Seismology and Structure of the New Hebrides

J. DUBOIS, B. LARUE, G. PASCAL AND C. REICHENFELD
Centre O.R.S.T.O.M., B.P.4, Noumea, New Caledonia

ABSTRACT

Study of the seismicity of the New Hebrides area over the last six years has established the existence of a Benioff zone. This can be defined between 0-350 km dipping north-east at angles varying between 45° and 70°. Propagation of body and surface waves along the New Hebrides Arc is abnormal. This is explained by the presence of an anomalous wedge of high-level, low-velocity upper mantle extending from about a depth of 20-150 km and with a width of 120 km.

The O.R.S.T.O.M. (Office de la Recherche Scientifique et Technique Outre-Mer) network of seismological stations in the South-west Pacific has added much data within the last ten years to what is known about the seismicity and structure of the island arc of the New Hebrides.

Eight stations are operated in this network: Noumea (NOU—N.O.A.S. code) and Koumac (KOU) in New Caledonia; Ouanaham (OUA) in the Loyalty Islands; and Port Vila (PVC), Luganville (LUG), Lonorore (LNR) and Lamap (LMP) in the New Hebrides (Fig. 1*b*).

SEISMICITY

Over the length of the New Hebrides Archipelago a belt of great seismic activity extends from 10° S-24° S, and active volcanism is associated with it. The epicentres of earthquakes of magnitude greater than 5 are plotted on Figs 1*a* and 1*b*, determined from 1961-1966 by the International Seismological Centre. The accuracy of epicentres depends on the influence of the nearest stations used in the computation and especially of the New Hebrides stations which are in an anomalous area of seismic wave propagation. This influence was studied for six New Hebrides earthquakes after two computations, one with and one without the use of New Hebrides network data. The differences in the calculated positions of the epicentres vary from 3-20 km (3, 5, 6, 16, 20, 22 km); for three earthquakes the two different epicentres are inside the error ellipse. Given strong shocks and a large number of recording stations with good distribution in azimuth, which we have in this area, the accuracy achieved is better than ± 10 km.

