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MODEL OF A YOUNG INTRA-OCEANIC ARC : THE NEW HEBRIDES ISLAND ARC

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Abstract This paper summarizes the results of a reconnaissance seismic survey undertaken by the *IFP-CEPM-ORSTOM* group in 1972 in the young intra-oceanic arc of the New Hebrides.

In the northern and southern segments of this NNW-SSE trending arc the following structural zones can be recognized : a trench, an inner wall with one or two slope breaks and an intermediate basin between the upper slope break and the frontal arc, the frontal arc itself, a median sedimentary basin with a volcanic range located in its eastern part and finally a horst and graben province, which separates the North Fiji Plateau from the arc. The survey provided a more accurate definition of the frontal arc, a better description of the median sedimentary basin and led to the discovery of a strip characterized by magmatic intrusions, apparently related to transverse fracture zones.

In the central segment, however, the features mentioned above are less evident. Here the position of the trench is occupied by the island of Espiritu Santo and Malekula. The survey suggests that the two slope breaks on the inner wall of the northern trench continue into the western part of the Espiritu Santo Island. Also the median central basin is here replaced by the central basin.

It is believed that the rectilinear nature of the northern New Hebrides arc is due to the presence of a recently arrived oceanic high at the subduction zone. In similar fashion the unusual central segment of the arc is related to the underthrusting of the complex E-W trending d'Entrecasteaux fracture zone and its associated high. This is supported by seismologic evidence given by Pascal (1974).

The central basin is filled by two sequences, which are separated by an unconformity at its western edge. The maximum thickness exceeds 2,000 m in these sequences.

The lower sedimentary sequence dates from the Middle to the uppermost Miocene, while the upper sequence includes the Plio-Pleistocene. The lower sequence can also be recognized in the median sedimentary basin to the North, suggesting a once continuous basin.

I. INTRODUCTION

The New Hebrides Island Arc (fig. 1) strikes north-northwest to south-southeast and is located between 165° and 175° E longitude and 10° and 23° S latitude. In contrast with most island arcs the New Hebrides Arc is rectilinear for some 900 km and curves only in its southern part. Like the Solomon and Luzon arc this arc is concave to the Pacific and its trench is located on the western side. The arc is some 250 km wide as measured from the axis of the trench to the margin of the Fiji

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Plateau and is some 1,100 km long as measured from Matthew to Hunter Islands.

The New Hebrides Arc extends to the Solomon Arc in the North and to the Hunter Ridge in the South. The Fiji Plateau to the East is considered to be a young oceanic area characterized by high heat flow and the virtual absence of sediments. Its crustal thickness, between 8 and 15 km, appears to be intermediate between oceanic and continental crust (Dubois et al., 1974). The area to the West of the New Hebrides Arc has not yet been studied in detail.

II. MAJOR STRUCTURAL SUBDIVISIONS AND THEIR LATERAL DEVELOPMENT

Well defined island arc subdivisions can only be recognized in the northern and southern segments of the New Hebrides Arc, i.e. north of 14°30' S latitude or South of 17°30' S latitude. The central segment corresponding to the Espiritu Santo Island is anomalous which is probably due to its position at the west end of the Entrecasteaux fracture zone.

As shown on cross section figure 2b, the following elements can be distinguished from West to East.

1. Outer Swell.

The outer swell of the North segment is arched and has a fairly steep eastern slope which suggests the presence of a high which is about to reach the subduction zone. In the southern segment, that is to the West of the North Loyalty Plateau (Dubois et al., 1974), we observe a series of gently dipping blocks. The sedimentary layer in that area is thin (1,000 m maximum). The outer swell is generally characterized by normal faulting.

2. Trench.

The trench is very narrow and rectilinear to the North. In the southern segment the trench widens and becomes slightly convex towards Australia. The trench is not filled with sediments.

3. Inner Wall.

The slope of the inner wall is steeper in the North than in the South. Two morphologic elements are recognized :

- the first slope break is distinct in the North but is less evident in the South. It is always close and parallel to the axis of the trench;
- the second slope break is more conspicuous and corresponds better to Dickinson's (1973) trench slope break or Karig's (1970) mid slope basement high. An intermediate basin intervenes between the second slope break and the frontal arc. This basin is not as well developed as in other West Pacific arcs, a fact which earlier led Karig and Mammerickx (1972) to question its existence.

4. Frontal Arc.

The axis of the frontal arc is defined by the highest elevations along the western edge of the arc. Its position and its relation to the previously described units are evident in figure 3.

5. Median Sedimentary Basin.

The median sedimentary basin is located between the frontal arc to the West and the horst-graben unit to the East. It is a flat to gently eastward dipping basin in slightly greater water depth than the frontal arc and it extends over a width of about 70 km. Only in this province does seismic work reveal undisturbed sediments of appreciable thickness, i.e. exceeding 2,000 m. The basin axis shows a slight convexity towards Australia.

6. Volcanic Arc.

The volcanic arc is slightly convex to Australia and its location can be seen in figure 3. It intersects the Eastern third of the median sedimentary basin at an average distance of 140 km from the trench axis. Banks, Aoba, Ambrym, Epi, Erromango, Tanna and Matthew Islands are all volcanic islands included in this arc.

7. Horst-Graben Zone.

The horst-graben zone forms the eastern part of the arc. In figures 3 and 4 it can be seen that it is not a series of en echelon rifts but that instead the structures are parallel to the axis of the arc and are occasionally cut and offset by transverse features. A main graben is flanked by a westerly horst which also forms the east side of the sedimentary basin and by an easterly horst forming the edge of the North Fiji Plateau. This structural arrangement is fairly obvious to the South but farther to the North several transverse breaks obscure the main features.

The lateral development of the subdivisions can be seen in figures 1, 2, 3 and 4. In the northern segment and proceeding from North to South we can see that the trench decreases gradually in depth until it merges into the northern spur of the western range of Espiritu Santo.

The two slope breaks on the inner wall also decrease in depth and then emerge above sea level at the Northern extension of the west half of Espiritu Santo where its geomorphology is entirely different. The geology of this island has been described and interpreted by Robinson (1969). This author noted the presence of slumped shallow water calcarenites in deep water calcilutites, which could correspond to the extension of the intermediate basin sediments.

The frontal arc extends into the Eastern half of Espiritu Santo, which appears to be underlain by volcanic rocks which are mantled by recent sediments.

The median sedimentary basin (fig. 4b and 5c) decreases in width towards the South. Its transition to the central basin is particularly abrupt and coincides with the submergence of Banks Island to the South. The sudden eastward inflection of the structures to the South of Banks Island relates to fractures which caused the submergence of Banks Islands.

