UPPER MANTLE VELOCITY STRUCTURE IN THE NEW HEBRIDES ISLAND ARC REGION

K.L. KAILA and V.G. KRISHNA

National Geophysical Research Institute, Hyderabad, India

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Upper mantle velocity structure in the New Hebrides island arc region has been determined to a depth of 240 km from the analysis of P and S wave travel times of 39 deep earthquakes using KAILA's (1969) analytical method. The present analysis reveals a linear increase of P wave velocity from 8.06 km/sec at a 40-km depth to 8.19 km/sec at a 240-km depth with a gradient of only 0.06 ± 0.01 km/sec per 100 km. For S waves also, the velocity increases linearly from 4.55 km/sec at a 40-km depth to 4.64 km/sec at a depth of 220-km with a gradient of only 0.04 ± 0.02 km/sec per 100 km. The velocity gradients for P and S waves, from 40 to 240 km depth in the upper mantle beneath the New Hebrides arc are found to be extremely small as compared to those at similar depths in the adjacent Tonga-Kermadec-New Zealand region. Consequently, the P and S velocities, to a depth of 240 km, beneath the New Hebrides arc are found to be about 6% lower, on the average, than those in the Tonga-Kermadec-New Zealand region. This velocity difference is attributed primarily to very high upper mantle temperatures in the New Hebrides region which may be about 1,000°C higher than those in the Tonga-Kermadec-New Zealand region. An alternative explanation based on existence of high temperatures in this region is also presented which explains deep seismic activity at 600 km depth in the New Hebrides region without invoking the concept of a detached lithospheric slab proposed by some of the earlier workers.

1. Introduction

The New Hebrides island arc region in the southwest Pacific forms a belt of great seismic activity to intermediate depths extending from 10°S, 166°E to 24°S, 172°E and a belt of active volcanism is also associated with it. The intermediate depth earthquakes in this region occur along the northeasternly dipping New Hebrides seismic zone which appears as a plane dipping at about 30° at shallow depths and about 70° at intermediate depths (PASCAL *et al.*, 1973). There is a remarkable gap in seismic activity between depths of about 300–600 km in this region. Deep focus earthquakes with depths greater than 600 km are concentrated mainly in a region northeast of the New Hebrides arc although a very few deep earthquakes have also occurred in the southern part of the New Hebrides arc. However, the deep earthquake activity in this region is very limited. BARAZANGI *et al.* (1973) studied the seismic wave propagation beneath the New Hebrides island arc and interpreted the gap in seismic activity between deep and intermediate depth earthquakes at the northern part of the arc as corresponding to a gap in the lithospheric slab descending beneath the arc. They interpreted the deep earthquakes occurring in the northeastern region of the arc as representing a detached piece of lithosphere. PASCAL *et al.* (1973) found that the observed travel time residuals along the New Hebrides arc can be explained by P travel times computed for a velocity model which includes a 6% higher velocity relative to a normal mantle inside a dipping lithospheric slab 300 km deep, a 6%

higher velocity inside a detached slab at a depth of 600 km, and a 4% lower velocity in the wedge of the mantle above the inclined seismic zone. However, these are only the estimates of relative differences of the velocity structure in different parts of the upper mantle and the actual velocity structure as a function of depth, for P and S waves, is not well known in the New Hebrides island arc region. In the present study, we have determined the upper mantle velocity structure to a depth of 240 km in the inclined seismic zone beneath the New Hebrides island arc region from the analysis of P and S wave travel times. The resulting velocity functions for P and S waves are compared with those determined by KAILA and KRISHNA (1978) for the Tonga-Kermadec-New Zealand region and also with the velocity functions for various regions of the earth determined by other workers. The gross differences in the velocity structure between the New Hebrides island arc and

Fig. 1. Map of the southwest Pacific region showing the seismological observatories and epicenters of earthquakes in the New Hebrides region used in the present study. Epicenters of earthquakes used by KAILA and KRISHNA (1978) for determining the upper mantle velocity structure in the Tonga-Kermadec-New Zealand region are also shown.

Table 1. Earthquake epicentral data.

