the Pacific Plate including the ill-defined north Bismarck Plate, the south Bismarck Plate and the Solomon Plate (Denham, 1969, 1973; Johnson & Molnar, 1972; Krause, in press). Using the nomenclature of McKenzie & Morgan (1969) the junction is of the TTR type and is stable, since the transcurrent fault across the Bismarck Sea would seem to be tangential to the Solomon Islands subduction zone. The continuity of the fault in the St Georgs Channel is not well defined from earthquake locations, probably owing to crustal weakness and volcanism having prevented the build-up of strain energy.

The seismic refraction interpretations of crustal structure given in this paper help to describe the structural differences across the plate boundaries. The Bismarck Sea crust, which increases in thickness from approximately 10 km to over 20 km (including 2 km of water), as the New Britain coast is approached, is slightly thicker on average than the Solomon Sea crust (Furumoto et al., 1970), which is approximately 12 km thick (including about 5 km of water). The crustal thickness of the Pacific Plate east of New Ireland is between 35 and 40 km and is consistent with the suggestions by Kroenke (1972) that the Ontong/Java Plateau area northeast of the Solomon Islands has a crust of considerable thickness (Furumoto et al., 1971).

The crustal structures under the islands of New Britain and New Ireland show a diversity to be expected in active or latent island arc systems, but there is no gross structural difference across the boundary between the two. This conclusion seems to be substantiated by the fact that data from under the two islands can be included in the same time-term analyses without obvious disparity.

One of the reasons for conducting the BMR crustal investigations in the region was to provide information that would permit the precise location of earthquakes and magmatic activity associated with the active Rabaul volcanic complex and thus assist with safeguarding of the Rabaul community. Within the assumptions made in seismic refraction interpretation, the near-surface and basement structures in the Rabaul area are determined; but the interpretation does not define magma chambers or conduits, although they probably contribute to the spread of the travel-time residuals. The broad aspects of the overall intra-crustal and Moho structures are defined.

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TABLE 1

Time-terms and depths to 4.64 km/s refractor, Rabaul Caldera

Shot or Station	Latitude Deg. Min. Sec(S)	Longitude Deg. Min. Sec(E)	Time-term s	Depth km	No. of Datum Points
RBL	4 11 33	152 09 46	0.54	1.6	15
RAL	4 13 18	152 11 42	0.45	1.3	14
SUL	4 13 15	152 11 08	0.65	1.9	13
TAV	4 13 57	152 12 48	0.40	1.2	15
VUL	4 17 03	152 08 19	0.53	1.6	11
WAN	4 11 44	152 10 07	0.34	1.0	16
PRAED PT	4 14 56	152 13 51	0.60	1.8	11
WATOM I.	4 06 53	152 05 35	0.26	0.8	3
TAVUI	4 08 09	152 10 02	0.44	1.3	5
NONGA	4 08 26	152 09 56	0.35	1.0	5
KURAKAKAL	4 12 54	152 07 36	0.50	1.5	7
BURMA RD	4 13 58	152 09 03	0.63	1.9	6
VULCAN	4 16 17	152 09 31	0.29	0.9	6
VUNAKAKAR	4 15 31	152 05 47	0.60	1.8	4
67/A	4 15 49	152 11 53	0.53	1.6	7
67/B	4 17 29	152 11 46	0.64	1.9	6
67/C	4 17 04	152 13 34	0.24	0.7	6
67/D	4 15 29	152 13 15	0.30	0.9	5
67/2	4 14 14	152 16 22	0.72	2.1	5
67/3	4 10 37	152 14 01	0.52	1.5	4
67/5	4 14 31	152 16 26	0.48	1.4	6
67/6	4 11 44	152 14 49	0.45	1.3	6
67/11	4 10 14	152 06 46	0.33	1.0	6
69/30	4 05 15	152 06 32	0.66	2.0	6
69/31	4 08 28	152 08 27	0.51	1.5	13
69/32	4 14 10	152 09 49	0.38	1.1	14
69/33	4 15 15	152 10 51	0.35	1.0	13
69/34	4 16 56	152 11 25	0.52	1.5	13
69/35	4 17 18	152 12 43	0.49	1.4	10
69/36	4 18 30	152 14 47	0.61	1.8	11

TABLE 2

Time-terms and depths to basement (6.11 km/s) refractor, Gazelle Peninsula/southern New Ireland

Shot or Station	Latitude Deg. Min. Sec (S)	Longitude Deg. Min. Sec (E)	Time-term s	Depth km	No. of Datum Points
RBL	4 11 33	152 09 46	0.94	5.0	43
RAL	4 13 18	152 11 42	0.75	4.0	43
SUL	4 13 15	152 11 08	1.04	5.5	29
TAV	4 13 57	152 12 48	0.78	4.2	49
VUL	4 17 03	152 08 19	0.94	5.0	48
WAN	4 11 44	152 10 07	0.74	4.0	42
PRAED PT	4 14 56	152 13 51	0.94	5.0	17
TAVUI	4 08 09	152 10 02	0.81	4.3	18
BURMA RD	4 13 58	152 09 03	1.17	6.2	13
NORDUP	4 11 58	152 12 53	0.44	2.4	7
VULCAN	4 16 17	152 09 31	0.84	4.5	14
RALUANA	4 17 52	152 12 50	1.20	6.4	8
MALAPAU	4 19 54	152 13 37	0.97	5.2	12
RAPOPO	4 20 19	152 19 20	0.83	4.4	31
KARAKAKAL	4 12 54	152 07 36	0.94	5.0	18
VUNAKAKAR	4 15 31	152 05 47	1.20	6.4	14
NATAVA	4 11 39	151 59 43	0.77	4.1	21
KABIARA	4 14 48	152 01 57	0.73	3.9	4
KILINWATA	4 15 52	151 50 44	0.70	3.7	21
LASSUL BAY	4 13 09	151 43 21	0.65	3.5	14
WARANGOI	4 27 21	152 14 21	0.79	4.2	34
MT VARZIN	4 23 35	152 09 47	0.57	3.1	13
KABANGA	4 26 42	152 20 59	0.80	4.3	23
SUM SUM	4 45 03	152 22 12	0.58	3.1	15
TALILIS	4 37 50	152 22 47	0.75	4.0	6
KAMBUBU	4 35 12	152 22 00	0.68	3.6	11
ULU	4 12 38	152 24 46	0.59	3.2	29
KAMDARU	4 12 42	152 41 27	1.32	7.0	25
ULUPUTUR	3 43 23	152 22 46	0.88	4.6	10
NAMATANAI	3 39 56	152 26 36	0.83	4.4	10
DOILENE	4 11 59	151 33 04	0.31	1.7	14
PONDO	4 33 22	151 37 14	0.17	0.9	5
POWELL HBR	4 48 26	151 41 43	0.63	3.4	5
MULIAMA/MANGA	4 06 19	152 59 54	0.62	3.3	21
NARUM	4 32 11	153 03 29	1.38	7.3	4
WATOM I.	4 06 53	152 05 35	0.69	3.7	12