The horst and graben unit on the eastern margin of the arc splits towards the southwest into several elements, thus reducing the width of the median sedimentary basin. The eastern range corresponding to Maevo and Pentecost Islands are considered to be morphological continuation of the western horst of that horst and graben unit.

The Central Region (fig. 2c, 3 and 4) differs from the segments to the North and South by :

- the absence of a trench and slope breaks on the inner wall;
- the presence of the central basin which is located in the prolongation of the median sedimentary basin. The volcanic island Aoba is located in this basin;
- the presence of an eastern range corresponding to Aurora and Pentecost Islands and representing the horst and graben province.

Thus, the central basin is flanked by the islands of Espiritu Santo and Malekula to the West and Aurora and Pentecost Islands to the East. A gentle and unfaulted slope forms the Western flank of the basin whereas the contact with the Eastern range appears to be abrupt and appears to be characterized by a fault system paralleling that range.

In the Southern Region and proceeding from South to North the trench stays at about the same depth but its width decreases. Also from South to North the first slope break becomes more accentuated. The second slope break frequently is a double break in a quite variable depth range. It emerges in the area due west of Malekula. The definition of the frontal arc is difficult. Proceeding from South to North the median sedimentary basin decreases in width and the presence of volcanic extrusions accompanies the merging of this basin into the central basin. The definition of the horst and graben unit in the Southern region is not quite as clear as in the North and the unit probably does not extend North of Efate. Allowing for the offsetting of structures by transverse faults it is more likely that the Eastern range of the Hebrides arc should be related to the horst and graben unit and more specifically to the Western horst of that unit.

III. VOLCANISM

In the median sedimentary basin, that is in the only area with an appreciable thickness of undisturbed sediments, it can be shown that seismic reflections disappear abruptly in a strip about 30 km wide which parallels the axis of the arc and which is located in the Eastern two-thirds of the median sedimentary basin (fig. 3 and 4). The area devoid of seismic reflections is coinciding with the occurrence of magnetic anomalies (Luyendyck et al., 1973). The disappearance of seismic reflections can only be seen in the vicinity of volcanoes. All Pliocene-Quaternary volcanoes occur in this area and they appear to be located at the intersection of transverse features (for example, Aoba, Ambrym and especially the Northern island of the Banks group which marks the end of a large fault with substantial vertical displacement).

All these features suggest that the area devoid of seismic reflections corresponds to a zone of magmatic intrusions.

IV. BASEMENT

As is often the case in marine work here it is difficult to define acoustic basement for the following two reasons (fig. 5a, b, c) :

1) With increasing depth reflections gradually attenuate and disappear. The transition from good reflections to total absence of reflections is gradual and there is little concrete evidence for a definable acoustic basement.

2) A strongly diffracting reflector is often equated with an acoustic basement. However, the appearance of organized reflections underlying such a basement is frequently seen whenever that "acoustic basement" is attenuated. Such reflectors probably correspond either to volcanic extrusions or to thick volcanic clastic layers and occasionally they might correspond to reefs or reefal debris.

Even in areas where it appears to be reasonable that the acoustic basement may correspond to the actual basement (e.g. the North Fiji Plateau), deep and fairly prominent reflections appear occasionally and suggest vertical layering of the crust (successive extrusions ?).

V. CENTRAL BASIN AND ITS SEDIMENTARY BLANKET

Because the acoustic basement cannot be determined the thicknesses given for these basins should be viewed only as minimum thicknesses.

The distribution of the sediments (fig. 4) is controlled by the major structural features. In the center of the median sedimentary basin the thickness of the sediments exceeds 1,000 m and is often greater than 2,000 m. Other areas of sedimentary infill are located in basins and structural grabens where they occur in long narrow strips with thicknesses between .5 and 1 km.

In the North and South regions the sedimentary sequence of the median sedimentary basin is seismically characterized by the decrease and gradual attenuation of reflector intensity with depth and by the occasional presence of a strong discontinuous reflector located in the middle of the sequence. Lateral discontinuities are frequent. The character of the reflections and the geology of the adjacent islands, suggest the predominance of volcanic and volcano-clastic deposits and associated volcanic-derived sediments. Most lateral and vertical discontinuities are probably related to the nature of these volcanic deposits. However, it is conceivable that some of them may indicate carbonate intercalations of reefal origin (Mitchell, 1966 and 1970).

In the central basin (fig. 5c) an angular unconformity separates a recent series of horizontal reflections from an older series. This unconformity is visible on sections of the western edge of the basin. Both series appear to be conformable in the middle part of the basin and they terminate abruptly against the Eastern range. The dips observed in the Eastern range are approximately 30° W according to Obellianne (1958).

The lower series, which exceeds 1,000 m, shows the same seismic character in the North and South regions of the median sedimentary basin. The upper series, however, is totally different and suggests fine bedding and more continuous reflectors. The similarity of the lower series of the central basin with the sequence of the median sedimentary basin leads us to assume that in both areas these sequences have been deposited under similar conditions. This, as well as structural and morphological data, supports the assumption that the central basin and the median sedimentary basin once were continous.

VI. SEISMICITY OF THE NEW HEBRIDES ARC

In a recent study (Pascal et al., 1976) about 600 earthquakes were relocated with the JHD method (Joint Hypocenter Determination). All available focal mechanism solutions were collected for the period 1962 through 1972. The relocated events are plotted on a map (fig. 6) and projected onto a series of vertical cross-sections perpendicular to the strike of the trench. The seismicity is continuous from the North to the South, despite the remarkable lack of a trench in the central part of the arc. This part is indeed seismically very active and most of the large recent earthquakes occurred beneath Espiritu Santo and Malekula Islands. The distribution of the shallow events differs between the Northern and the Southern parts of the arc. Shallow seismic activity in the South is concentrated in narrow zones perpendicular to the trench axis related may be to large transverse faults or fractures. The intermediate depth earthquakes are irregularly distributed along the arc. Between 16° S and 18°5' S an important gap is found at depths between 50 and 120 km. Two important nests of events exist at depth below areas North and South of Aoba Island and Beneath Tanna Island. The cross-section (fig. 8) shows a seismic zone of finite thickness not exceeding 20 km at intermediate depth. This seismic zone curves very steeply downdip from the trench, and consequently the inferred zone of contact between the subducted slab and the overlying plate is considerably smaller in width than in most other subduction zones, e. g. Japan or South America. Focal mechanism solutions give a measure of plate motion directions. The constancy of the direction of slip is remarkable for the New Hebrides arc. The average of 15 solutions of shallow events gives a horizontal azimuth of 75° for the slip inferred from these shallow thrust type focal mecanisms. Most of the solutions of the intermediate-depth events represent downdip extension; the T axis (axis of minimum compressive stress) is approximately parallel to the dip of the seismic zone. This pattern, except for some events in the South, appears to be characteristic of the intermediate-depth events in the New Hebrides arc. In the central part of the arc a prominent East-West trending aseismic ridge, the d'Entrecasteaux fracture zone, abuts the central part of the Islands. The morphologic trench is missing between 14° S and 17°5' S. Similar discontinuities are present in other trenches of the world (Tonga-Kermadec, Solomon and Mariana Islands, South America) and there the corresponding shallow seismic activity is very low. In contrast to these regions the central part of the New Hebrides Island arc is very active and many large shallow-focus earthquakes occurred in the last 14 years, most of them between 15° S and 16° S. In August 1965, the Northern part of Malekula Island was uplifted by about 1 meter. The subduction of the fracture zone could be responsible for the tectonics of the central part. The focal mechanism solutions of the shallow events are characterized by an underthrusting plate slippage type mechanism North of 16°5' S, whereas, between 16°5' S and 18° S, the focal solutions are in accordance with an uplift to the Espiritu Santo-Malekula area and consequently a lateral compression of the arc.

