Travel Times of Seismic Waves between the New Hebrides and Fiji Islands: A Zone of Low Velocity beneath the Fiji Plateau[1]

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Shallow earthquakes that occurred during 10 years between the New Hebrides and Fiji islands are relocated by using a digital computer. The spatial distribution of the earthquakes may outline plate boundaries in the Fiji plateau; these boundaries, however, are diffuse and could be broad zones of deformation. In the center of the plateau west of Fiji times of *P* and *S* waves traveling in the uppermost mantle indicate velocities of 7.70 and 4.30 km/sec, respectively. Along the seismically active margins of the plateau *P* velocities are 7.30–7.40 km/sec. These velocities are considerably lower than *P* and *S* velocities of about 8.45 and 4.75 km/sec, respectively, of the normal oceanic basins of the Pacific plate to the north and east of the plateau. The zone of low velocity beneath the Fiji plateau and its boundaries seems to coincide with a high seismic wave attenuation zone that exists in the uppermost mantle between the Fiji and New Hebrides islands. These observations and other geophysical and geological aspects of the Fiji plateau clearly imply that the different lithospheric plates between the two opposite-facing lithospheric consumption zones of Tonga and New Hebrides arcs were recently generated and are not part of the oceanic Pacific plate.

In this study we use data from shallow earthquakes that have occurred during the last 10 years in the Fiji plateau area to determine the seismic velocities of the uppermost mantle. The seismicity of the Fiji plateau was examined recently by *Sykes et al.* [1969]. *Hess and Maxwell* [1953] indicated that a sinistral strike slip fault may be present between the southern end of the New Hebrides arc and the northern end of the Tonga arc, and *Menard* [1964] suggested that a fossil oceanic ridge, the Melanesian rise, may have been offset by subsequent movements along this fault. *Isacks et al.* [1969] and *Sykes et al.* [1969] observed that the presence of four seismic zones in this area rather than one continuous zone between the ends of the two arcs indicates that the tectonic pattern is not adequately modeled by a simple transform fault of the arc-arc type. In addition to the Pacific and Australian plates, the shallow seismic activity between the Tonga and New Hebrides islands appears to outline two additional plates, A and B. Plate A is bounded on the east by shallow activity near the Tonga trench. However, plate B is bounded on the west by shallow activity that occurs beneath the New Hebrides Islands.

A study of magnetic anomalies, submarine geology, and reconstruction of the past motions of the Pacific and Australian plates leads *Chase* [1971] to consider three active sea floor spreading centers in the Melanesian area, which are part of a very complicated system of plate boundaries linking the Tonga and New Hebrides crustal consumption zones. Chase distinguishes six small plates in addition to the large Pacific and Australian plates. *Karig and Mammerickx* [1972] suggest that the northerly-oriented linear troughs close to the active New Hebrides volcanoes are extensional in origin and represent an interarc basin that started to open in the Quaternary. Heat flow distribution behind the New Hebrides arc sug-

[1] Cornell University, Department of Geological Sciences, contribution 547.

gests to *MacDonald et al.* [1973] that the Hazel Holme fracture zone (15°S) is a plate boundary and separates warm, newly generated Fijian lithosphere to the south from cooler, older Pacific lithosphere to the north. For *Johnson and Molnar* [1972] the high heat flow, the low *Pn* velocity, the high attenuation of *Sn* waves, the low density and the absence of well-defined narrow belts of seismicity all imply a thin, weak lithosphere beneath the Fiji plateau and therefore imply the absence of plates.

In this paper we examine propagation of body and Rayleigh waves in the area of the Fiji plateau west of Fiji after a brief study of its seismicity. The basic data for this study were provided by the seismograph stations of the Department of Geological Sciences of Cornell University in the Fiji Islands and of the Office de la Recherche Scientifique et Technique Outre-Mer network in the New Hebrides Islands (Figure 1).

Seismicity of the Fiji Plateau

We have relocated 91 shallow earthquakes that occurred in the Fiji plateau from 1960 to 1971 (a list of the relocated events can be obtained from the authors on request). The locations were computed on an IBM 360-40 digital computer with the program originally written by *Bolt* [1960] and modified by L. R. Sykes. Data from seismological stations at epicentral distances less than 30° and from stations in abnormal zones such as island arcs or midocean ridges were not included in the input. The deleted stations that are located at distances less than 30° are in most cases located west of the Fiji plateau (e.g., the eight stations of the New Hebrides network).