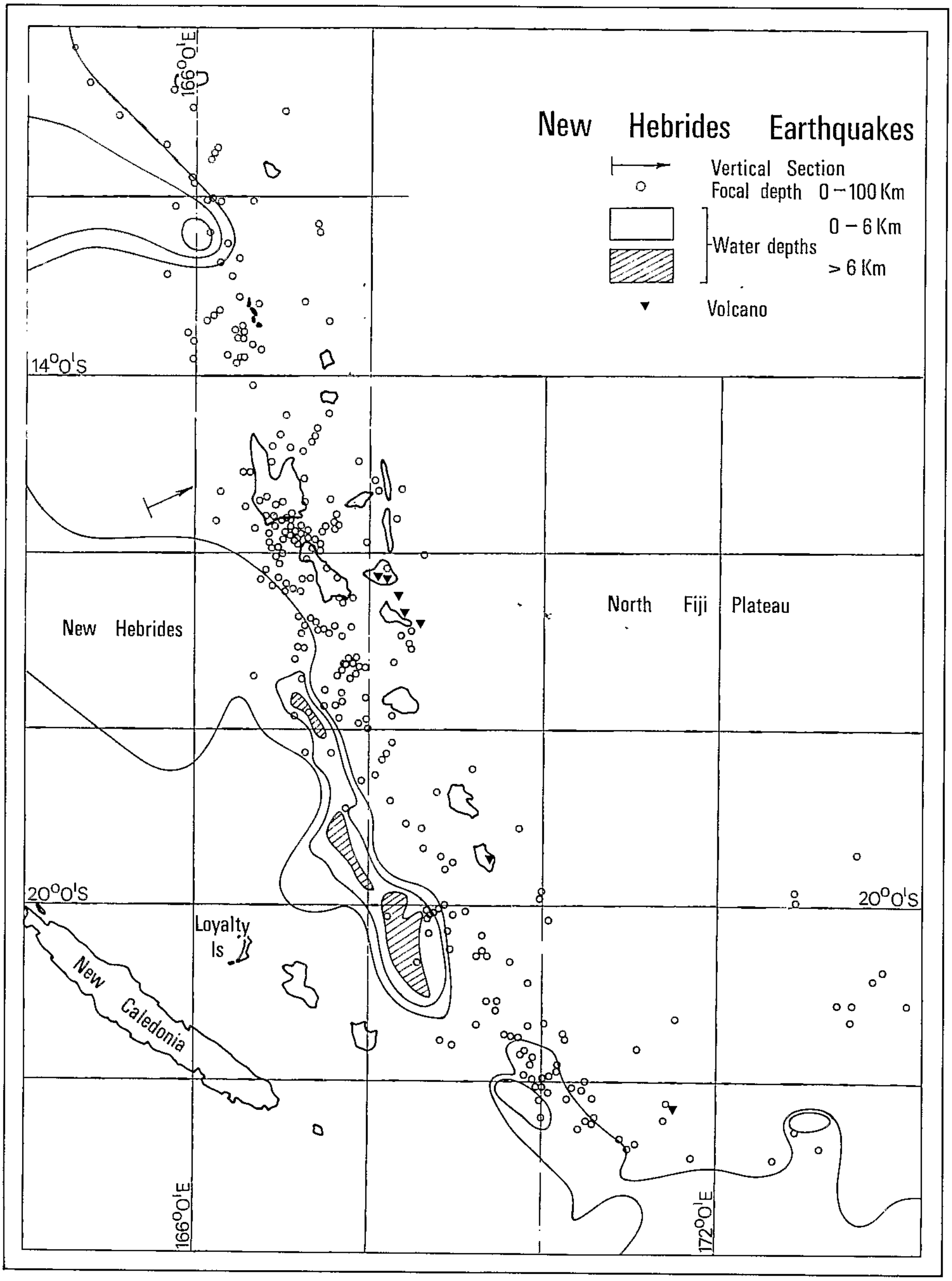

Fig. 1*a* Seismicity in the New Hebrides area, 1961-66, showing epicentres of earthquakes with focal depth 0-100 km. From Dubois, 1971 (by permission of the American Geophysical Union).