VII. SYNTHESIS AND DISCUSSION

The subparallel structural grain of the New Hebrides arc appears to be offset by transverse trends. While typical Island arcs are convex toward the trench, this arc is unusually rectilinear in its northern part, and steep as well as faulted slopes dominate the morphology of the inner and outer trench walls. It is suggested that all these features can be related to the arrival of a large oceanic basement uplift in the subduction zone. The ensuing collision would so cause the deviation from a normally more arcuate pattern.

Dickinson (1973) suggests that underneath a shallow sedimentary veneer the "Trench Slope Break" (here the second slope break) is underlain by folded and faulted pelagites and turbidites which at depth would be underlain by ophiolitic mixtures and high-pressure metamorphic rocks. The formation and development of the inner trench wall is often believed to be due to structural accretion in the form of imbrications of oceanic pelagites and turbidite sequences, which were scraped off the subducted oceanic plate. These imbrications commonly dip towards the arc (Seely et al., 1974; Karig and Sharman, 1975).

Such imbrications cannot be documented by our seismic work in the New Hebrides, although two pronounced slope breaks can be recognized. It could be speculated that these breaks may be due to variations in sedimentary influx or else that they record variations in the rate of subduction. Thus it is conceivable that a faster subduction rate would cause an increase in stress which in turn would cause the formation of imbrications involving the uppermost part of the crust. Also it should not be overlooked that the unstable slope of the inner wall could be affected by superficial sliding phenomena which could interfere with the orderly accretion of imbricate structures.

The central region of the New Hebrides arc is unique because of the absence of a trench, the disappearance of the structural features of the inner wall, the formation of a Western range, a central basin and an Eastern range.

On the basis of seismologic considerations, Pascal (1974) suggested two possible explanations :

1) Espiritu Santo is part of the d'Entrecasteaux fracture zone, which in turn is an East-West trending submarine ridge apparently linked with the Northern prolongation of New Caledonia. This zone is some 80 km wide and the faulted aspect of its Northern flank is the reason for its interpretation as a fracture zone. This fracture zone would now replace the trench into which it was subducted.
2) The formations underlying the islands of Espiritu Santo and Malekula were roughly at their present position and the arrival of the fracture zone in the subduction zone would cause the uplift of these Islands which thus were overthrust on oceanic crust (or else underthrust by oceanic crust).

Our work which shows these islands to be an integral part of the structure of the arc would support the second hypothesis. Therefore, the anomalous features of the central zone (except for the Eastern range) are viewed to be the effect of the collision of the arc with the subducted d'Entrecasteaux fracture zone.

Luyendyck (1973) suggested that the central basin was created between the upthrusted Eastern and Western ranges and that its formation caused the Western range to migrate Westward. Karig and Mammerickx (1972) interpret the central basin as "a narrow extension zone", i.e. an interarc basin as defined by Karig (1970) which opened with the intrusion of material in the center, as in a rift.

We were unable to find such a rift. Moreover we observe the continuity of the lower sedimentary series of the Median Sedimentary Basin with its counterpart in the central basin. A variation of the width of the arc which would support such an opening cannot be observed. Quite to the contrary one sees that most structural elements in the northern and southern segments of the arc do not continue into the central region. These observations, particularly the continuity of the median sedimentary basin with the central basin, suggest that they were not formed by extension.

Onshore work by Coleman (1970) and Warden and Mitchell (1974) has revealed and dated three important tectonic phases, which in turn allow to date the lower and the recent seismic sequences of the central basin.

A first and important tectonic phase occurred between Lower and Middle Miocene in both the Western and the Eastern ranges. This phase was responible for the upthrusting and faulting of the eastern range (Mallick, 1959; Warden and Mitchell, 1974) and for the block tectonics and the rise of the Western range (Robinson, 1969; Mitchell, 1970; Warden and Mitchell, 1974). This phase corresponds to the first of the three unconformities observed on the Western edge of the basin, which separates the lower series from the basement. The rise of the frontal arc accompanied this tectonic event.

A second unconformity visible on reflection sections of the western edge of the basin separates the lower series from the recent series, whereas in the middle and the East of the basin these two series are conformable. The uppermost Miocene which outcrops only in the Western range dates the lower series which was deformed only near the Western range. Therefore the lower series ranges from Middle Miocene to Uppermost Miocene. The latest Miocene tectonic phase can be demonstrated on the Islands of Espiritu Santo and Malekula by the block tectonics and the upthrusting of the Islands (Robinson, 1969; Mitchell, 1966 and 1970; Warden and Mitchell, 1974). We have suggested that the Western part of Espiritu Santo is on trend with the two slope breaks of the northern inner trench wall and that the area immediately west of Malekula is the extension of the main slope break of the southern inner trench wall. Strike slip movements could be responsible for offsets separating the structures on both islands (Pascal, 1974). Onshore geology thus confirms that the inner walls of the central region emerged at that time.

The last Plio-Pleistocene tectonic phase (Coleman, 1970; Mitchell, 1966 and 1970, Obelianne, 1958; Robinson, 1969; Warden and Mitchell, 1974) was responsible for final great upthrusting of the islands. This phase is evident from the faults associated with the abrupt contact of the Eastern range with the adjacent central basin and from the gentle dips on the West side of the basin. This phase was probably responsible for the formation of the basin.

The horst and graben province coincides with the Eastern margin of the arc. The unit appears to be continuous and is not characterized by en echelon rifts as postulated by Karig and Mammerickx (1972). Its extensional origin is quite obvious. Dubois et al. (1975) showed that the axis of its central graben corresponds to a zone presently underlain by magma. Our data suggest an additional magmatic zone underlying the Median Sedimentary Basin. These zones suggest a possible graben-forming mechanism, related to the formation of transcurrent faults at the inflection points of the arc combined with the formation of convection cells in the asthenosphere overlying the Benioff zone. This process may very well indicate the initiation of a process ultimately leading to the formation of extensional inter-arc basins as defined by Karig (1970).