TABLE 2 (contd)

PALIE	3 11 35	152 36 24	0.63	3.4	5
LONDOLOVIT	3 04 03	152 38 01	0.21	1.2	8
LAMBOM	4 48 23	152 51 29	1.48	7.9	5
RAVALIEN	4 20 13	152 15 14	1.04	5.5	9
KARLAI	5 02 30	151 57 40	1.00	5.3	2
BOANG I.	3 23 02	153 16 44	0.63	3.4	4
67/A	4 15 49	152 11 53	1.09	5.8	2
67/B	4 17 29	152 11 46	0.84	4.5	6
67/C	4 17 04	152 13 34	0.92	4.9	2
67/D	4 15 29	152 13 15	0.57	3.1	2
67/2	4 14 14	152 16 22	0.92	4.9	2
67/3	4 10 37	152 14 01	0.88	4.7	3
67/5	4 14 31	152 16 26	0.63	3.4	6
67/6	4 11 44	152 14 49	0.79	4.2	7
67/7	4 12 06	152 22 05	0.51	2.7	9
67/8	4 15 06	152 29 41	0.61	3.3	10
67/9	4 12 59	152 33 32	0.88	4.7	11
67/10	4 12 56	152 38 36	1.33	7.1	8
67/11	4 10 14	152 06 46	0.76	4.1	10
67/12	4 05 18	152 06 33	1.00	5.3	12
67/13	4 09 20	152 01 27	0.77	4.1	12
67/14	4 10 03	151 57 54	0.68	3.6	12
67/15	4 15 01	151 54 54	1.10	5.9	12
67/16	4 10 17	151 49 57	0.81	4.3	12
67/17	4 10 17	151 42 34	0.32	1.7	7
67/18	4 07 39	151 37 34	0.28	1.5	8
67/19	4 10 33	151 33 24	0.34	1.8	9
67/20	4 13 14	151 27 33	0.17	0.9	5
67/21	4 18 46	152 23 45	0.51	2.7	13
67/22	4 13 20	152 22 17	0.47	2.6	15
67/23	4 06 09	152 23 28	0.52	2.8	15
67/24	3 59 05	152 23 03	0.87	4.6	15
67/25	3 53 48	152 22 08	0.80	4.3	14
67/25A	3 54 30	152 18 55	0.97	5.2	13
67/26	3 50 10	152 21 34	1.18	6.3	13
67/27	3 45 26	152 23 39	0.71	3.8	8
67/30	4 26 09	152 22 18	0.67	3.6	13
67/31	4 33 27	152 25 06	1.07	5.7	13
67/32	4 39 08	152 25 05	1.04	5.5	14
67/33	4 45 36	152 22 52	0.88	4.7	13
67/34	4 50 14	152 24 10	0.97	5.2	14
67/35	4 58 19	152 21 30	0.79	4.2	12

TABLE 2 (contd)

67/36	5 01 41	152 10 27	1.25	6.7	11
67/37	3 35 40	152 25 05	0.94	5.0	4
67/38	3 27 38	152 27 04	0.94	5.0	8
67/40	3 16 03	152 35 10	0.88	4.7	7
67/43	2 59 48	152 48 34	0.97	5.2	3
67/47	4 03 53	152 59 43	0.50	2.7	7
67/48	3 03 08	152 32 21	0.96	5.1	4
69/A	4 05 00	152 26 00	0.62	3.3	6
69/B	4 02 00	152 31 00	0.84	4.5	6
69/3	4 10 32	153 32 12	0.73	3.9	8
69/4	4 03 56	153 04 53	0.90	4.8	12
69/5	4 27 18	152 35 26	1.43	7.6	7
69/5A	3 51 36	151 54 20	0.70	3.7	12
69/6	4 53 28	152 21 16	0.63	3.4	13
69/9	3 58 18	151 24 19	0.31	1.7	9
69/10	3 40 03	151 31 54	0.46	2.5	4
69/13	4 23 40	151 20 38	0.69	3.7	4
69/28	3 50 18	151 53 04	0.95	5.1	18
69/28A	3 37 15	151 51 39	0.31	1.7	7
69/29	3 57 50	151 59 19	0.96	5.1	17
69/30	4 05 15	152 06 32	0.85	4.5	16
69/31	4 08 28	152 08 27	0.87	4.6	9
69/32	4 14 10	152 09 49	0.85	4.5	4
69/33	4 15 15	152 10 51	0.85	4.5	4
69/34	4 16 56	152 11 25	0.87	4.6	7
69/35	4 17 18	152 12 43	0.70	3.7	7
69/36	4 18 30	152 14 47	0.88	4.7	9
69/37	4 20 19	152 17 24	0.89	4.7	11
69/38	4 29 35	152 24 13	0.77	4.1	17
69/38A	4 36 15	152 29 36	1.06	5.6	13
69/39	4 43 09	152 32 10	0.95	5.1	13
69/40	4 46 52	152 39 07	1.51	8.0	5
69/40A	4 52 25	152 46 01	1.00	5.3	13
69/41	4 19 58	152 38 31	1.33	7.1	3
69/42	4 14 49	152 28 41	0.70	3.7	13
69/43	4 15 18	152 19 49	0.72	3.8	14
69/44	4 15 43	152 12 15	0.80	4.3	9
69/45	4 15 25	152 00 41	0.75	4.0	17
69/46	4 17 10	151 53 18	0.69	3.7	18
69/47	4 14 33	151 27 15	0.16	0.9	15

TABLE 3

Time-terms and depths to intra-crustal (6.84 km/s) refractor, New Britain/New Ireland