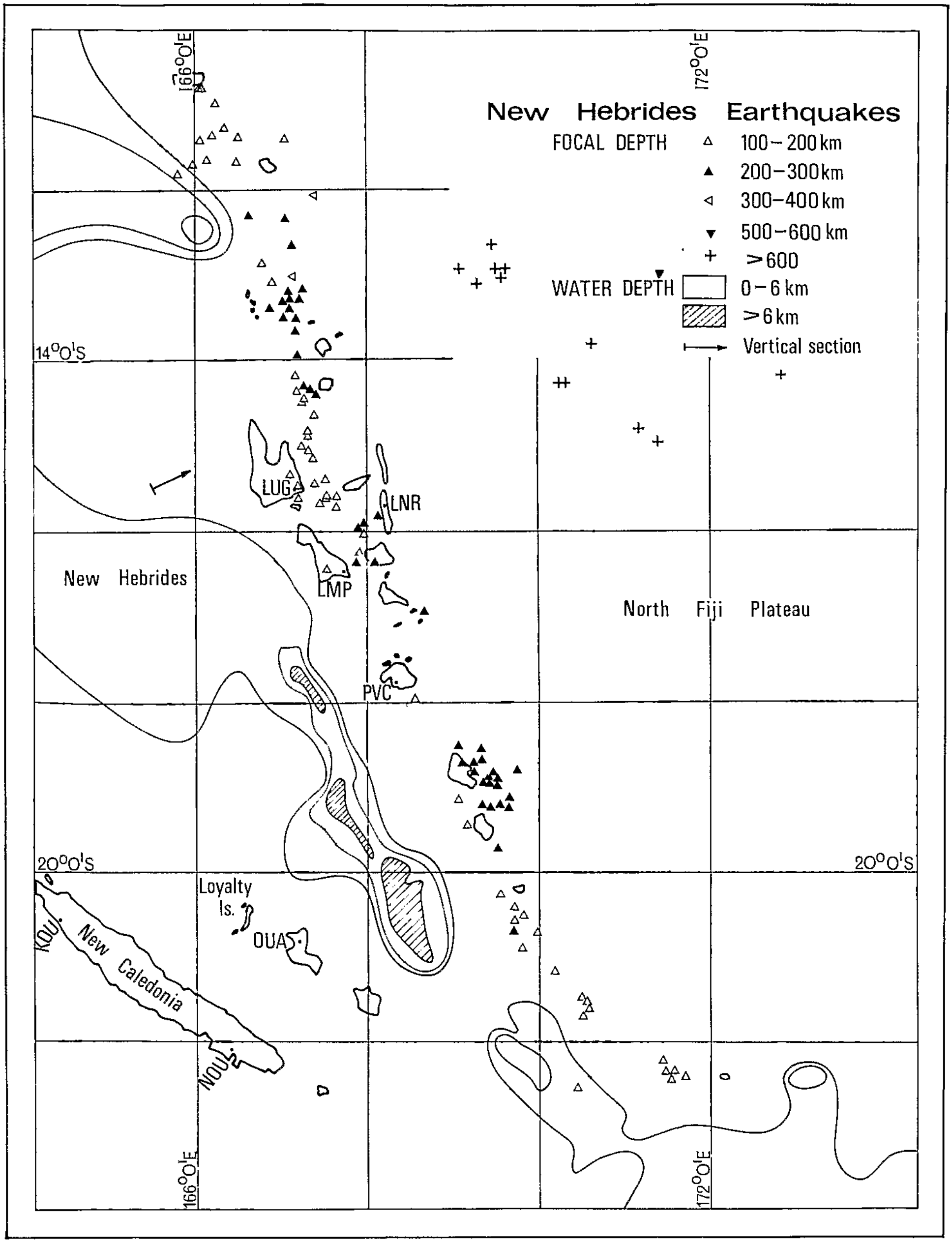

Fig. 1*b* Earthquake epicentres in the New Hebrides area, 1961-66, with focal depth greater than 100 km. O.R.S.T.O.M. seismological stations are shown: Noumea (NOU), Koumac (KOU), Ouanaham (OUA), Port Vila (PVC), Lamap (LMP), Lonorore (LNR) and Luganville (LUG). After Dubois, 1971.