Finally, three points need particular emphasis :

1) Marine geology confirms that the extension tectonics described from the onshore areas with its subvertical or steeply dipping faults and the absence of folds does continue in the offshore areas.

2) The structural subdivisions, which here are relatively subdued compared with other typical Pacific Island arcs, can readily be explained by the recent Neogene age of the New Hebrides arc.

3) The current reconstruction of the history of the New Hebrides arcs does not allow for an explanation of the ultrabasic rocks found on Pentecost Island. Their origin has to be sought for elsewhere, as suggested by Gill and Gorton (1973). These authors postulate that during the Lower Miocene the New Hebrides arc was the extension of the Tonga-Kermadec arc.

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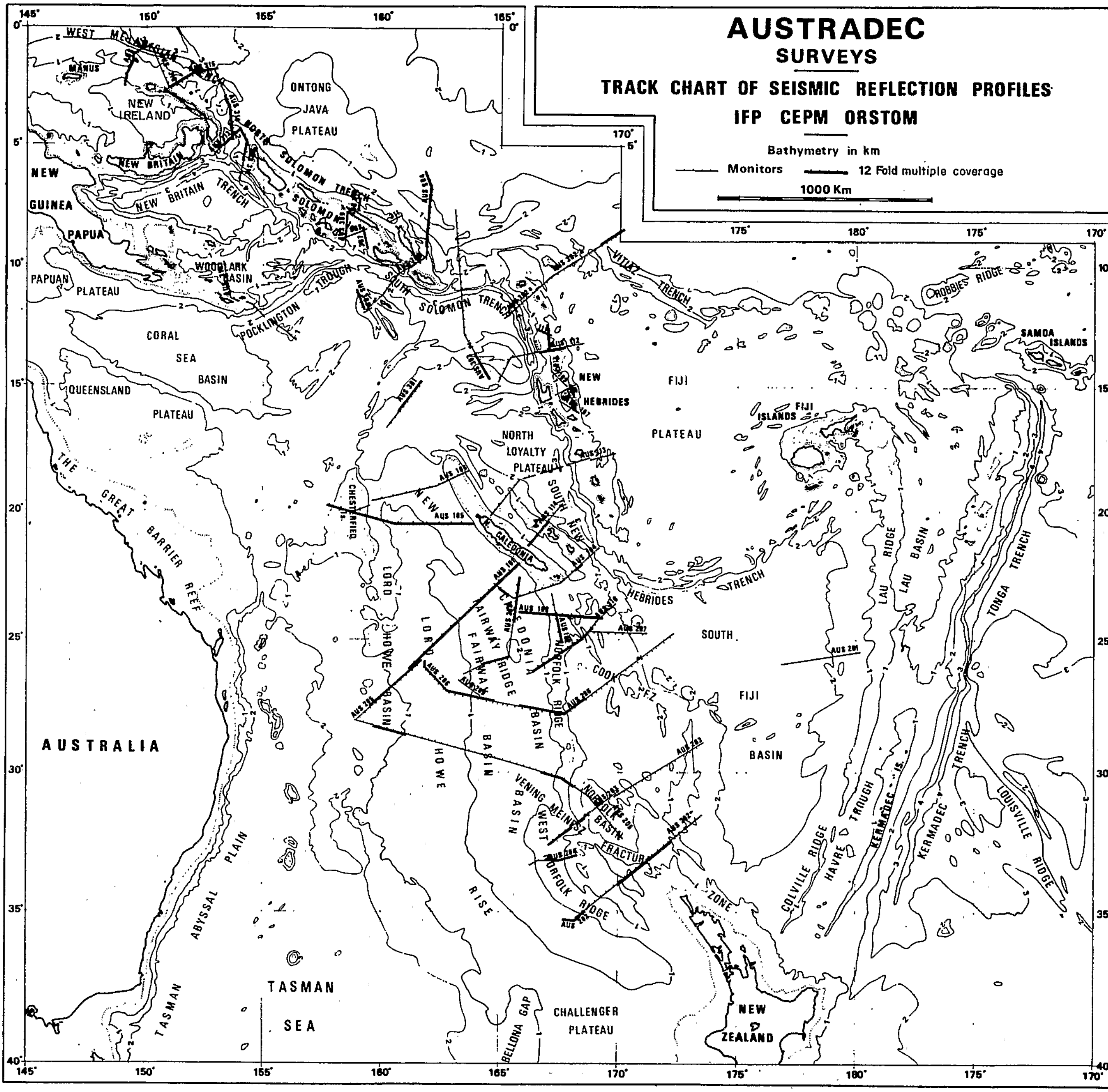
Fig.1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SOLOMON TRENCH
WOODLARK BASIN
POCKLINGTON TROUGH
SOUTH SOLOMON TRENCH
CORAL SEA BASIN
QUEENSLAND PLATEAU
NEW HEBRIDES
NORTH LOYALTY PLATEAU
FIJI PLATEAU
FIJI ISLANDS
SAMOA ISLANDS
VITIAZ TRENCH
ROBBIES RIDGE
THE GREAT BARRIER REEF
NEW CALEDONIA
LORD HOWE BASIN
LORD HOWE RISE
FAIRWAY RIDGE
NORFOLK RIDGE
SOUTH FIJI BASIN
COOK F.Z.
LAU RIDGE
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TONGA TRENCH
AUSTRALIA
VENING MEINESZ FRACTURE ZONE
WEST NORFOLK RIDGE
NORFOLK BASIN
COLVILLE RIDGE
HAVRE TROUGH
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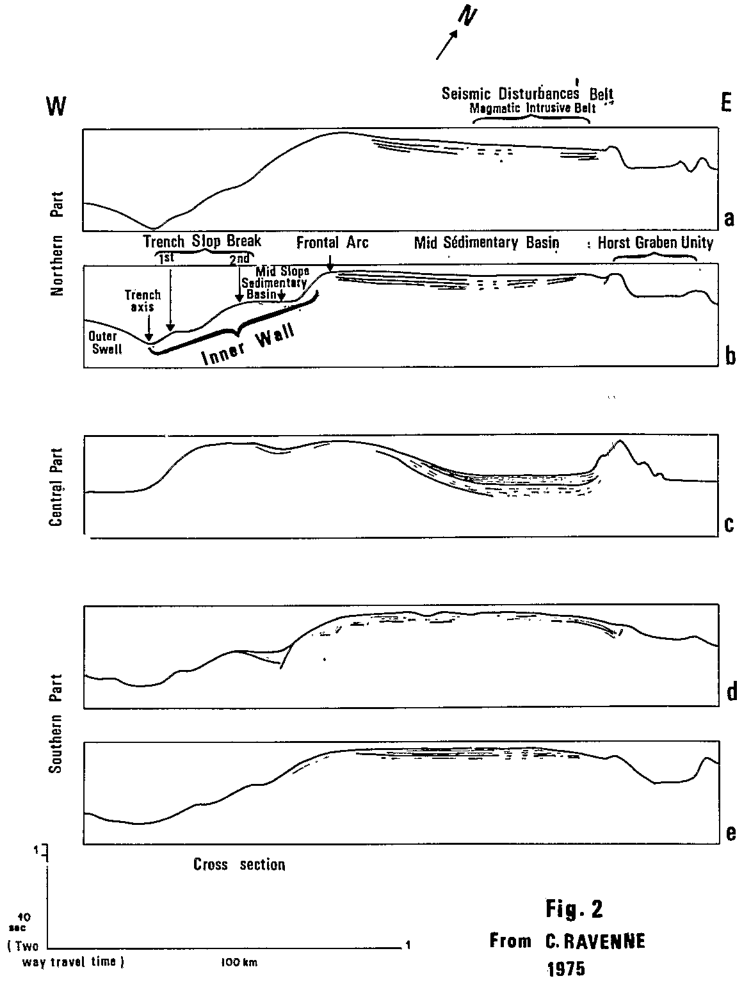


