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SEISMIC WAVE ATTENUATION IN THE UPPER MANTLE BENEATH THE SOUTHWEST PACIFIC*

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ABSTRACT

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A detailed study of P and S seismic waves produced by hundreds of earthquakes located along the New Hebrides, Fiji plateau, Solomon, New Britain and New Guinea seismic zones and recorded at stations in Fiji, New Hebrides and New Caledonia shows significant variations in the amplitudes and frequencies of the waves. The data define zones of anomalously high seismic wave attenuation in the uppermost mantle beneath the Fiji plateau and the Woodlark basin. The active volcanoes of the New Hebrides arc seem to mark the western boundary of the high-attenuation zone that exists beneath the Fiji plateau. Our observations are in agreement with the hypothesis that the Fiji plateau and the Woodlark basin are young oceanic features formed by crustal extension. In addition, a zone of high attenuation exists in the uppermost mantle somewhere between the northeastern coast of Australia and the New Hebrides arc; the data further require that this zone be located not closer than about 400 km to the New Hebrides trench. Observations at New Caledonia stations of very low frequency shear waves from intermediate-depth earthquakes in the westward dipping Tonga—Kermadec seismic zone yield an estimate of Q_s of about 10 in the zone of extremely high attenuation located beneath the Lau basin, the actively spreading inter-arc basin behind the Tonga arc.

INTRODUCTION

In this paper we map the lateral variations of seismic wave attenuation in the uppermost mantle beneath the Fiji plateau, New Hebrides arc, the Coral Sea and the Solomon and Woodlark basins. Fig. 1 shows the results of this study combined with those of Barazangi and Isacks (1971). Zones of extremely high attenuation exist in the uppermost mantle beneath the Fiji plateau, the Woodlark basin and the Lau basin. These areas are also the site of variable

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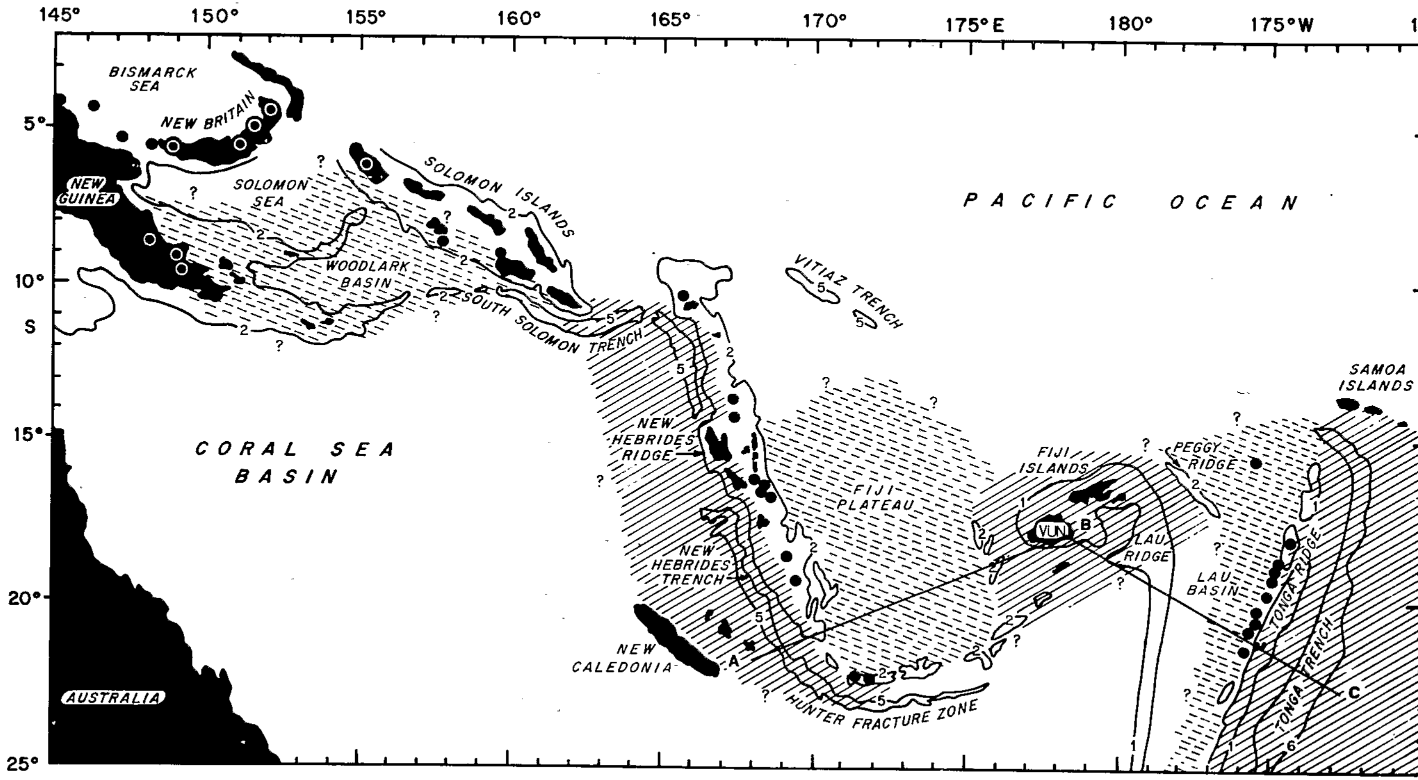