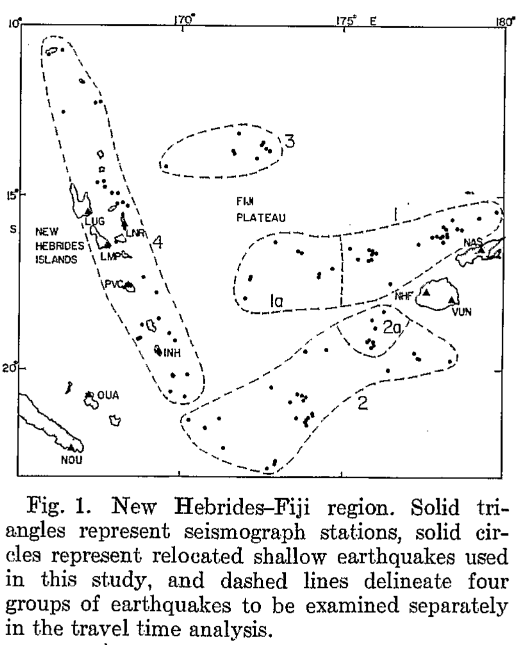

Fig. 1. New Hebrides–Fiji region. Solid triangles represent seismograph stations, solid circles represent relocated shallow earthquakes used in this study, and dashed lines delineate four groups of earthquakes to be examined separately in the travel time analysis.

We observe that the relocated epicenters are displaced from 0 to 20 km from the epicenters given by the International Seismological Centre and are generally pulled toward the azimuth of the stations that were deleted. This observation indicates the existence of low-velocity material in the uppermost mantle beneath the Fiji plateau. Figure 1 shows the distribution of the epicenters. The spatial pattern of the earthquakes is similar to that obtained by *Sykes et al.* [1969] and outlines the relatively aseismic plate B. A few shocks may be considered as an outline that divides plate B into two parts [*Chase,* 1971]. An important feature of the seismicity in the Fiji plateau is the presence of a boundary on the west side of the plate along the concave side of the New Hebrides arc. On the cross section (Figure 2) we can see that many shallow earthquakes cannot be connected with the underthrusting plate; their epicenters are above the intermediate depth shocks. Although few, these earthquakes are observed all along the arc. We interpret them as the western outline of plate B. They are probably associated with the opening of the narrow interarc basin that probably exists behind the New Hebrides arc [*Karig and Mammerickx,* 1972].

The continuous distribution of shallow earthquakes around the Fiji plateau makes it possible to determine the velocities in the uppermost mantle in the region in some detail. We excluded the data from the shallow earthquakes beneath the New Hebrides Island arc because the propagation from these events would be contaminated by the anomalies associated with the inclined lithospheric plate.

Propagation of *P* and *S* Waves

According to the distribution of epicenters and recording stations and the indications of the existence of plate B, we separate the earth-

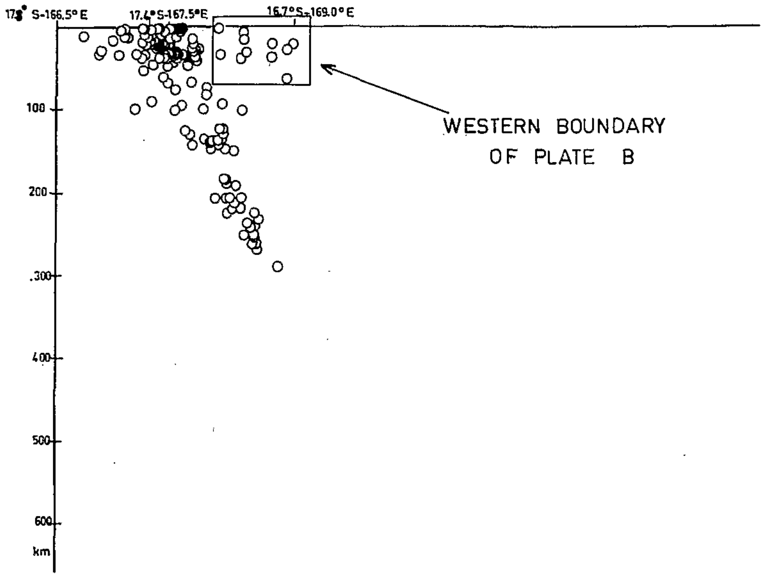

Fig. 2. Vertical cross section oriented perpendicular to the New Hebrides arc [from *Dubois,* 1971]. The shallow earthquakes on the east side of the arc and above the dipping seismic zone are interpreted as the western boundary of plate B.