Shot or Station	Latitude(S) Deg. Min. Sec	Longitude(E) Deg. Min. Sec	Time-term s	Depth km	No. of Datum Points
RBL	4 11 33	152 09 46	1.94	17.6	4
RAL	4 13 18	152 11 42	1.57	14.3	5
SUL	4 13 15	152 11 08	1.86	15.6	5
TAV	4 13 57	152 12 48	1.68	15.5	5
VUL	4 17 03	152 08 19	1.63	13.4	12
WAN	4 11 44	152 10 07	1.17	8.9	2
WARANGOI	4 27 21	152 14 21	2.29	23.8	2
RAPOPO	4 20 19	152 19 20	1.74	16.0	7
DOILENE	4 11 59	151 33 04	0.88	9.0	17
PONDO	4 33 22	151 37 14	1.53	19.2	11
POWELL HBR	4 48 26	151 41 43	1.52	14.7	16
VITU I.	4 41 56	149 27 42	0.81	4.0	3
TALASEA	5 16 38	150 00 33	1.56	12.5	10
BULUMURI	5 01 03	150 08 45	1.61	13.2	8
ULAMONA	4 49 36	151 16 03	1.59	10.5	14
BIALA	5 19 40	151 00 36	2.12	17.7	4
PAKIA	5 21 01	151 24 22	2.17	18.4	7
AUUNA	5 44 50	151 02 24	1.58	10.5	6
CRA	5 44 10	150 04 20	1.50	9.3	4
KANDRIAN	6 12 20	149 33 00	1.92	15.7	5
LINDENHAFEN	6 13 36	150 27 18	1.38	8.3	9
PALMALMAL	5 37 56	151 29 30	2.11	18.2	10
MULIAMA/MANGA	4 06 19	152 59 54	1.22	10.8	12
NAMATANAI	3 39 56	152 26 36	0.91	4.7	7
ULUPUTUR	3 43 23	152 22 46	0.93	4.6	6
67/10	4 12 56	152 38 36	1.92	13.6	2
67/20	4 13 14	151 27 33	0.45	4.6	2
67/21	4 18 46	152 23 45	1.39	14.1	3
67/22	4 13 20	152 22 17	1.17	11.3	3
67/23	4 06 09	152 23 28	1.21	11.5	3
67/24	3 59 05	152 23 03	1.29	9.5	3
67/25	3 53 48	152 22 08	1.42	11.8	3
67/25A	3 54 30	152 18 55	1.46	10.8	3
67/26	3 50 10	152 21 34	1.38	7.7	3
67/27	3 45 26	152 23 39	1.24	10.2	2
69/2	3 58 53	153 50 35	1.86	17.2	2
69/3	4 10 32	153 32 12	1.86	18.4	2
69/4	4 03 56	153 04 53	2.10	20.2	3

TABLE 3 (contd)

69/5	4 27 18	152 35 26	2.15	15.9	5
69/5A	3 51 36	151 54 20	1.09	8.3	2
69/6	4 53 28	152 21 16	1.66	16.6	4
69/7	5 18 37	152 19 46	1.83	14.5	5
69/8	5 43 51	151 36 42	2.51	23.7	4
69/9	3 58 18	151 24 19	0.94	9.9	9
69/10	3 40 03	151 31 54	0.95	8.5	7
69/11	3 57 25	151 05 36	0.81	4.0	8
69/12	4 51 20	151 34 59	1.18	5.8	7
69/12A	4 30 21	150 57 10	0.71	3.5	9
69/13	4 23 40	151 20 38	0.90	4.4	9
69/14	4 48 07	151 16 21	1.07	5.3	12
69/15	5 20 44	150 25 23	1.08	5.3	10
69/16	4 59 33	150 13 25	1.08	5.3	6
69/17	4 32 25	150 27 11	0.96	4.7	4
69/18	4 18 11	150 06 07	0.79	3.9	2
69/19	4 52 39	150 05 38	1.05	5.2	4
69/20	4 47 12	149 35 39	1.04	5.1	4
69/21	5 16 37	149 52 48	0.95	5.9	3
69/22	6 13 46	149 27 35	1.54	10.5	4
69/23	6 19 04	150 17 40	1.54	10.5	7
69/24	6 26 29	150 30 00	1.94	15.9	7
69/25	6 14 20	150 50 47	1.47	9.6	5
69/26	6 22 38	151 23 45	1.62	11.6	5
69/27	6 02 20	151 32 36	2.52	23.8	8
69/47	4 14 33	151 27 15	0.78	9.1	7

TABLE 4

Time-terms and depths to Moho (7.92 km/s) refractor, New Britain/New Ireland

Shot or Station	Latitude(S) Deg. Min. Sec	Longitude(E) Deg. Min. Sec	Time-term s	Depth km	No. of Datum points
RBL	4 11 33	152 09 46	4.08	40.6	6
RAL	4 13 18	152 11 42	3.32	33.2	8
TAV	4 13 57	152 12 48	3.38	33.0	15
VUL	4 17 03	152 08 19	3.68	36.8	13
WAN	4 11 44	152 10 07	3.44	37.0	9
RAPOPO	4 20 19	152 19 20	3.62	35.8	9
DIOLENE	4 11 59	151 33 04	1.68	16.5	10
PONDO	4 33 22	151 37 14	2.39	23.1	10
POWELL HBR	4 48 26	151 41 43	2.49	22.6	12
VITU I.	4 41 56	149 37 42	1.26	9.4	9
TALASEA	5 16 38	150 00 33	2.01	14.5	6
BULUMURI	5 01 03	150 08 45	2.36	19.0	8
ULAMONA	4 49 36	151 16 03	3.24	30.0	16
BIALA	5 19 40	151 00 36	2.82	21.4	8
PAKIA	5 21 01	151 21 22	3.54	30.9	6
AUUNA	5 44 50	151 02 24	3.13	28.6	5
CRA	5 44 10	150 04 20	3.29	31.3	5
KANDRIAN	6 12 20	149 33 00	3.89	37.4	8
LINDENHAFEN	6 13 36	150 27 18	2.96	2.79	6
PALMALMAL	5 37 56	151 29 30	3.40	29.7	10
MULIAMA/MANGA	4 06 19	152 59 54	3.79	42.0	5
LAMBOM	4 48 23	152 51 29	1.98	10.9	2
BOANG I.	3 23 02	153 16 44	3.54	37.2	3
69/1	4 19 19	154 04 05	3.42	33.2	7
69/2	3 58 53	153 50 35	3.83	38.0	6
69/3	4 10 32	153 32 12	4.03	41.2	7
69/4	4 03 56	153 04 53	4.00	38.7	4
69/5A	3 51 36	151 54 20	1.68	13.7	3
69/6	4 53 28	152 21 16	2.61	23.4	4
69/7	5 18 37	152 19 46	2.70	21.7	5
69/8	5 43 51	151 36 42	3.47	28.5	4
69/9	3 58 18	151 24 19	1.17	9.9	6
69/10	3 40 03	151 31 54	1.33	10.8	2
69/11	3 57 25	151 05 36	1.43	11.7	8
69/12A	4 30 21	150 57 10	1.69	16.1	10
69/13	4 23 40	151 20 38	1.55	12.5	7
69/14	4 48 07	151 16 21	1.51	10.3	8

TABLE 4 (contd)