Fig. 1. Map of the southwestern Pacific showing regions of high and low attenuation in the uppermost mantle. Solid circles represent the historically active volcanoes. Depth contours are in km. Zones of high attenuation are shown as dashed lines and zones of low attenuation as solid lines. Question marks indicate that the boundaries of the zones are not well known. Lines *ABC* show the location of the section of Fig. 6.

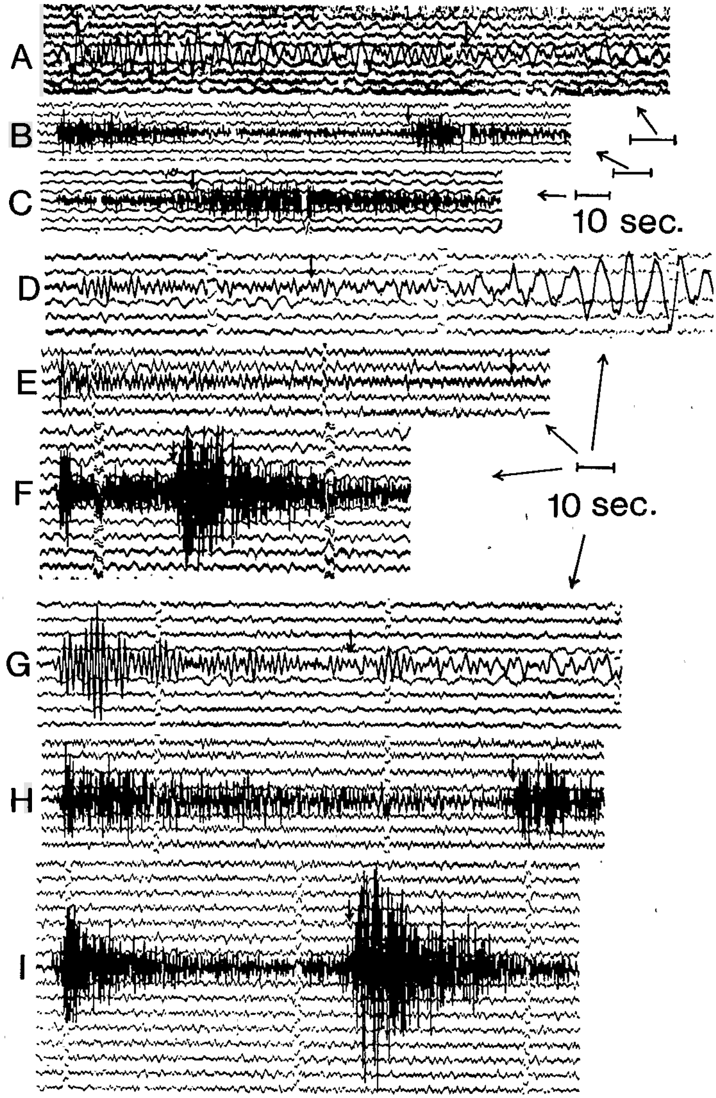

Fig. 2. Seismograms from LNR, PVC and NOU stations. *A*, *B* and *C* are examples from LNR; *D*, *E* and *F* are examples from PVC; *G*, *H* and *I* are examples from NOU. *A*, *D*, *E* and *G* are examples from shallow events of inefficient P-and S-transmission (dashed lines in Figs. 3, 4 and 5); *B* and *H* are examples from shallow events of efficient propagation (solid lines in Figs. 3 and 5); *C*, *F* and *I* are examples from mantle earthquakes of efficient P-and S-propagation.