quakes into four groups (Figure 1). We have computed the travel time equations from the different groups to the seismological stations of the New Hebrides and Fiji islands.

We fit the observations of travel time versus distance with a linear equation. The data (epicentral distances and travel times) are computed from the relocated epicenters, and the phases were reread on the seismograms. The accuracy in reading the P phases is about 0.2–0.4 sec, and the accuracy in calculating the epicentral distances is about 5 km. The depths of the earthquakes are not well determined since there are no stations close to the hypocenters. This will not significantly affect the slope of the travel time plots but may affect the intercept times. In Table 1 we give the velocity of seismic waves V and intercept time a in $T = \Delta/V + a$ and the value of the standard errors.

Rayleigh Waves Propagation

Some earthquakes on the Hunter fracture zone (about 21°S and 174°E) and on the seismic belt north of the Fiji Islands produce good records of Rayleigh waves at station PVC. The recording instrument is a 15-sec-period vertical seismometer and an 80-sec-period galvanometer. The group velocity of Rayleigh waves was computed with the classical peak-to-trough method, appropriate allowances being made for the phase shift of the instrument.

Two groups of earthquakes are considered. The first (group 1) gives mixed propagation paths along the northeastern boundary of plate B and crosses the northern part of the plate. The second (group 2) on the Hunter fracture zone gives paths crossing plate B. The dispersion data for the two groups of earthquakes yield two families of curves that are significantly different (Figure 3). The propagation across plate B shows higher velocities at shallower depths than the propagation along the northern boundary. This result will be quantitatively supported by travel time analysis as discussed below.

Discussion and Results

The average value of the velocity of P waves in the uppermost mantle under the Fiji plateau is 7.67 ± 0.10 km/sec. The value of the intercept time (2.13 sec) has uncertain significance; it depends on the depth of the focus and the thickness of the crust under the recording stations.

TABLE 1. Parameters of Linear Travel Time Plots for Different Combinations for the Fiji Plateau

Propagation Paths	*V*, km/sec	Standard Deviation of *V*, km/sec	Intercept Time, seconds	Number of Observations
	P Waves to Fiji and New Hebrides Stations			
Groups 3 and 4 to Fiji stations plus groups 1 and 2 to New Hebrides stations	7.67	0.10	2.13	87
	P Waves to New Hebrides Stations			
Groups 1, 2, and 3 to all New Hebrides stations	7.62	0.07	+2.59	57
Groups 1 and 2*a* to PVC, LUG, LNR, and LMP	7.48	0.11	+0.05	31
Groups 1, 2, and 3 to PVC	7.68	0.13	+2.78	37
Groups 1, 2, and 3 to PVC, without three scattered data	7.76	0.12	+3.95	34
Groups 1, 2, and 3 to LUG	7.52	0.28	+2.01	20
Groups 1, 2, and 3 to LUG, without three scattered data	7.63	0.21	+3.73	17
Group 4 to PVC and LNR	7.42	0.21	+1.67	15
	S Waves to New Hebrides Stations			
Groups 1, 2, and 3 to PVC	4.30	0.14	+5.62	23
	P Waves to Fiji Stations VUN, NAS, and NHF			
Groups 1*a*, 3, and 4 to all Fiji stations	7.62	0.16	-1.74	93
Groups 1*a*, 3, and 4 to all Fiji stations, without scattered data	7.54	0.08	-2.22	70
Groups 1*a*, 3, and 4 to VUN	7.67	0.23	-1.08	35
Groups 1*a*, 3, and 4 to NAS	7.50	0.18	-3.55	27
Groups 1*a*, 3, and 4 to NHF	7.47	0.22	-2.03	16
Group 4 to all Fiji stations	7.65	0.13	-0.14	30
Group 2 to all Fiji stations	7.32	0.13	-5.62	28
Groups 1 and 2 to all Fiji stations	7.27	0.15	-3.67	26

The travel times for paths in the direction east to west (to New Hebrides stations) yield interesting data on the structural heterogeneities of the plateau (Figure 1 and Table 1).