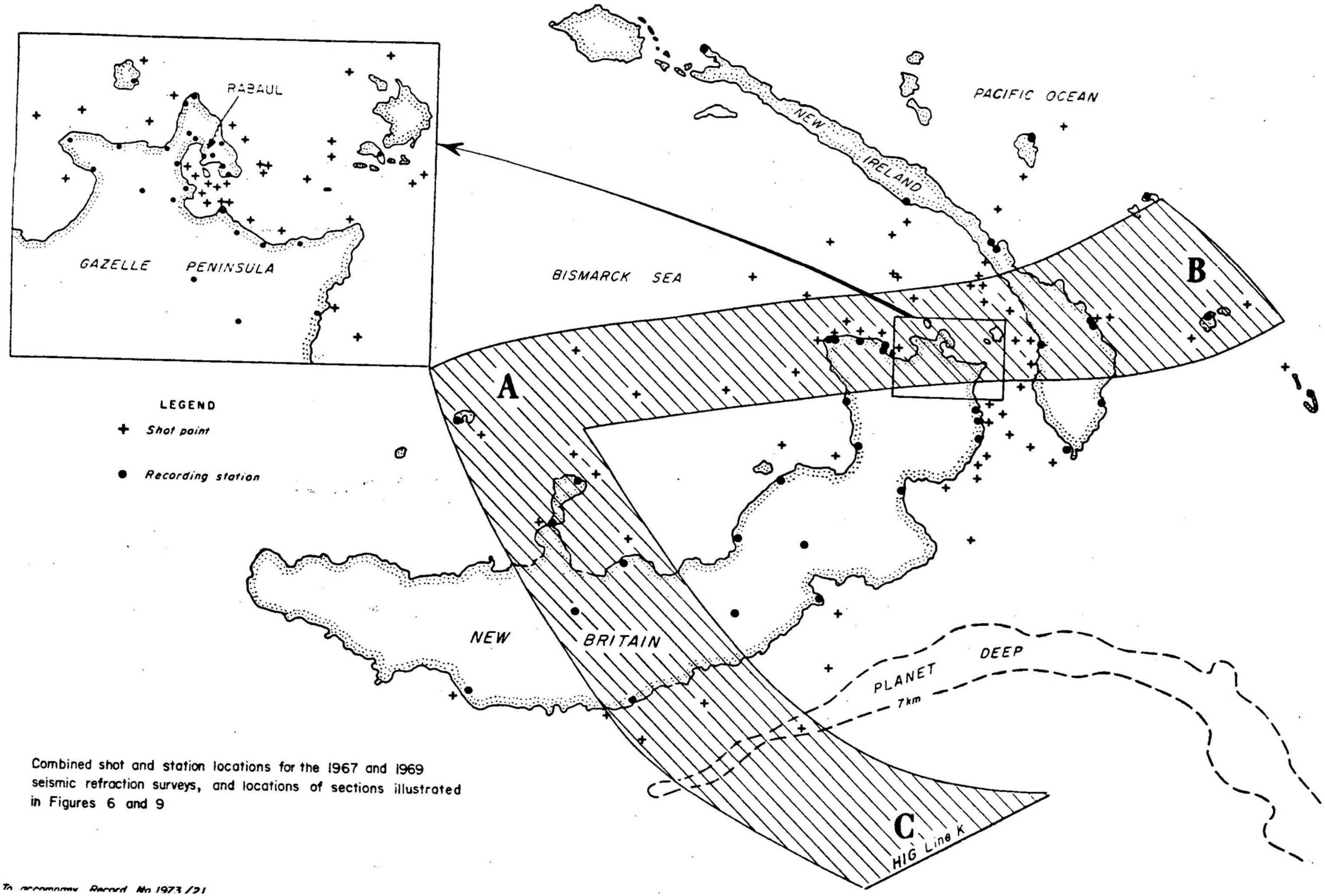
69/15	5 20 44	150 25 23	2.17	19.3	6
69/16	4 59 33	150 13 25	1.71	13.0	9
69/17	4 32 25	150 27 11	1.37	9.5	14
69/18	4 18 11	150 06 07	1.74	16.0	10
69/19	4 52 39	150 05 38	1.38	8.7	13
69/20	4 47 12	149 35 39	1.48	10.3	13
69/21	5 16 37	149 52 48	2.69	28.0	8
69/22	6 13 46	149 27 35	3.95	40.3	4
69/23	6 19 04	150 17 40	3.46	33.7	6
69/24	6 26 29	150 30 00	3.63	33.8	6
69/25	6 14 20	150 50 47	3.42	33.6	5
69/26	6 22 38	151 23 45	2.34	18.1	6
69/27	6 02 20	151 32 36	3.41	27.6	5
69/40A	4 52 25	152 46 01	1.99	16.1	2

TABLE 5

Pairs of sites used to determine unique time-term solutions

4.64 km/s Refractor				Time-Term Constant
TAVUI	&	1969/31		0.64
NONGA	&	1969/31		0.68
PRAED PT	&	1967/D		0.45
BURMA RD	&	1969/32		0.48
VULCON	&	1969/34		0.72
			Average	0.60
6.11 km/s Refractor				
DOILENE	&	1967/19		0.94
KABIARA	&	1969/45		0.95
RAVALIEN	&	1969/37		1.04
KAGANGA	&	1967/30		1.02
MULIAMA	&	1967/47		1.02
ULUPUTUR	&	1967/27		1.04
NAMATANAI	&	1967/37		0.90
SUM SUM	&	1967/33		0.81
KILINWATA	&	1969/46		0.92
			Average	0.96
6.84 km/s Refractor				
DOILENE	&	1969/47		0.84
MANGA	&	1969/4		0.35
BULUMURI	&	1969/19		1.07
TALASEA	&	1969/21		1.10
LINDENHAFEN	&	1969/23		0.71
PALMALMAL	&	1969/8		0.59
VITU I.	&	1969/20		0.68
POWELL HBR	&	1969/12		0.96
			Average	0.79
7.92 km/s Refractor				
MANGA	&	1969/4		3.40
VITU I.	&	1969/20		3.40
BULUMURI	&	1969/16		2.96
LINDENHAFEN	&	1969/23		3.54
PALMALMAL	&	1969/8		3.32
LAMBOM	&	1969/40A		3.30
			Average	3.29