A. Feb. 4, 1970, 22.8°S, 171.3°E, 57 km, Z component;
B. May 30, 1968, 10.3°S, 161.6°E, 41 km, Z component;
C. Jan. 25, 1970, 13.2°S, 167.1°E, 219 km, Z component;
D. May 4, 1970, 20.6°S, 173.4°E, 14 km, Z component;
E. May 19, 1965, 9.2°S, 159.0°E, 50 km, Z component;
F. April 24, 1970, 19.1°S, 169.3°E, 273 km, Z component;
G. May 4, 1970, 20.6°S, 173.4°E, 14 km, N—S component;
H. Jan. 27, 1970, 10.8°S, 165.9°E, 50 km, N—S component;
I. June 10, 1970, 15.4°S, 167.5°E, 122 km, N—S component. The small arrows on the records where S is highly attenuated correspond to the expected Jeffreys-Bullen arrival time of S.

but generally high heat flow (Sclater et al., 1972a; Macdonald et al., 1973) and low seismic wave velocities (Dubois et al., 1973; Aggarwal et al., 1972; Shor et al., 1971; Furumoto et al., 1970). Thus it is reasonable to infer that hot and probably partially melted upper-mantle materials exist beneath these areas. Recent geological and geophysical land and submarine data and construction of the past movements of lithospheric plates (Karig, 1970; Chase, 1971; Karig and Mammerickx, 1972; Sclater et al., 1972b; Luyendyk et al., 1973; Gill and Gorton, 1973) show that crustal extension and some form of sea-floor spreading have taken place in these areas during the last few million years.

The data used in this study are the records of the Fiji—New Hebrides—New Caledonia seismic network. There are three stations in Fiji and eight stations in New Hebrides and New Caledonia. VUN (Vunikawi, Fiji), PVC (Port Vila, New Hebrides) and NOU (Noumea, New Caledonia) have three-component short-period seismographs. The rest have only short-period vertical components. The response of the New Hebrides and New Caledonia instruments is relatively flat for seismic frequencies between about 0.5 and 10 Hz, and are thus particularly suited to a study of the characteristics of high-frequency shear waves. For more information on the instrumentation see Dubois (1971) and Oliver and Isacks (1967).

We have examined hundreds of seismograms produced by shallow earthquakes located inside the Fiji plateau and along the Hunter fracture zone, the New Hebrides arc and the Solomon—New Britain—New Guinea area. The amplitudes and frequencies of P- and, particularly, S-waves change drastically depending on the paths of the waves. The changes are very clear and obvious on the records. We classified the propagation paths as efficient or inefficient according to the observed amplitudes and frequency content of P- and S-waves. Efficient transmission is characterized by impulsive S-waves with predominant frequencies of about 3—5 Hz and amplitudes comparable to or larger than the P-wave amplitudes. Inefficient transmission is characterized by weak (or, as is often the case, the absence of) S-waves with frequencies less than 1 Hz and amplitudes less than those of the P-waves. The predominant frequencies of P-waves also change from about 5 Hz for efficient propagation to about 1 Hz for inefficient propagation. Examples of efficient and inefficient propagation of P- and S-waves are shown in Fig. 2. The consistency of the data is quite remarkable. Barazangi and Isacks (1971) show how these gross features are primarily related to attenuation effects along the paths of the seismic waves rather than to source or station effects.

ZONES OF HIGH ATTENUATION BENEATH THE FIJI PLATEAU, THE WOODLARK BASIN AND THE CORAL SEA

Figs. 3, 4 and 5 show the pattern of efficient and inefficient propagation of P-and S-waves produced by shallow earthquakes and recorded at NOU, PVC and LNR (Lonorore, New Hebrides). Fig. 2 shows some examples of records