Fig. 2
From C. RAVENNE
1975

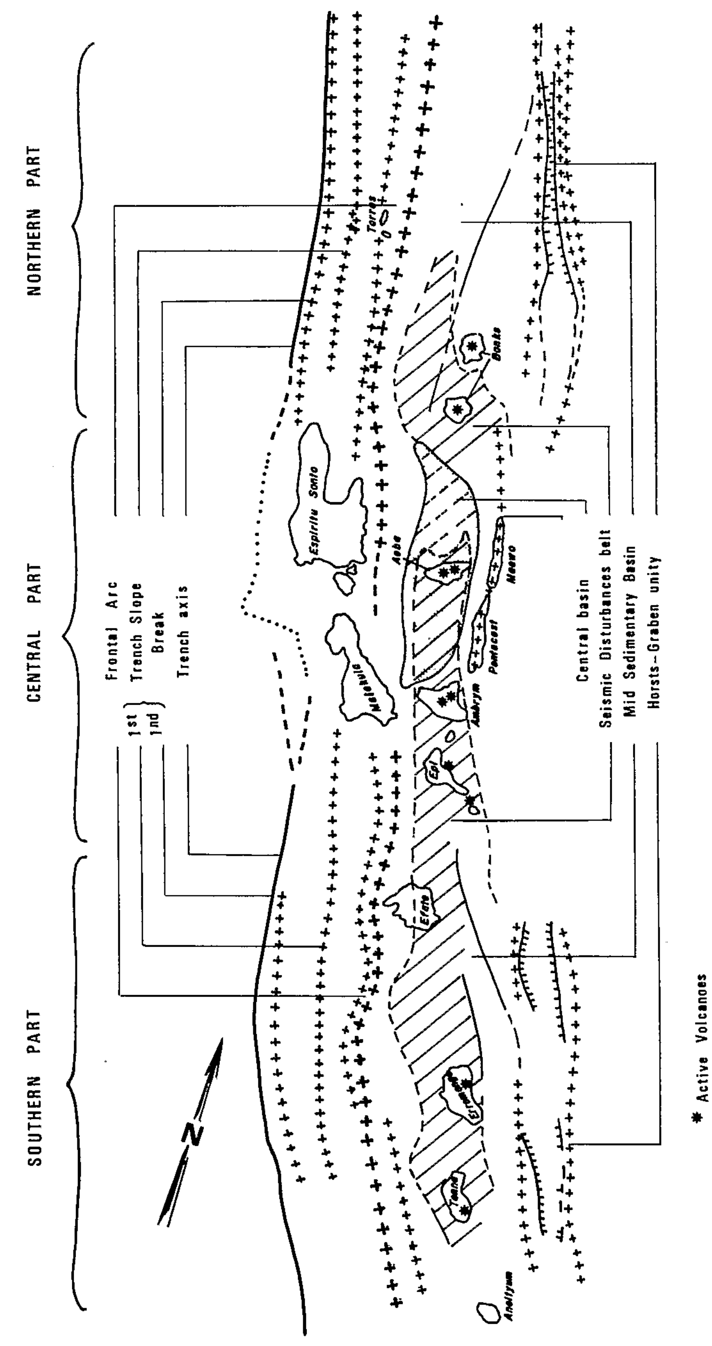
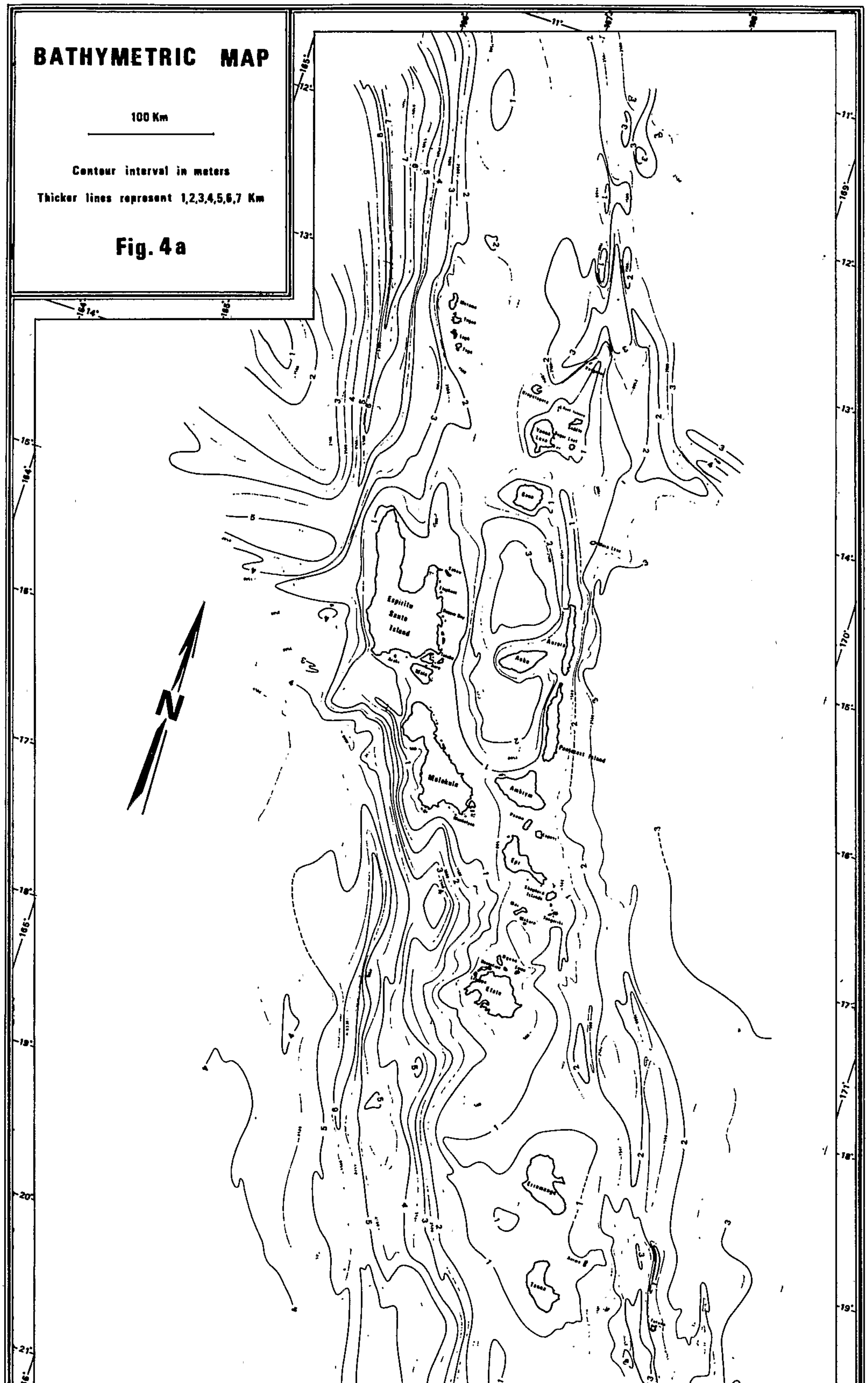