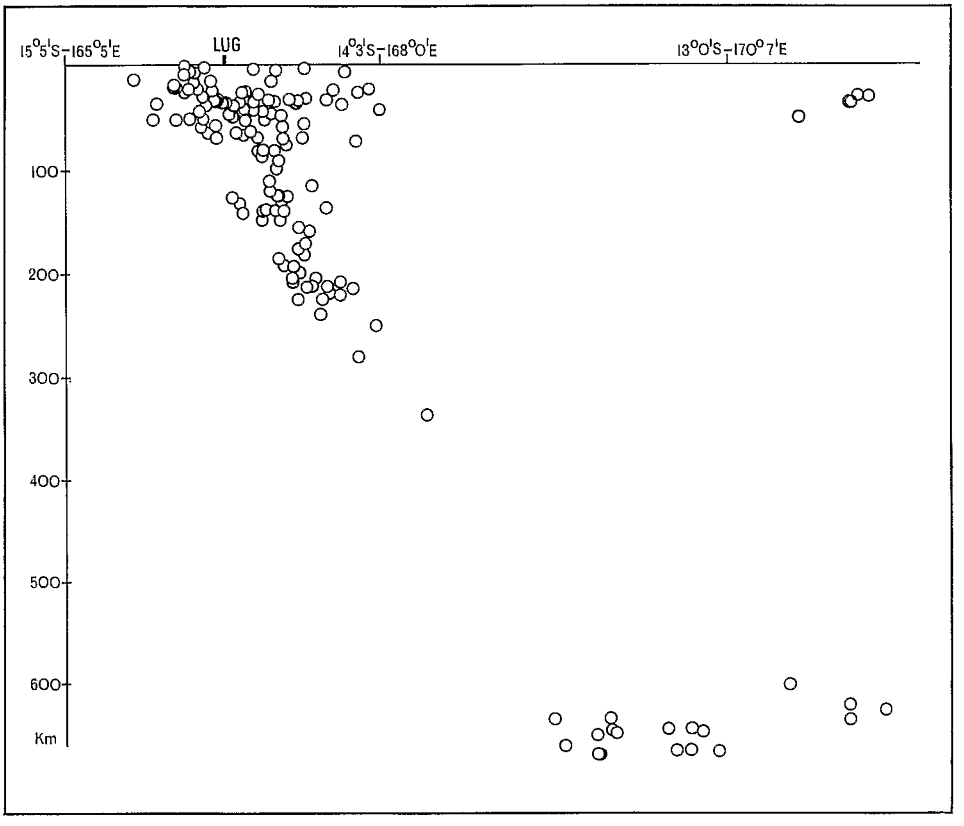

Fig. 2 A typical cross-section of earthquake hypocentres (Luganville, Espíritu Santo profile; see Figs 1*a* and 1*b*). From Dubois 1971, with permission.

Accuracy in depth was studied by using two methods: from *P* and from *pP-P*. The error is less than ± 15 km when data from more than twenty stations is used.

The vertical sections (e.g. Fig. 2) show the foci concentrated around a plane dipping north-eastwards beneath the island arc at about 60°, but between it and the earth's surface there is a marked diffusion of shallow and intermediate foci.

This leads us to believe that there exist different 'populations' of earthquakes (Larue 1970). According to the plate tectonic theory (Oliver & Isacks 1967) one set of the shocks would be associated with movements of the sinking lithosphere, the second set would be the result of tectonic readjustments (Benoit & Dubois 1971).

It was possible to determine on ten vertical sections the surface around which the foci are grouped and then to draw the isodepth lines of this surface (Fig. 3). There is a gap in focal depths below 350 km. Deep focus earthquakes are limited to a belt running between 12-15° S and 169-174° E. We cannot assume that these earthquakes are associated with the dipping slab.