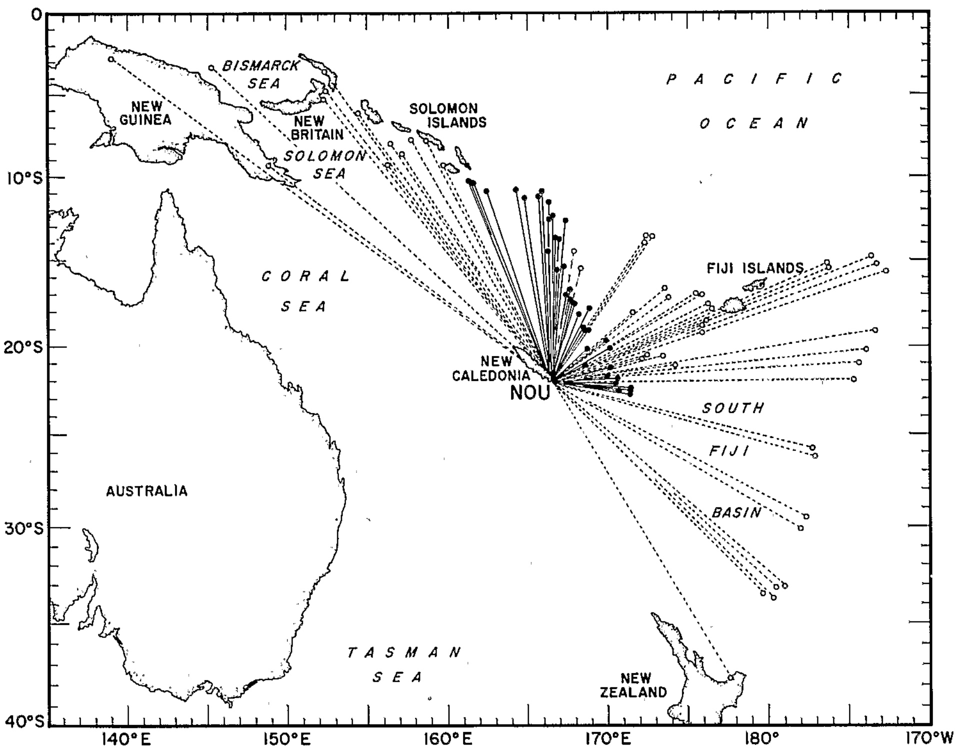

Fig. 3. Pattern of efficient and inefficient propagation of P-and S-waves from shallow earthquakes recorded at NOU (Noumea) in New Caledonia. Solid and open circles represent earthquake epicenters. Solid lines from solid circles to NOU represent efficient P-and S-transmission. Dashed lines from open circles to NOU represent inefficient P-and S-propagation.

from these three stations. Paths to NOU, PVC and LNR from earthquakes located east of the line of active volcanoes are in all cases inefficient. In most cases S-waves are not perceptible, even for earthquakes located only 200 km east of the volcanoes. Fig. 5 also shows that earthquakes located along the western part of the Hunter fracture zone (about 171.5°E and 22°S) produce attenuated P-and S-waves at LNR, the station located very close to the volcanic ridge. The ray paths from these events traverse the uppermost mantle just to the east of the active volcanoes. In contrast, intermediate-depth earthquakes that occur along the northeasterly dipping New Hebrides seismic zone and located beneath the line of active volcanoes produce strong high-frequency P-and S-waves at LNR and also at INH, (Isangel; 19.5°S, 169.3°E) another station located on the active volcanic ridge. These observations indicate that the western boundary of the high-attenuation zone that occurs beneath the Fiji plateau is close to the line of active volcanoes. This agrees with our observations for the Tonga island arc and with observations reported for Japan (Utsu, 1971) and the North Island of New Zealand (Mooney, 1970).