FIG. 3

From C. RAVENNE
1975


BATHYMETRIC MAP
100 Km
Contour interval in meters
Thicker lines represent 1,2,3,4,5,6,7 Km
Fig. 4a
Espiritu Santo Island
Malekula
Ambrym
Epi
Efate
Aoba
Erromango
Tanna

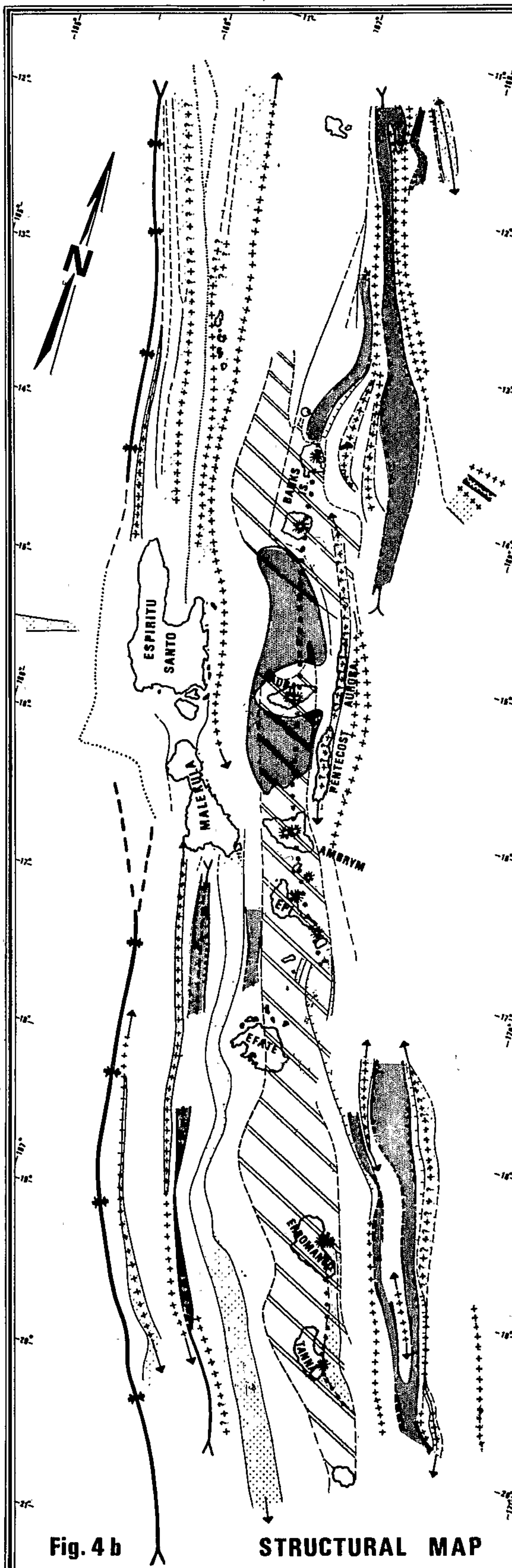


Fig. 4 b STRUCTURAL MAP

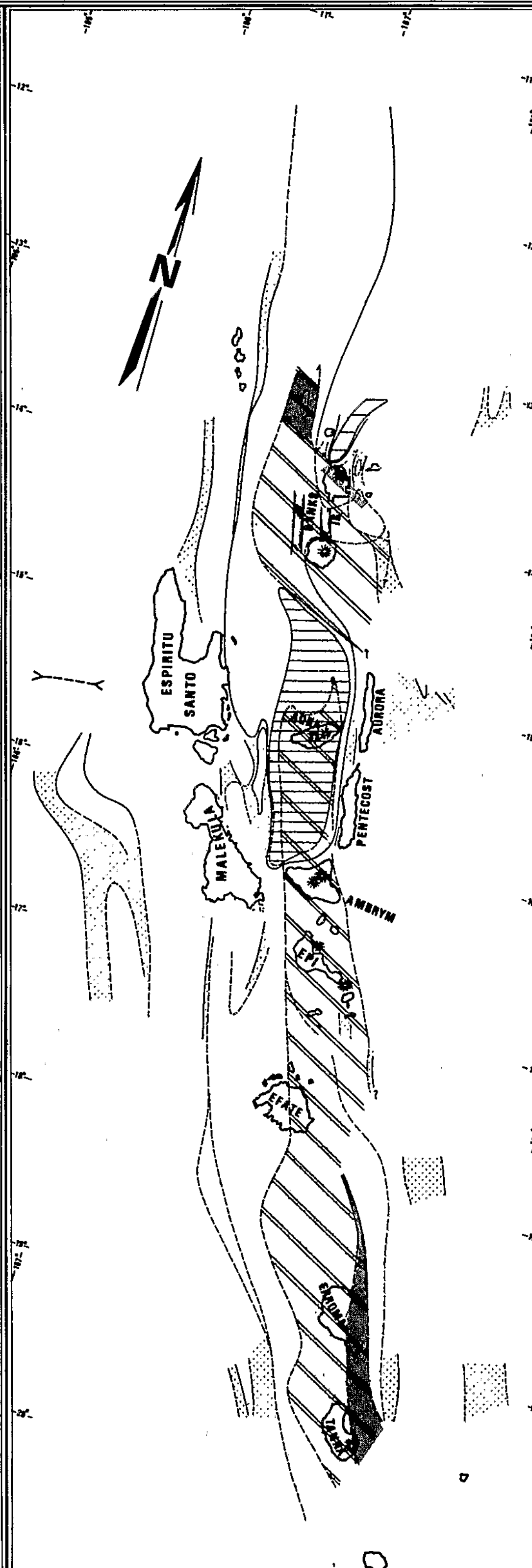
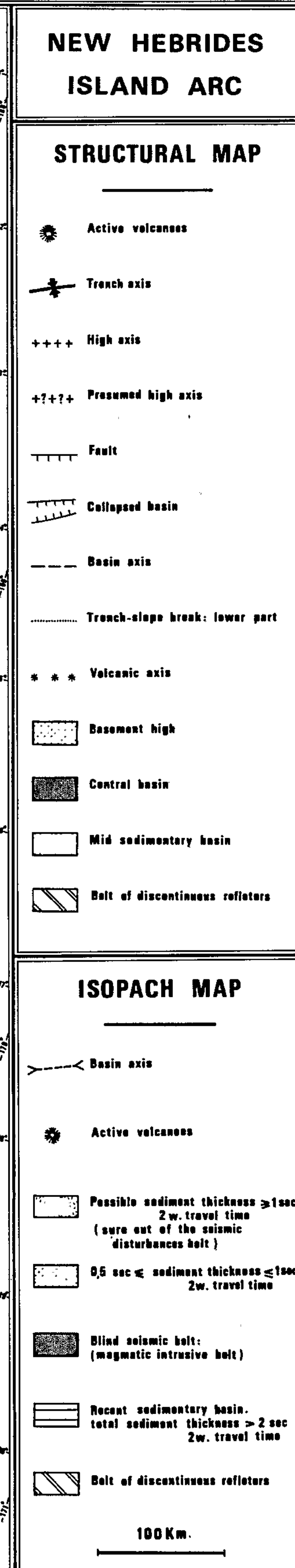


Fig. 4 c ISOPACH MAP (total sediment thickness)