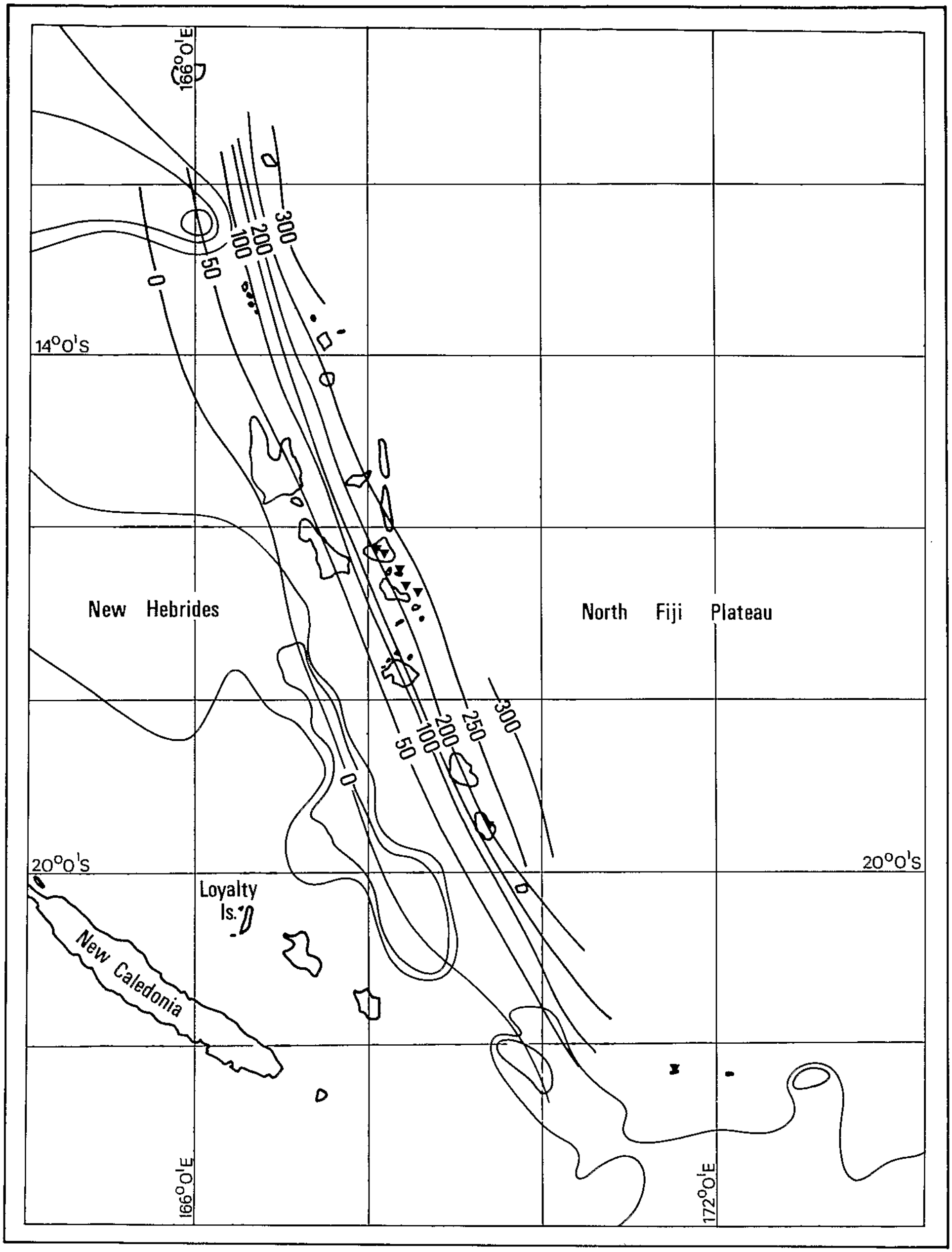

Fig. 3 Map of isodepth lines which define a seismic surface or zone (Benioff zone) dipping to the north-east. Depths in km.

ANOMALIES OF PROPAGATION

The anomalies of propagation of *P* waves and Rayleigh waves along the seismic belt were studied using earthquakes or events from both remote areas and the New Hebrides as recorded in Port Vila, Luganville, Lamap and Lonorore.