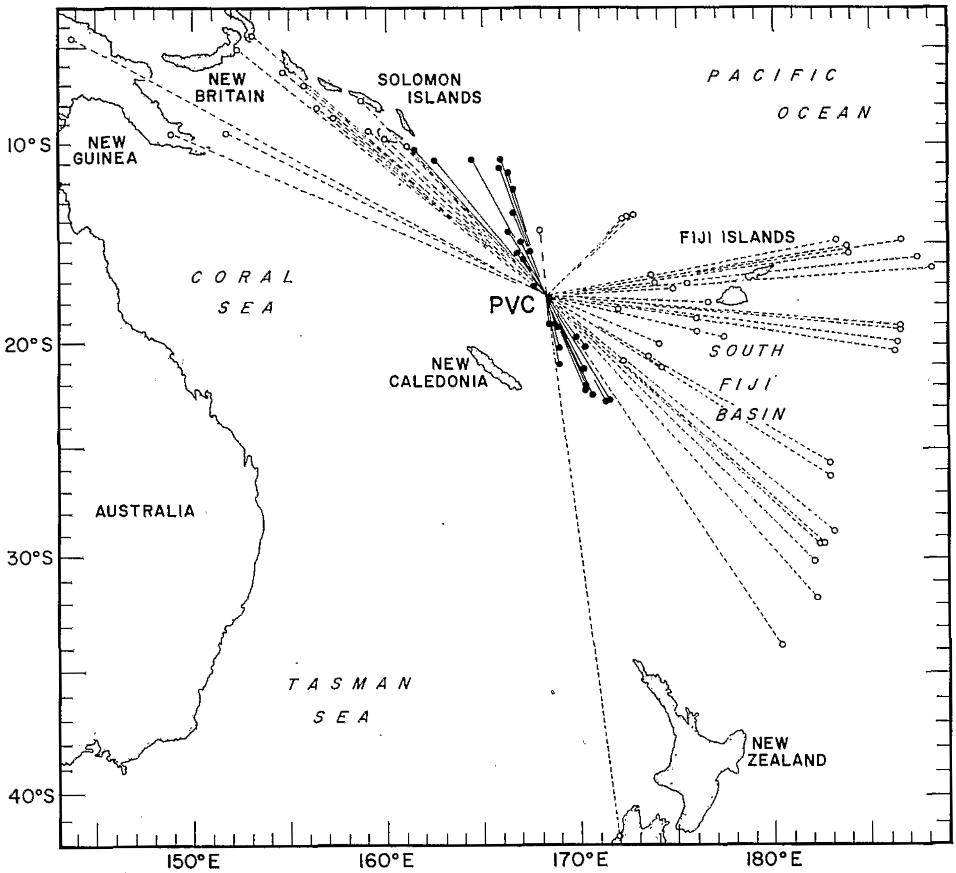

Fig. 4. Pattern of efficient and inefficient P-and S-transmission as obtained from the data of PVC (Port Vila) in New Hebrides. Symbols are the same as in Fig. 3.

Observations at Fiji stations (summarized in fig. 7 of Barazangi and Isacks, 1971) indicate that the southeastern boundary of the high-attenuation zone beneath the Fiji plateau occurs close to the sharp submarine rifts that are located approximately along the 176°E meridian west of Fiji (see Fig. 1). The boundary of the high-attenuation zone to the north is not known. In general, the existence of high-attenuation, or low Q, zone in the uppermost mantle beneath the Fiji plateau is in agreement with the recent extensional origin of the plateau (Chase, 1971; Karig and Mammerickx, 1972; Gill and Gorton, 1973).

Fig. 3 shows that shallow earthquakes located along the Kermadec arc (south of about 26°S) produce attenuated P-and S-waves at NOU. The propagation paths of these events traverse the uppermost mantle beneath the Havre trough and the South Fiji basin. The Havre trough is a young oceanic basin of extensional origin located behind the Kermadec arc and it is a southwestward