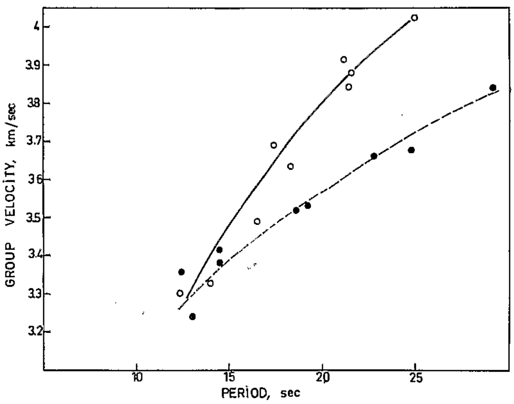

Fig. 3. Group velocity of Rayleigh waves across plate B (open circles) and along east-west paths (solid circles).

We can observe the difference between the propagation along the east-west seismic zone north and west of Fiji (groups 1 and 2*a* to New Hebrides stations) with a *P* velocity of 7.48 km/sec and that for plate B over all with a velocity of 7.6–7.7 km/sec (Figure 4). The velocity of *S* waves is about 4.30 km/sec for plate B.

The travel time equations for paths to Fiji stations give for the data from groups 1*a*, 3, and 4 combined an average velocity of 7.62 km/sec. However, important differences exist for different subsets of data, and the intercept times are negative. We interpret these results as consequences of large lateral variations of velocities near the Fiji Islands. We separate computations of velocities under plate B from those beneath the northern and southern boundaries.

The *P* velocities in the uppermost mantle obtained from groups 1 and 2 to Fiji stations along the southern outline of plate B and along the seismic belt north of the Fiji Islands are about 7.30 km/sec. This value probably explains why the value of 7.48 km/sec observed along the path from north Fiji to New Hebrides is different from the value observed beneath the whole plateau (7.62 km/sec). The slightly lower velocity determined at station LUG compared to that at station PVC for groups 1, 2, and 3 may also be due to the low velocities north of Fiji (Table 1).

We have seen that the western outline of plate B may be marked by the zone of shallow earthquakes that are located above the inclined seismic zone of the New Hebrides arc (Figure 2). The locations of these epicenters along the eastern concave side of the arc allow computation of the velocity of P waves in this zone. The existence of low velocities in this zone is demonstrated by *Dubois* [1971] with data from stations LUG and PVC. He found that the apparent velocity of P waves increases with epicentral distances and interpreted this observation by a model with linear increase of velocity with depth from 7.4 to 8.1 km/sec between depths of 20 and 100 km. The existence of the dipping lithosphere beneath the zone of low velocity may explain that velocity increase with depth. Since the events are located east of the island arc, the seismic rays reach stations LNR and PVC without entering the dipping lithosphere. A least squares computation gives for stations PVC and LNR a velocity in the uppermost mantle of 7.42 km/sec and an intercept time of 1.7 sec, in good agreement with Dubois' study.

In summary, the uppermost mantle beneath the Fiji plateau has a P velocity of about 7.7 km/sec and an S wave velocity of about 4.3 km/sec, and beneath the boundaries of the plateau the P wave velocities are 7.30–7.40 km/sec. If we consider this study in a larger framework including Tonga–Fiji–New Hebrides–New Caledonia, we can include the results of seismological data in the overall tectonic pattern of this area. Figure 5 shows plates A and B, the two oppositely-facing island arcs, and the results of other seismological studies. The values of P wave velocities in the uppermost mantle are indicated for several regions. The relatively low value of P velocity under plate B is consistent with other evidence that the Fiji plateau is not an oceanic lithosphere belonging to the Pacific Ocean but is a recently generated plate. Additional evidence includes the high seismic wave attenuation [*Barazangi and Isacks*, 1971], the thinness of the sediments