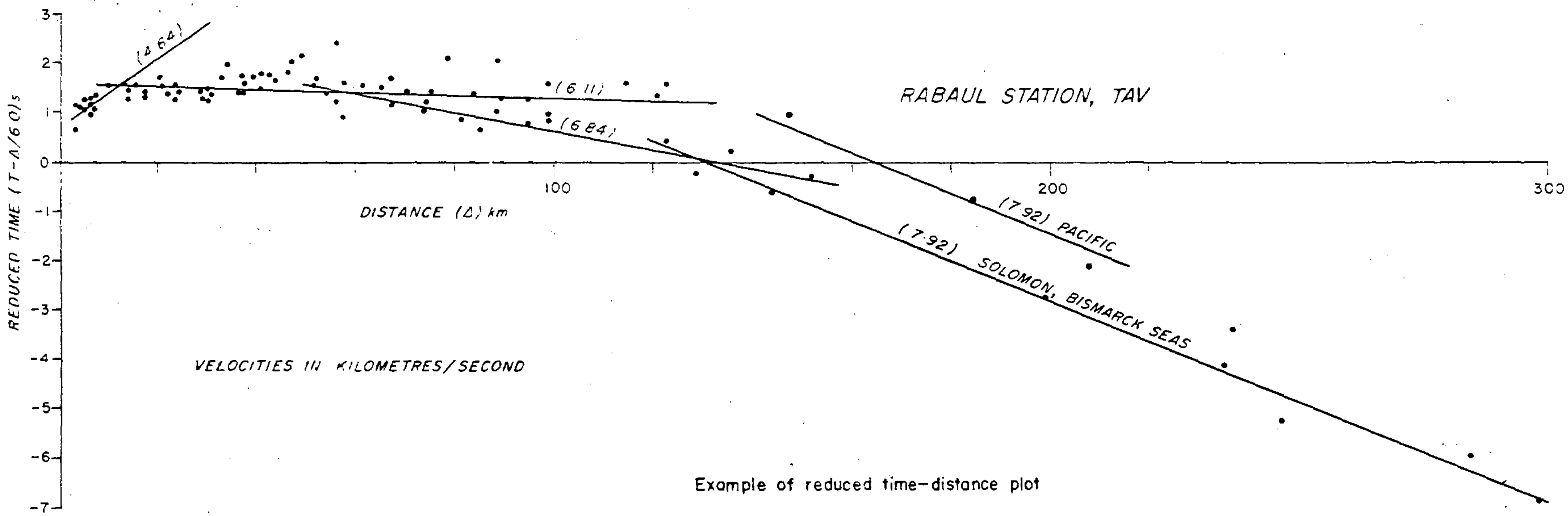
Figure 1



Combined shot and station locations for the 1967 and 1969 seismic refraction surveys, and locations of sections illustrated in Figures 6 and 9

To accompany Record No 1973/21

Figure 2

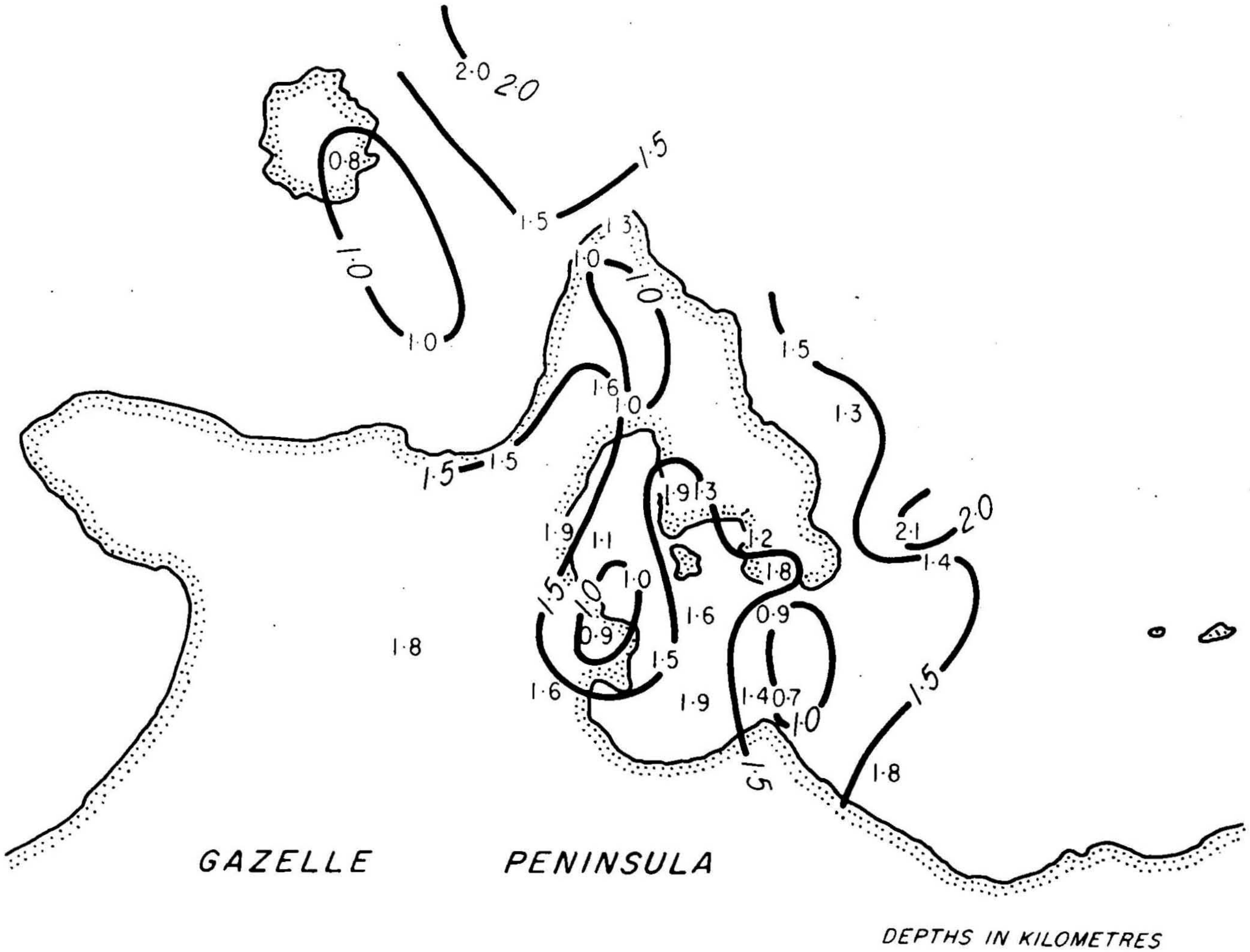


Example of reduced time–distance plot

To accompany Record No 1973/21

PNG/B10-257A

PNG/BIO-258A



Shot and station locations and depths to 4·64 km/s refractor in the region of the Rabaul Caldera.

accompany Record No. 1973/21

Figure 4

Histograms of travel-time residuals from time-term analyses of (a) 4·64 km/s, (b) 6·11 km/s, (c) 6·84 km/s and (d) 7·92 km/s refractors