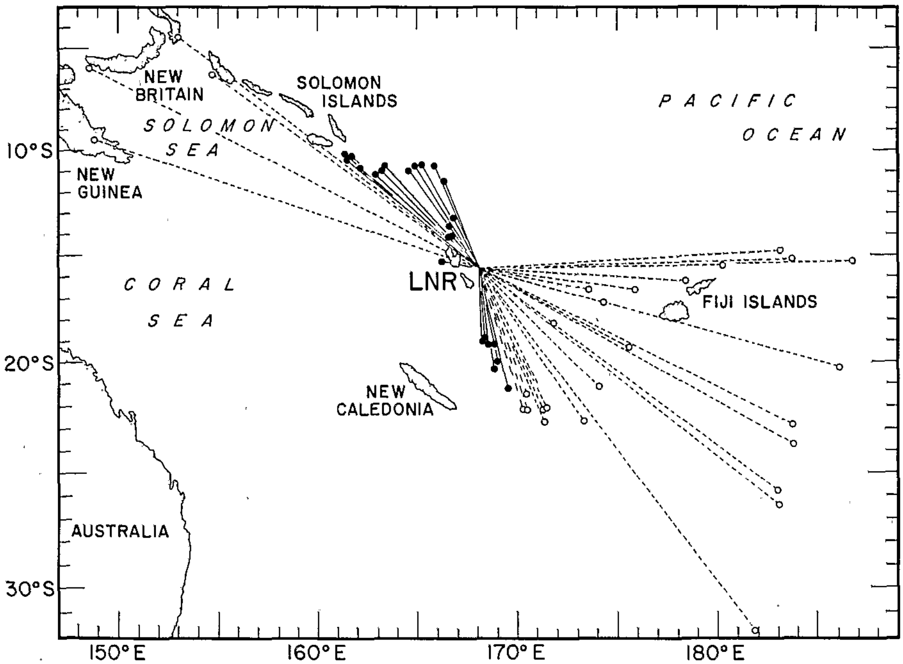

Fig. 5. Pattern of efficient and inefficient P-and S-propagation as found from the data of LNR (Lonorore) in New Hebrides. Symbols are the same as in Fig. 3.

continuation of the Lau basin (Karig, 1970). The South Fiji basin has normal uppermost-mantle seismic velocities (Shor et al., 1971) and normal heat-flow values (Sclater et al., 1972a). It is therefore probable that the uppermost mantle beneath the Havre trough is the cause of the observed attenuated P-and S-waves at NOU.

Figs. 3, 4 and 5 show that shallow earthquakes located along the Solomon, New Britain and New Guinea seismic zones west of about 161°E produce attenuated P-and S-waves at LNR, PVC and NOU. Propagation of seismic waves from shallow events located along the South Solomon trench between about 161°E and 165°E is, however, very efficient. From marine-geological and geophysical evidence Milsom (1970) and recently Luyendyk et al. (1973) showed that the Woodlark basin (Fig. 1) is an extensional feature and sea-floor spreading is currently taking place there. Thus, the observed attenuation for paths that cross the basin is probably due to the anomalous upper-mantle material that exists beneath the basin.

Molnar and Oliver (1969) observed that propagation paths from shallow events located along the New Hebrides and South Solomon trenches to CTA (Charters Towers) in northeastern Australia are inefficient. This is an anomalous observation since regions on the convex side of island arcs generally transmit P-and S-waves very efficiently. In this study we have examined additional data from CTA and confirmed the observations of Molnar and Oliver. However, the efficient transmission of P- and S-waves from shallow events along the New Hebrides and South Solomon trenches to New Caledonia stations (a zone of about 400 km in width, see Fig. 1) indicates that the zone of attenuation is not near the New Hebrides trench, as suggested by Molnar and Oliver. Evidence from the submarine geology of the western Coral Sea (Gardner, 1970) indicates that the Coral Sea basin was probably formed by rotational spreading of New Guinea from Australia during Late Eocene. The region, however, seems to be relatively stable since then. There seems to be no obvious explanation for the observations at CTA.

Propagation paths from New Hebrides intermediate earthquakes to all New Hebrides and New Caledonia stations are very efficient. Some examples of seismograms are shown in Fig. 2. The efficient propagation to stations on the non-volcanic ridge (e.g., PVC) is mainly the result of propagation through the descending lithosphere which is associated with the inclined seismic zone (Oliver and Isacks, 1967; Dubois, 1971). The efficient propagation to New Caledonia stations, located a few hundred kilometers to the west of the northeasterly dipping seismic zone, from intermediate-depth events in the central and northern New Hebrides arc suggests that the high-frequency P- and particularly S-waves are guided upward along the descending lithosphere and then travel horizontally through the oceanic lithosphere to New Caledonia. Similar observations are found for the Tonga and South American arcs (Barazangi et al., 1972; Isacks and Barazangi, 1973). The above observations imply that the descending lithosphere is continuous with the horizontal, suboceanic lithosphere to the west of the New Hebrides arc.

P- and S-waves with large amplitudes and high frequencies are observed at the stations INH and LNR located near the active volcanic ridge of the New Hebrides arc from shallow and intermediate-depth earthquakes. Some of the earthquakes occur along the inclined seismic zone directly beneath the stations. The ray paths from these earthquakes, therefore, emerge close to the vertical beneath the volcanic ridge. These observations, therefore, reveal no extensive high-attenuation zones, such as large magma chambers beneath the stations LNR and INH. Similar observations are found by Mitronovas et al. (1969) for two volcanoes in the Tonga arc. Our data and those of Mitronovas et al., however, do not preclude the existence of small localized magma chambers such as those detected by Matumoto (1971) and Farberov and Gorelchik (1971), for example.