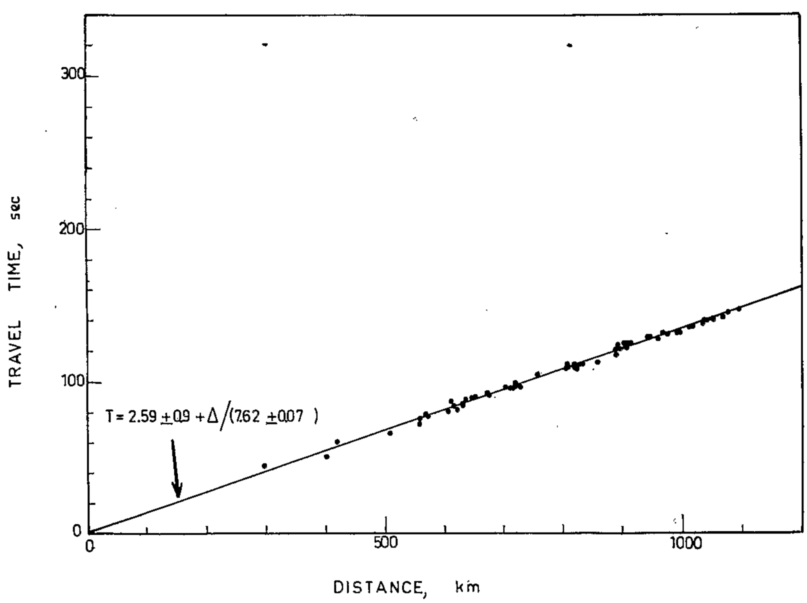

Fig. 4. Representative P travel time plot for New Hebrides seismological stations (PVC, LUG, LNR, LMP, and INH) for paths across the Fiji plateau from earthquakes of groups 1, 2, and 3 (Figure 1).

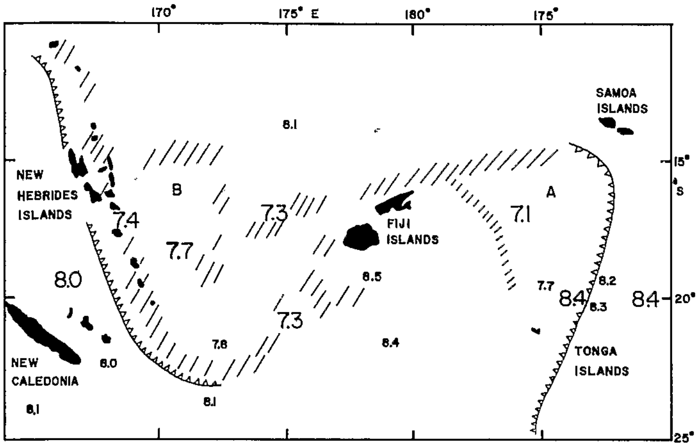

Fig. 5. Map of New Hebrides–Fiji–Tonga area showing locations of shallow earthquakes (dashed lines), P wave velocities in the uppermost mantle obtained in this study (between Fiji and New Hebrides) and by *Aggarwal et al.* [1972] (east of Fiji) (large numbers), and finally P velocities in the uppermost mantle obtained by *Shor et al.* [1971] (small numbers).

(less than 100 meters), the high heat flow (more than 3.0 HFU, or 3.0 μcal cm^{-2} sec^{-1}) [*Sclater and Menard,* 1967; *MacDonald et al.,* 1973] and the gravity measurements indicative of low-density uppermost mantle [*Solomon and Biehler,* 1969].

Acknowledgments. We thank Peter Molnar for his review of the paper and J. Coulomb and J. Goguel for valuable discussions and suggestions. This paper is one in a series of papers that will report the results of a cooperative research project started in the summer of 1971 between the Office de la Recherche Scientifique et Technique Outre-Mer Center of Noumea, New Caledonia, and the Institut de Physique du Globe, University of Paris, Paris, France, and the Department of Geological Sciences, Cornell University, Ithaca, New York. This work was partly supported by National Science Foundation grants GA-34140 and GA-30473.

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(Received November 3, 1972;
revised January 29, 1973.)