Earthquake No.	Date	Time			Epicenter		Focal depth (km)
		(h)	(m)	(s)	Latitude (deg)	Longitude (deg)	
1	Mar. 4, 1964	03	17	23.6	20.67S	168.59E	36
2	Nov. 20, 1961	11	44	21.0	21.81S	169.88E	36
3	Oct. 21, 1964	10	08	46.7	14.10S	166.70E	37
4	Feb. 7, 1964	23	12	52.8	19.24S	168.70E	38
5	Sept. 16, 1963	20	05	23.0	13.39S	166.53E	40
6	Nov. 3, 1964	17	07	41.8	22.80S	171.50E	41
7	June 6, 1964	02	14	11.0	16.20S	167.10E	41
8	Jan. 27, 1964	05	06	59.7	13.04S	166.60E	41
9	Sept. 6, 1960	14	03	01.0	20.57S	169.35E	44
10	Aug. 10, 1964	14	44	40.8	14.00S	166.70E	44
11	Feb. 18, 1964	01	31	18.7	16.32S	166.74E	50
12	Jan. 22, 1964	23	59	45.3	13.64S	165.96E	50
13	June 10, 1964	11	53	31.0	17.16S	168.10E	52
14	Dec. 24, 1963	11	18	15.0	13.17S	166.72E	53
15	Nov. 6, 1961	05	28	26.0	13.38S	166.14E	63
16	Apr. 17, 1964	14	44	21.3	16.19S	167.50E	66
17	Dec. 28, 1961	23	55	54.0	12.38S	166.16E	69
18	June 22, 1964	03	03	38.1	10.34S	161.11E	74
19	Nov. 11, 1962	16	09	58.0	12.88S	166.41E	75
20	Aug. 22, 1961	08	59	32.0	13.49S	166.46E	79
21	Aug. 9, 1964	05	30	47.5	10.27S	161.30E	86
22	Apr. 28, 1964	15	11	33.2	12.44S	166.01E	87
23	Mar. 27, 1964	08	01	31.0	11.55S	166.20E	96
24	Nov. 21, 1964	06	19	16.0	14.85S	167.24E	97
25	July 2, 1962	08	32	42.0	10.58S	165.99E	98
26	Apr. 3, 1964	19	08	16.5	15.03S	167.04E	99
27	May 2, 1964	10	55	59.4	14.84S	167.23E	102
28	July 15, 1964	08	24	53.6	11.34S	166.24E	103
29	May 22, 1962	08	06	38.0	12.24S	166.66E	121
30	Oct. 5, 1964	13	12	13.9	22.36S	171.65E	130
31	June 26, 1964	05	20	04.2	15.68S	167.79E	135
32	July 11, 1964	17	32	16.7	15.54S	167.68E	140
33	Oct. 24, 1964	22	06	07.8	16.00S	167.20E	141
34	Oct. 21, 1961	17	34	34.0	10.91S	166.19E	164
35	May 27, 1964	00	54	50.8	15.52S	167.99E	166
36	July 16, 1962	09	25	58.0	13.16S	167.07E	204
37	Dec. 5, 1961	13	02	37.0	16.35S	167.85E	205
38	Apr. 19, 1962	22	15	24.0	15.92S	167.92E	223
39	Sept. 1, 1962	04	52	14.0	15.81S	168.11E	238

the Tonga-Kermadec-New Zealand region are interpreted in terms of large lateral temperature variations prevailing even at great depths in the mantle beneath the two oppositely dipping seismic regions. Probable physical and thermal properties of the upper mantle in the New Hebrides region are discussed which provide an alternative explanation for the existence of deep seismic activity at 600 km depth that has been interpreted by some of the workers (BARAZANGI *et al.*, 1973; PASCAL *et al.*, 1973) as an evidence for a detached piece of lithospheric slab.

2. Data Analysis and Results

Thirty-nine shallow and intermediate depth earthquakes are selected in the seismic

region of the New Hebrides for determining the upper mantle velocity structure in the inclined seismic zone beneath this region. P and S wave travel times and epicentral distances (Δ) are taken from the bulletins of the International Seismological Summary (ISS) for the period 1960–1963 and from the bulletins of the International Seismological Center (ISC) for the year 1964. The epicenters of all the earthquakes in the New Hebrides region used in the present study along with the seismograph stations are shown in Fig. 1. The epicentral data for all the earthquakes is also given in Table 1.