From the east, deep-focus Fiji earthquakes produce late arrivals of *P* waves to

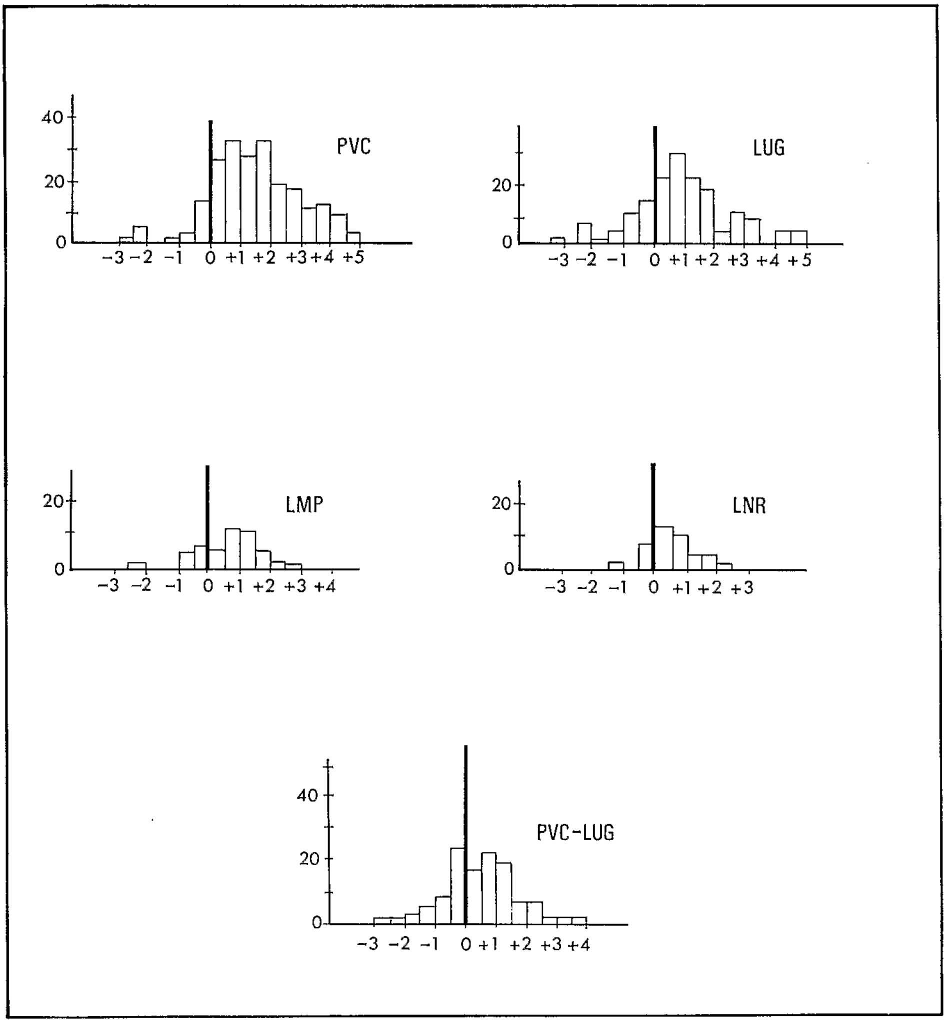

Fig. 4 Histograms of time residuals of *P* waves from Fiji deep-focus earthquakes at New Hebrides stations: Port Vila (PVC), Luganville (LUG), Lamap (LMP), and Lonorore (LNR). Interval of class is 0·5 s. Histogram for station pair PVC-LUG is shown. From Dubois, 1971, in part.

these four stations (Fig. 4). This fact is interpreted as due to the existence of a low-velocity upper mantle. There are local differences inside this area, as it is possible to see on the histogram of arrivals-delay between two stations PVC and LUG; the *P* wave arrivals are later in PVC than in LUG (slab effect under LUG?) and similarly between LNR and LMP.

From a northern direction the Longshot nuclear test gave a very late arrival in LUG. For the same epicentral distance (70°) we find a relative delay of 3·5 s between Melanesia and Australia. These delays may be explained by factors at the source, or under the recording stations, or along the raypath. Davies and MacKenzie (1969) show that a part of it is at the source, as an effect of a plate under the Aleutian Arc; the second part (1 s) between Australia and the New Hebrides is surely under Luganville because it cannot be found in the deep mantle along two very close paths (Dubois 1966).

So then, arrivals of *P* waves from the north and the east are usually late, 1 s and more, this fact probably due to the presence of low-velocity upper mantle in these directions. On the contrary, from the west and the north-west, for shocks in the Solomon, New Britain and New Guinea areas, early arrivals (0·7 s) are observed (Pascal 1970).

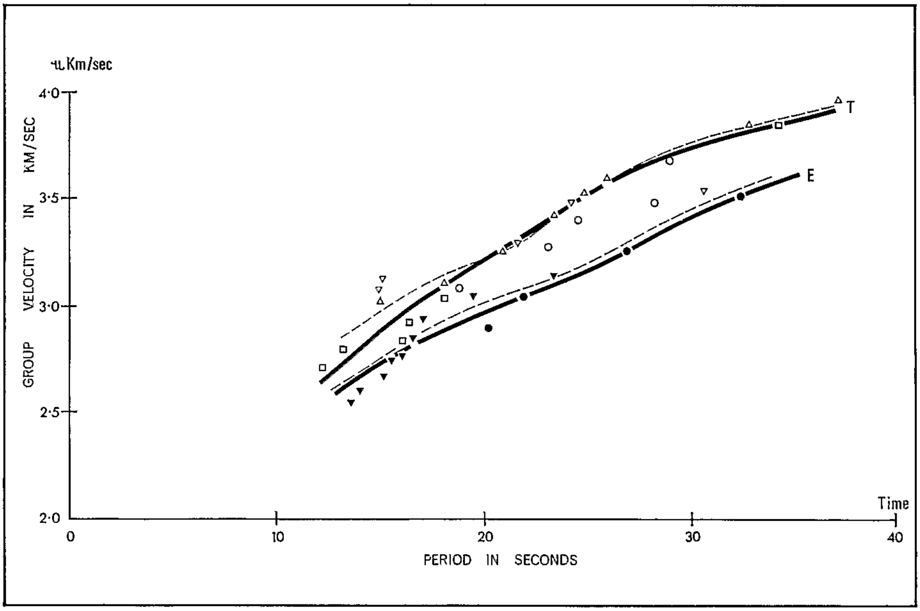

Fig. 5 Group velocity of Rayleigh waves, fundamental mode. Data from trench epicentres (see also Figs 1*a* and 1*b*) are shown in open symbols; from eastern slope epicentres in solid symbol (dashed lines). The theoretical dispersion curves of models T and E are indicated by heavy lines. From Dubois, 1971, with permission of the American Geophysical Union.