EVIDENCE FOR THE STRUCTURES OF THE ZONES OF HIGH ATTENUATION BEHIND THE NEW HEBRIDES AND TONGA ISLAND ARCS

Barazangi and Isacks (1971) observed striking variations in the amplitudes and frequencies of P- and S-waves recorded at VUN station in Fiji from intermediate and deep earthquakes located along the Tonga inclined seismic zone. P-waves change from 0.7 to 1 Hz for shallow and intermediate earthquakes to 2—3 Hz for deep earthquakes (deeper than about 300 km). S-waves are not

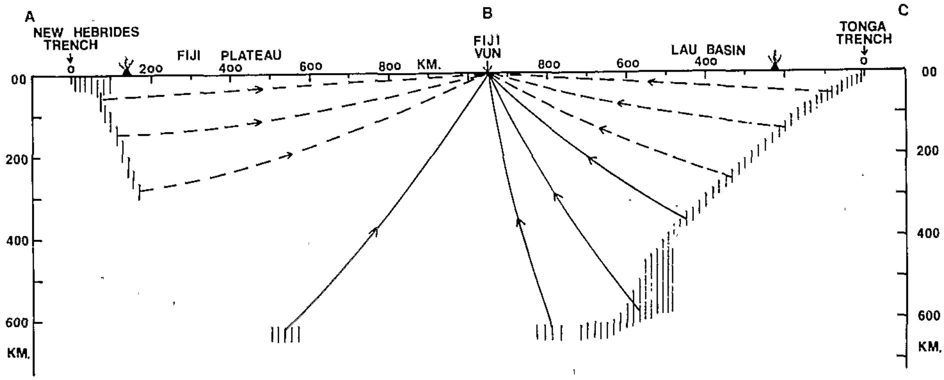

Fig. 6. Cross-section of Tonga and New Hebrides arcs (see Fig. 1 for the location of the section) showing location of seismic activity in the upper mantle (vertical lines) and representative ray paths to VUN in Fiji. Dashed rays represent paths where P- and S-waves are highly attenuated.

perceptible at all for events at depths less than about 300 km, while the predominant frequencies of S-waves are about 0.7 Hz for deep events (see Fig. 6). We interpreted these observations to indicate the presence of anomalous high-attenuation materials in the prism of mantle beneath the actively spreading Lau basin and above depths of about 150 and 300 km along the inclined seismic zone of Tonga. In this paper we report results for similar observations at Fiji for the New Hebrides arc. S-waves from New Hebrides shallow and intermediate earthquakes are not perceptible at the Fiji stations, and the P-waves have frequencies of about 0.7 Hz. These observations are similar to those reported by Barazangi and Isacks (1971) for the Tonga shallow and intermediate earthquakes. In New Hebrides there are no earthquakes between about 300 and 600 km of depth. New Hebrides deep earthquakes produce P- and S-waves with frequencies of about 2—3 and 0.7 Hz, respectively, at the Fiji stations (see Fig. 6). This is also similar to the observations at Fiji from Tonga deep earthquakes. The above data indicate that the high-attenuation zone exists beneath the Fiji plateau to depths of at least 300 km. Further evidence reported by Barazangi et al. (1973) indicates that the high-attenuation zone probably extends deeper than 300 km.

The data obtained for this paper also add new information about the zone of high attenuation behind the Tonga island arc. Barazangi and Isacks (1971) found that the average Q for the zone is about 50 for P-waves. We could only estimate an upper limit of about 20 for S-waves, since these waves are not perceptible on the Fiji seismograms. The response of the New Caledonia instruments is broader than that of the Fiji instruments and are, therefore, able to detect the very low-frequency S-waves as well as the P-waves from shallow and intermediate events in Tonga. Large variations in the predominant frequencies of P- and, particularly, S-waves are observed from earthquakes located along the inclined seismic zone of Tonga—Kermadec arc and recorded at New Caledonia. The epicentral distances vary from about 12° to 18°. Ray paths from