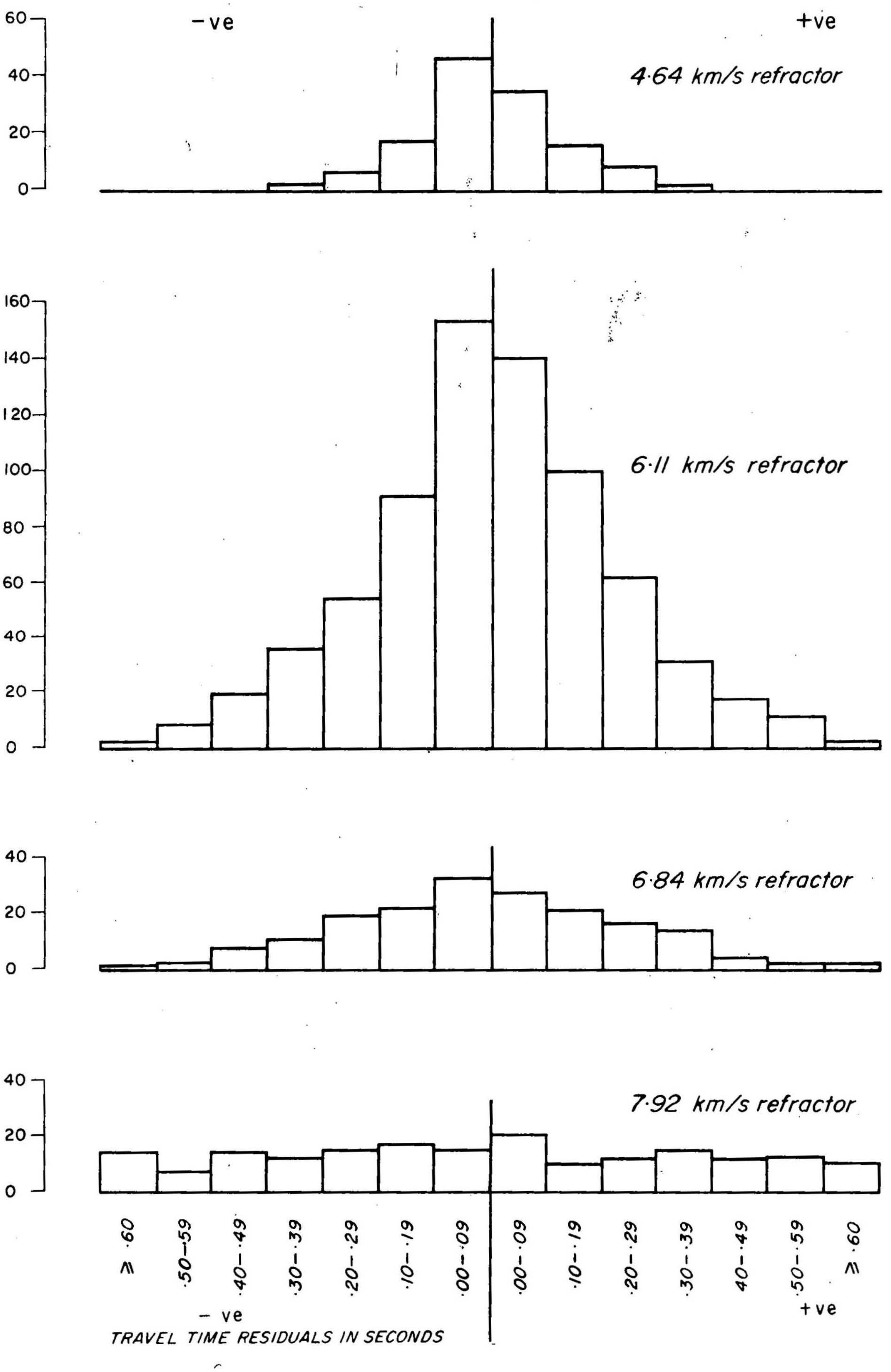
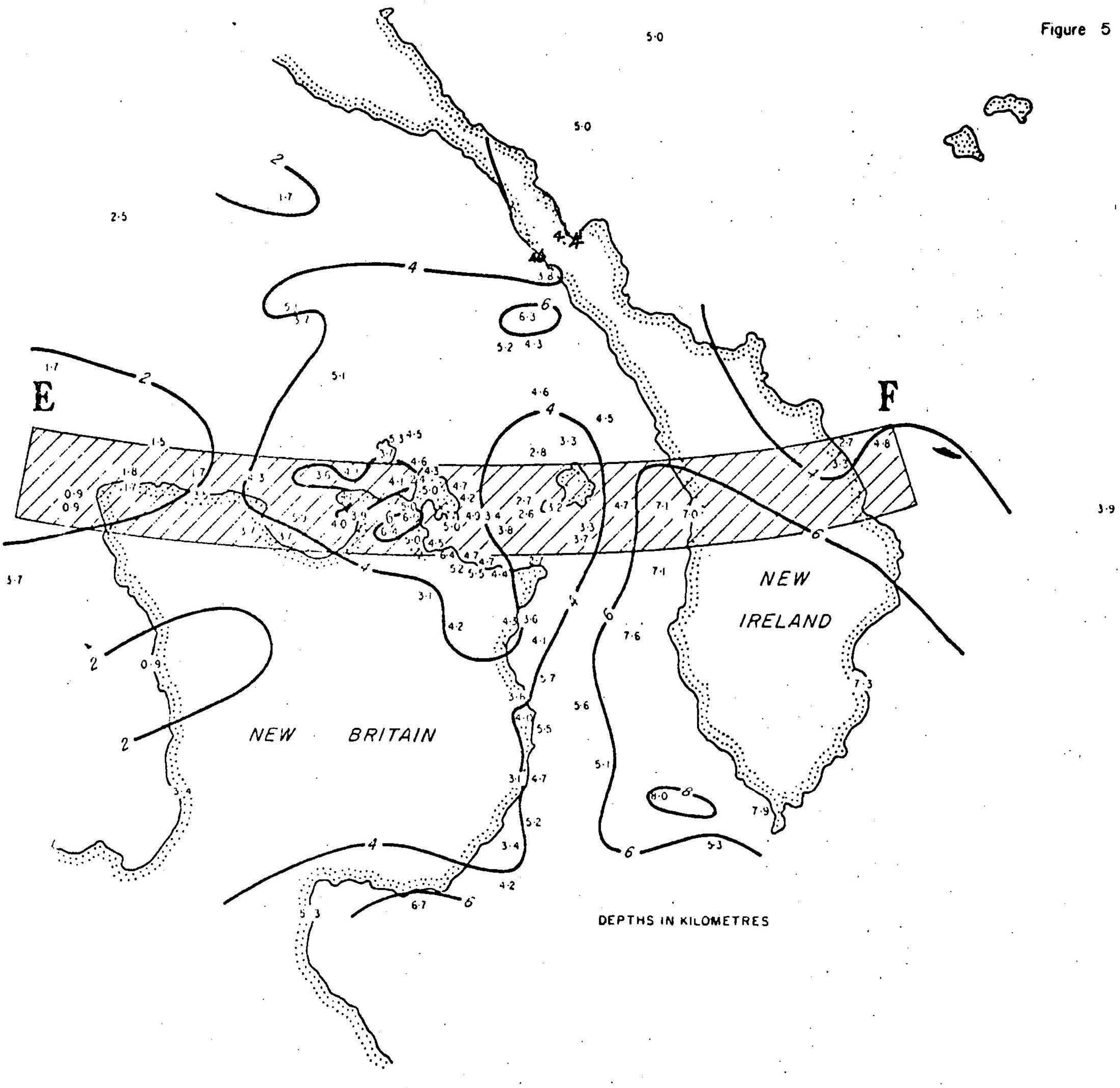