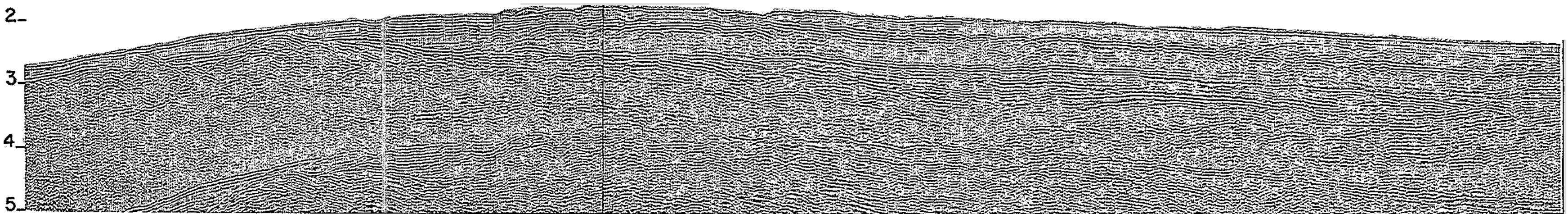


Fig. 5a

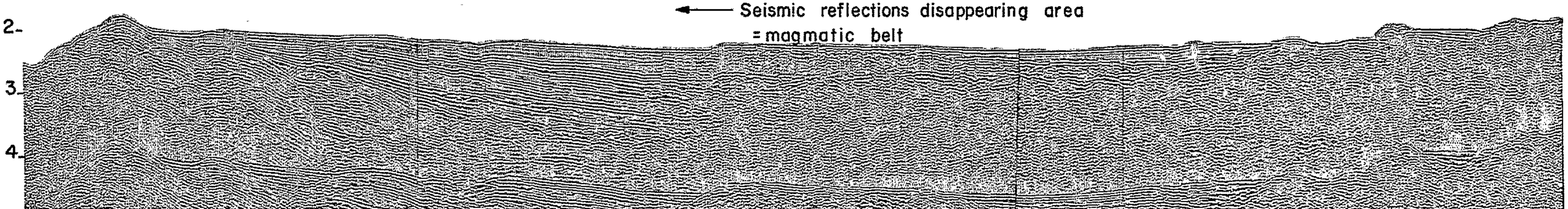


Fig 5b

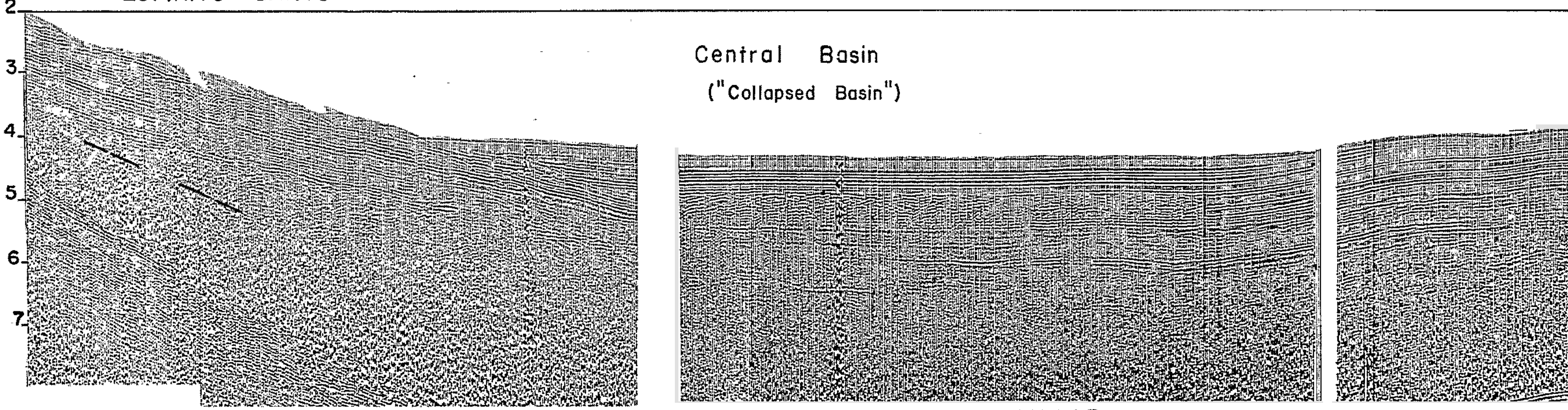


Fig 5c

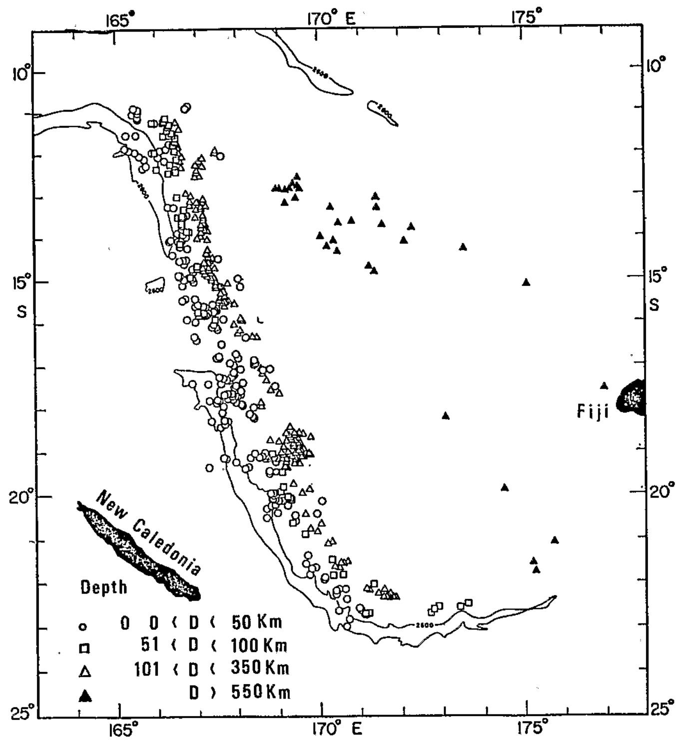


Fig. 6 New Hebrides Seismicity Map

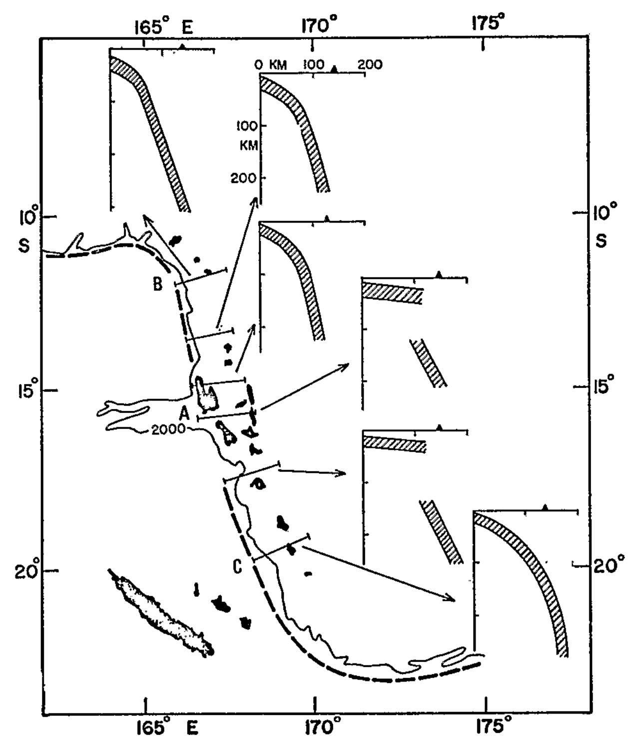


Fig. 7 Schematic sections across the New Hebrides Seismic zone (From Pascal 1974)