Studying the propagation times along the New Hebrides Arc it was possible to compute the apparent velocity between LUG and PVC. The velocity increases with the epicentral distance and, by applying the Herglotz-Wiechert method, a linear gradient is found in the upper mantle: from 7·4 km/s at a depth of 20 km (*P* wave velocity) to 8·1 km/s at a depth of 120 km. The late arrivals in New Hebrides stations from Fiji earthquakes and the Longshot Aleutian event are thus explained.

The propagation of *S* waves was not undertaken, for these phases are very weak on the raypath along the arc, implying a strong attenuation in the anomalous upper-mantle wedge, but it was possible to obtain indications of on the spatial variations of *S* wave velocity by the dispersion of the Rayleigh waves along the seismic belt. The influence coefficients of the different parameters on the phase velocity of Rayleigh waves were used to fit the theoretical curves to the experimental data. (For discussion see Dubois 1971, with Figs 7-11.) The observations for two groups of earthquakes in the Santa Cruz area show little difference between dispersion curves (Fig. 5). The theoretical models corresponding to this dispersion are in good agreement with the model chosen to explain *P* wave propagation, i.e. an upper mantle

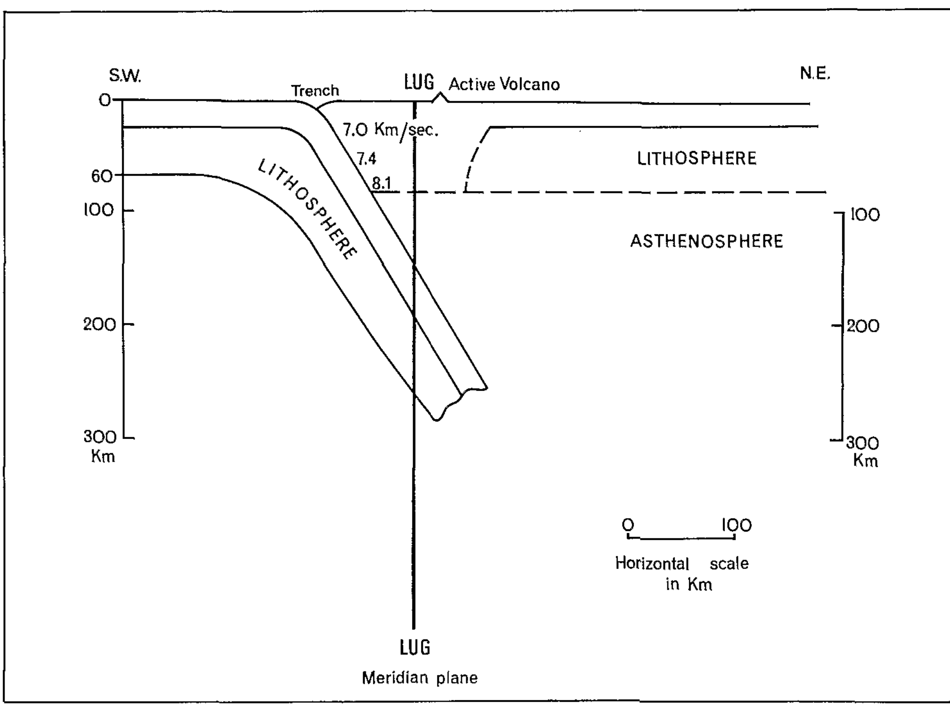

Fig. 6 Schematic cross-section of the New Hebrides Arc. Interruption of the dipping lithospheric slab corresponds to the lack of hypocentres below 350 km. The anomalous high-level, low-velocity mantle wedge is shown (below LUG). From Dubois, 1971, with permission.

with a vertical gradient of parameters α, β, ρ (*P* and *S* wave, velocities and density) from 20-120 km in depth. The little difference between group E (East slope group) and T (Trench group) is attributed to the effect of the differing thickness of the water layer on Rayleigh wave propagation (Dubois 1969).