Figure 5

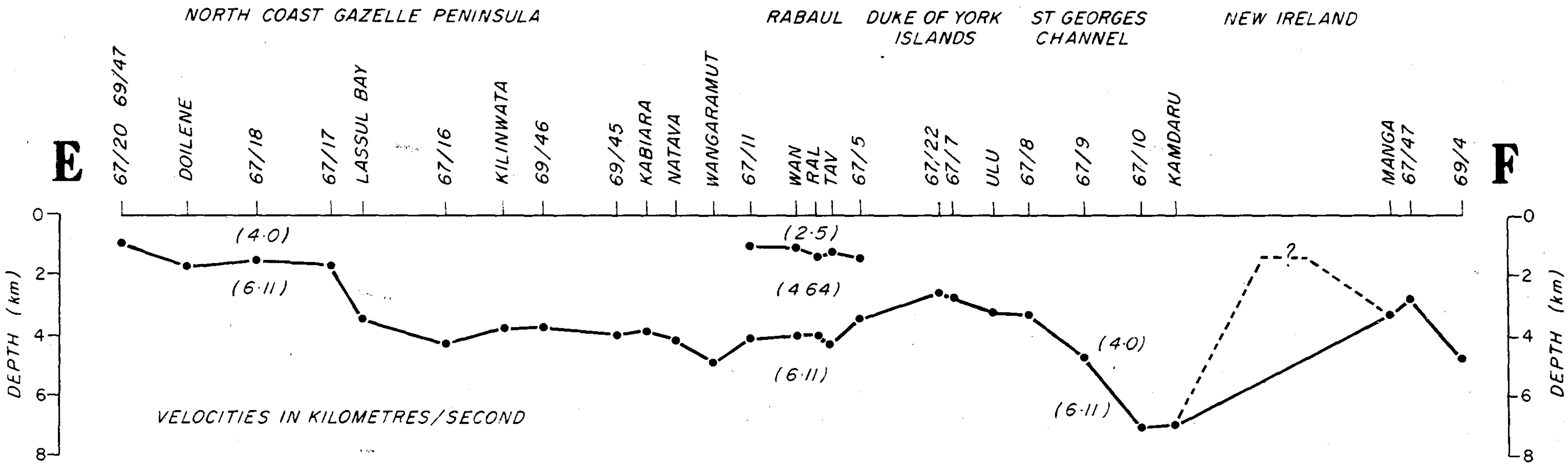


Depths to basement (6·11 km/s) refractor in the Gazelle Peninsula–southern New Ireland region.

To accompany Record No 1973/21

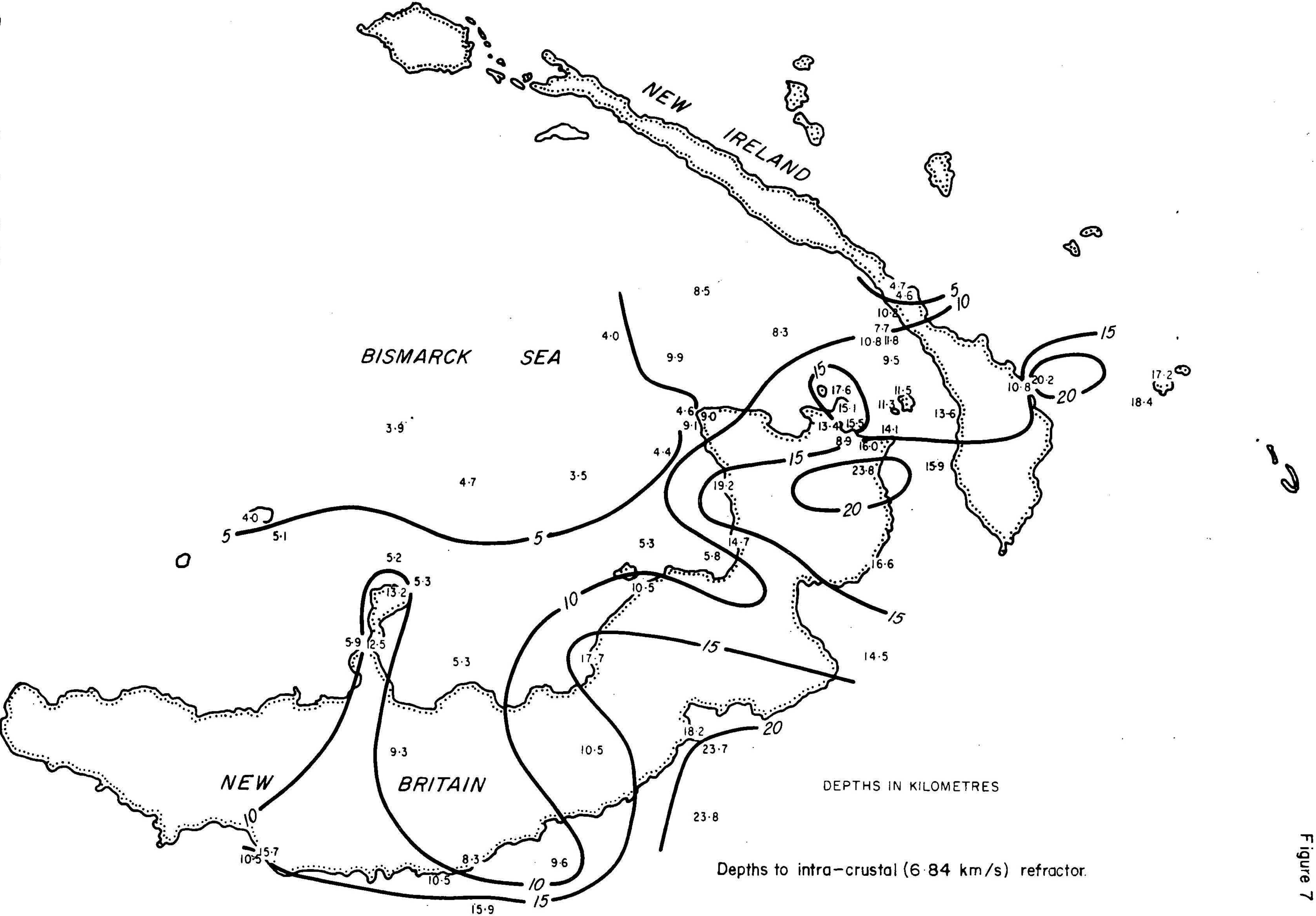
PNG/B10-260

Figure 6



East–west section through Rabaul illustrating basement structure.