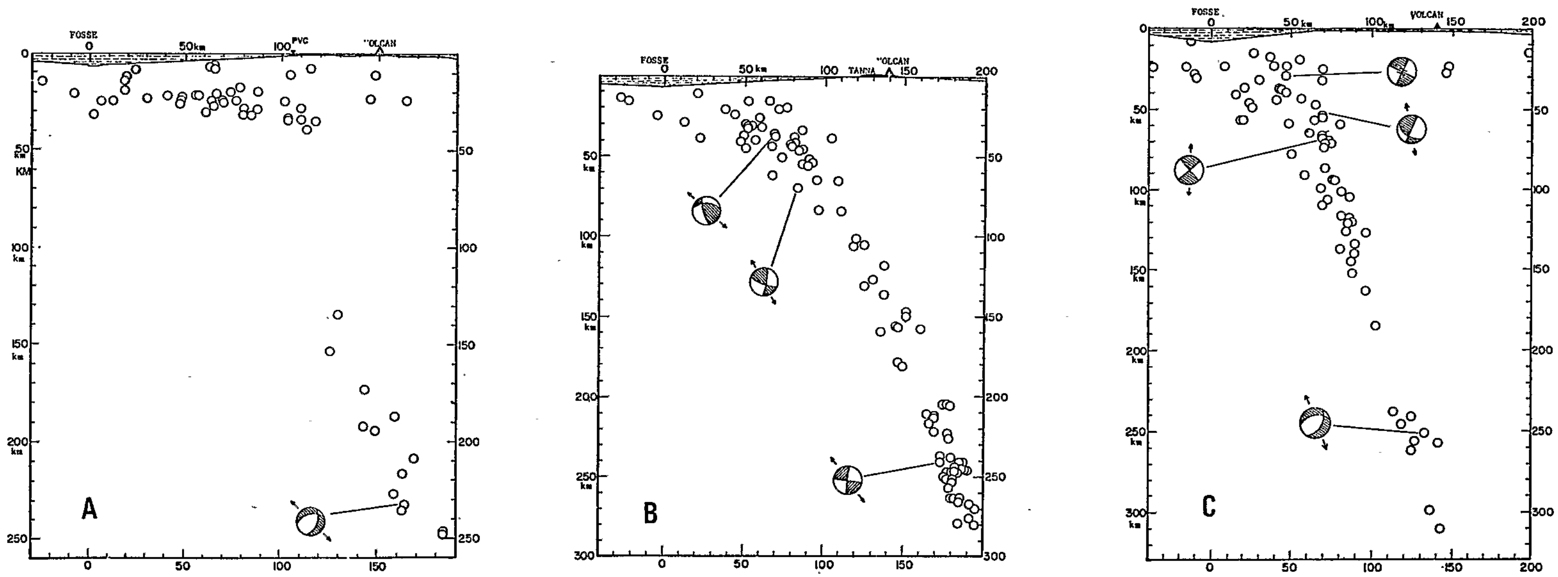


Fig. 8 Seismic cross-sections under the New-Hebrides Island arc

(From Pascal 1974)

[redacted]

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GÉODYNAMIQUE DU SUD-OUEST PACIFIQUE

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