A verification was done on phase velocity of Rayleigh waves inside the area delimited by LUG, LMP and LNR (Dubois & Reichenfeld 1971).

The first shear mode was also observed on records at PVC and their dispersion curves were compared with a theoretical one. This mode is strongly influenced by the bathymetry profile along the raypath; so for the north-south profiles the Tryggvason correction of sloping interface was applied. The verification after correction is good (Dubois 1971, Fig. 13).

STRUCTURAL IMPLICATIONS

Given the above data on seismicity and body wave and Rayleigh wave propagation we consider that the structure of the New Hebrides Arc may be represented schematically as in Fig. 6 (cf. Mitronovas & Isacks 1971, Barazangi & Isacks 1971, Jacobs 1970; and plate tectonics by Oliver & Isacks 1967).

This structure, which features a seismic surface (Benioff zone) dipping from 0-350 km at an angle varying from 45-70°, arises from a sinking lithospheric slab. The presence of the slab results in early arrival of *P* waves from west and north-west. Finally there is an anomalous wedge of low-velocity upper mantle. This shows a linear gradient in depth of α and β with high attenuation. The wedge extends to a depth of 150 km, with width 120 km, and explains the late arrivals from east and north and the particular nature of propagation along the island arc.

REFERENCES

Barazangi, M. & Isacks, B. L. 1971. Lateral variations of seismic wave attenuation in the upper mantle above the inclined earthquake zone of the Tonga Island Arc: Deep anomaly in the Upper Mantle. *J. geophys. Res.* **76** (35), 8493-516.

Benoit, M. & Dubois, J. 1971. The earthquake swarm in the New Hebrides Archipelago, August 1965. *Recent Crustal Movements, Bull. R. Soc. N.Z.* **9,** 141-8.

Davies, D. & MacKenzie, D. P. 1969. Seismic travel time residuals and plates. *Geophys. J. R. astr. Soc.* **18,** 51-63.

Dubois, J. 1966. Temps de propagation des ondes *P* à des distances épicentrales de 30 à 90 degrés, Région Sud Ouest Pacifique. *Annls Geophys.* **22** (4), 642-5.

——— 1969. Contribution a l'étude structurale du Sud Ouest Pacifique d'après les ondes sismiques observées en Nouvelle Calédonie et aux Nouvelles Hébrides. *Annls Geophys.* **25** (4), 923-72.

——— 1971. Propagation of *P* waves and Rayleigh waves in Melanesia: structural implications. *J. geophys. Res.* **76** (29), 7217-40.

Dubois, J. & Reichenfeld, C. 1971. Sur la vitesse de phase des ondes de Rayleigh aux Nouvelles Hébrides. Rapp. ORSTOM, Paris (unpubl.).

Jacobs, K. H. 1970. Three-dimensional seismic ray tracing in a laterally heterogeneous spherical earth. *J. geophys. Res.* **75** (32), 6675-89.

Larue, B. 1970. Séismicité aux Nouvelles Hébrides, rapport préliminaire. *Rapp. ORSTOM*, Paris.

Mitronovas, W. & Isacks, B. L. 1971. Seismic velocity anomalies in the upper mantle beneath the Tonga-Kermadec arc. *J. geophys. Res.* **76** (29), 7154-80.

Oliver, J. & Isacks, B. L. 1967. Deep earthquake zones, anomalous structures in the upper mantle and the lithosphere. *J. geophys. Res.* **72** (16), 4259-75.

Pascal, G. 1970. Etude des O-C des ondes P de 30° à 100°. Relation avec l'hypothèse des plaques. *Rapp. ORSTOM*, Noumea.

Reprinted from

The Western Pacific: Island Arcs,
Marginal Seas, Geochemistry

Patrick J. Coleman / Editor

Seismology and Structure of the New Hebrides

J. DUBOIS, B. LARUE, G. PASCAL AND C. REICHENFELD

UNIVERSITY OF WESTERN AUSTRALIA PRESS
1973