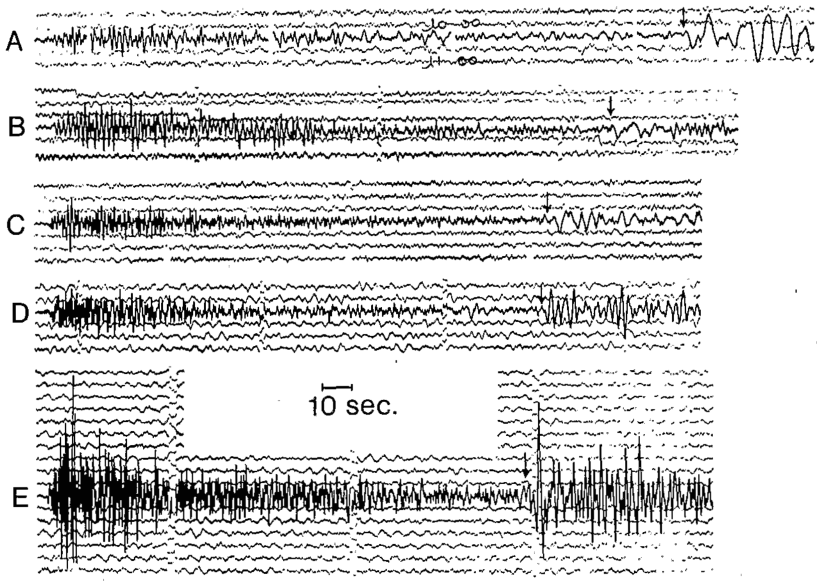

Fig. 7. Examples of seismograms recorded at NOU in New Caledonia from shallow, intermediate and deep earthquakes located along the Tonga-Kermadec seismic zone. The arrows on the records indicate the arrival times of S-waves.
A. Nov. 2, 1970, 15.4°S, 176.1°W, 44 km, N—S component;
B. April 20, 1970, 31.9°S, 179.3°W, 144 km, E—W component;
C. July 16, 1970, 25.3°S, 178.1°W, 225 km, N—S component;
D. June 2, 1970, 20.3°S, 177.4°W, 388 km, N—S component;
E. Aug. 7, 1970, 17.7°S, 178.2°W, 548 km, N—S component. Note that the frequency content of S-waves from shallow and intermediate events (A, B and C) is significantly different from that of deep events (D and E).

these earthquakes traverse the wedge of mantle above the Tonga—Kermadec seismic zone and the upper mantle to the west of it on their way to New Caledonia. Fig. 7 shows some examples of seismograms recorded at NOU in New Caledonia. Except for record A (which is produced by a shallow earthquake not located along the Tonga arc) all the ray paths pass too deep beneath the Fiji plateau or to the south of it to be affected by the anomalous high-attenuation zone described in the preceding section.

The most striking observation at NOU is that the periods of S-waves change from about 6 to 8 seconds for events located at depths less than about 300 km to about 2 seconds for events located deeper than about 300 km. The data are abundant and very consistent. These large changes in the periods of S-waves strongly support Barazangi and Isacks' interpretation of the changes in P-wave periods observed in Fiji.

Since S-waves from the Tonga—Kermadec intermediate earthquakes are well recorded at NOU then we can use the method of Oliver and Isacks (1967) to estimate the average Q of the material. We find an average Q for a path from an earthquake shallower than 300 km to New Caledonia to be about

50—80 for S-waves. If we take an average Q of 150 for shear waves in the upper mantle, then we obtain a Q-value of about 10 for the high-attenuation zone that exists in the upper 300 km of mantle beneath the Lau basin. This extremely low Q-value for shear waves is similar to that obtained by Solomon (1973) for material beneath the Mid-Atlantic Ridge. These low Q-values are best explained as the result of extensive partial melting of the upper-mantle materials (see Solomon for a detail discussion of this point).

CONCLUSIONS

Zones with anomalously high attenuation exist in the upper mantle beneath the Fiji plateau and the Woodlark basin. This is in agreement with the crustal spreading inferred to have occurred recently in these areas. The active volcanoes of the New Hebrides arc seem to mark the western boundary of the high-attenuation zone that exists beneath the Fiji plateau. There are no extensive high-attenuation zones directly beneath the two stations near the active volcanoes. The high-attenuation zone extends to depths of at least 300 km beneath the Fiji plateau.

Observations of S-waves at the New Caledonia stations for Tonga—Kermadec earthquakes strongly support the model obtained by Barazangi and Isacks (1971) for the lateral variations in attenuation behind the Tonga arc. The model includes a zone of very high attenuation in the upper 300 km of mantle beneath the young, actively spreading Lau basin. The average Q for S-waves inside the zone is about 10.

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