To accompany Record No. 1973/21

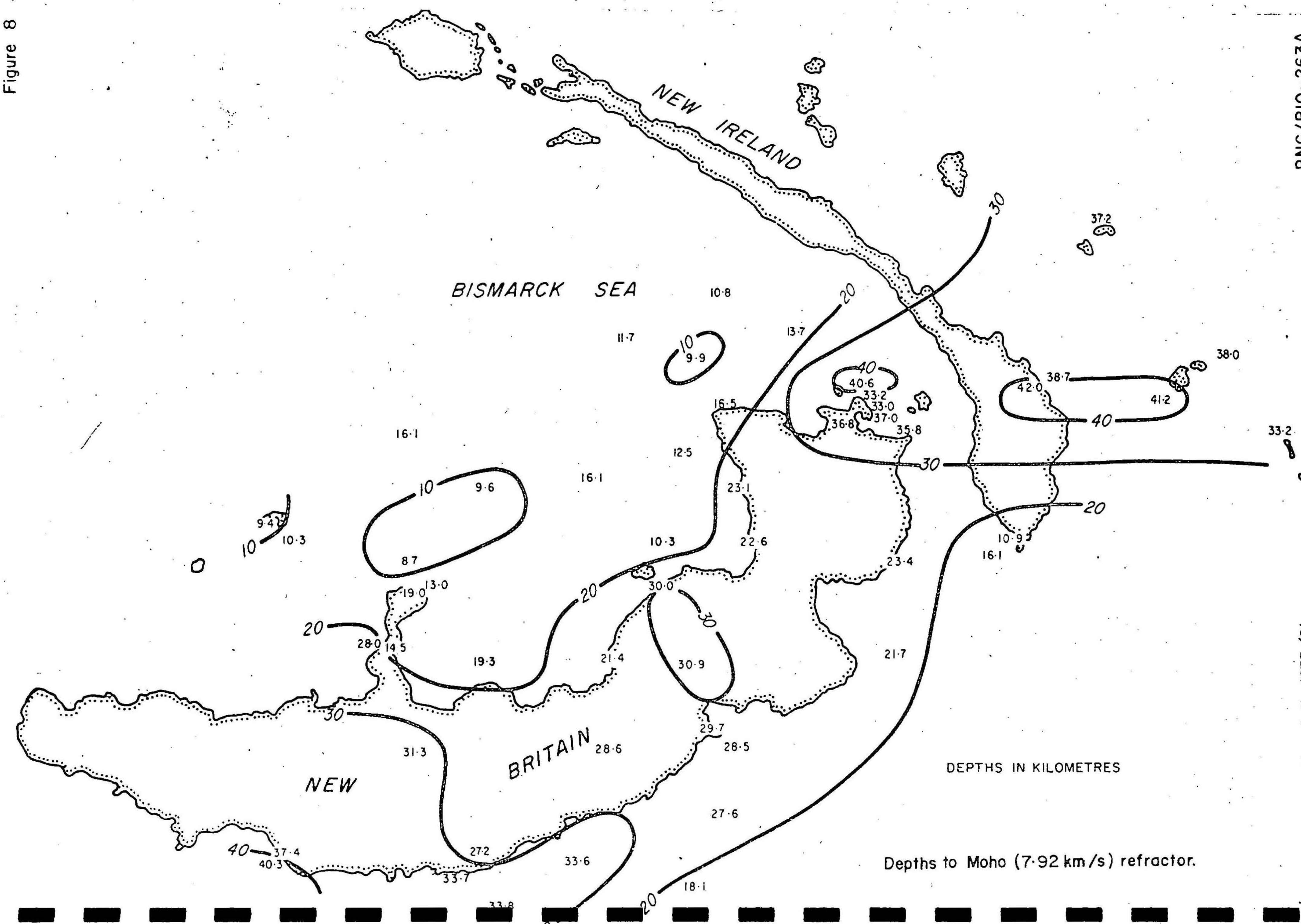


Depths to intra-crustal (6·84 km/s) refractor.

Figure 7

PNG/B10-262A

Figure 8



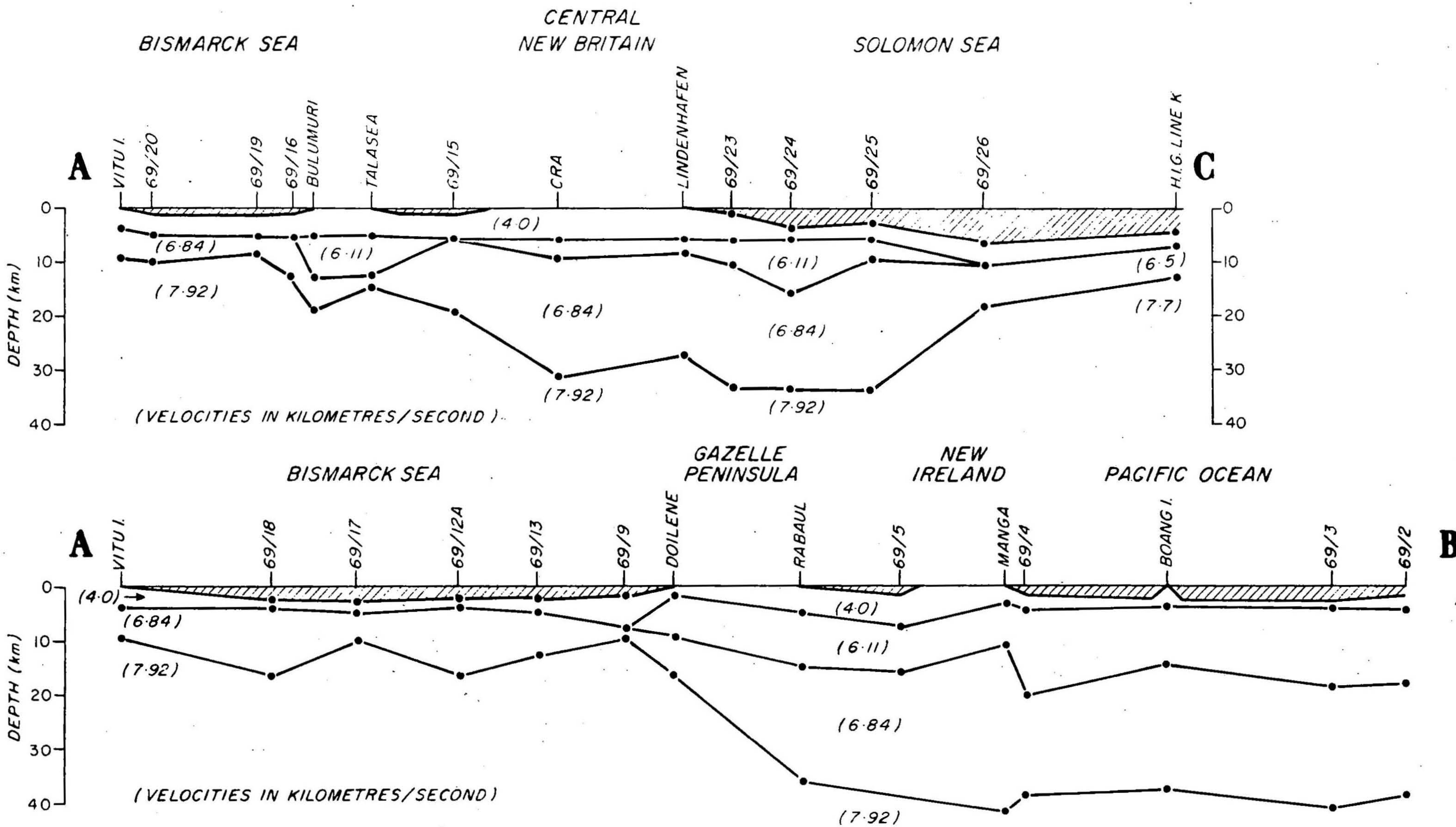
Depths to Moho (7·92 km/s) refractor.

PNG/BIO-263A

To accompany Record No. 1973/21

Figure 9

PNG/BIO-264A



Representative crustal cross-sections from time-term analyses in the New Britain / New Ireland region.

To accompany Record No. 1973/21