For obtaining the velocities at various depths in the seismic zone beneath New Hebrides island arc, we have analysed the P and S wave travel times of all the earthquakes listed in Table 1 by making use of KAILA's (1969) analytical method. The epicentral distance limits Δ_1 and Δ_2 , between which $p(=\partial T/\partial \Delta)$ is considered to remain stationary, are however not determined from the data for various earthquakes used in the present study. Instead, we have made use of the Δ_1 and Δ_2 curves plotted as functions of focal depth given by KAILA *et al.* (1971, Fig. 9 for P waves and 1974, Fig. 7 for S waves) for obtaining the Δ_1 and Δ_2 limits in each case, because in our opinion these estimates of Δ_1 and Δ_2 for various focal depths are quite accurate within the error limits and that they do not affect significantly the final velocity estimates. The travel time data available between the two limits is fitted by a least squares line in each case which yields the apparent $p(=\partial T/\partial \Delta)$ and the $a(=T-p\Delta)$ values with their standard deviations. The least squares fits

Fig. 2. P wave travel time curve T versus Δ for earthquake with focal depth 223 km between the limits Δ_1 and Δ_2 of epicentral distance. Reduced travel time curve $(T-p\Delta)$ versus Δ is also shown where $p=\partial T/\partial \Delta$ at the inflection point.

Fig. 3. S wave travel time curve T versus Δ for earthquake with focal depth 223 km between the limits Δ_1 and Δ_2 of epicentral distance. Reduced travel time curve $(T - p\Delta)$ versus Δ is also shown where $p = \partial T / \partial \Delta$ at the inflection point.

obtained for $T-\Delta$ points between the Δ_1 and Δ_2 limits for one specimen earthquake with focal depth 223 km are shown in Figs. 2 and 3 for P and S waves respectively. In the same figures are also shown the plots $(T - p\Delta)$ versus Δ . Using the apparent p values, the true velocities and their standard deviations are computed for each focal depth analysed. It may be mentioned here that the method of analysis adopted in the present study has the greatest advantage that we are able to determine the velocity for P and S waves at the hypocenter of each earthquake thus avoiding completely the effect of the travel path to different stations. Since all the earthquake hypocenters used in the present study are in the inclined seismic zone, the final velocity function resulting on the basis of all these velocity estimates will represent precisely the velocity structure in the inclined seismic zone beneath the New Hebrides island arc. The final results obtained for the p values and velocities with their standard deviations are given in Table 2 for both P and S waves.

The true velocities and the a values thus obtained at various depths are plotted as parts (a) and (b) respectively in Fig. 4 for P waves and in Fig. 5 for S waves. In these figures the velocity-depth and the a value-depth points are shown by circles and the truncated horizontal bars with them indicate the standard deviations of the plotted points. The velocity-depth points and the a value depth points, for both P and S waves, are fitted by straight lines using the method of least squares and are shown by thick lines in Figs. 4 and 5. The broken lines bounding these straight line fits represent the 95% confidence limits of the slopes in each case.

The velocity functions thus determined in the New Hebrides region reveal very small linear increase of velocity with depth for both P and S waves (Figs. 4a and 5a respectively). The velocity for P waves determined as 8.06 km/sec at a 40 km depth increases linearly to 8.19 km/sec at a depth of 240 km with a mild velocity gradient of only 0.06 ± 0.01 km/sec

Table 2. P and S wave true velocities V_P and V_S respectively as functions of depth (h) for the New Hebrides region as determined in the present study.

Earth-quake No.	h (km)	P waves			S waves		
		p (apparent) (sec/deg)	V_P (km/sec)	a_P (sec)	p (apparent) (sec/deg)	V_S (km/sec)	a_S (sec)
1	36	14.04 $\pm$ 0.51	7.91 $\pm$ 0.29	1.9 $\pm$ 1.8	—	—	—
2	36	—	—	—	25.03 $\pm$ 2.41	4.44 $\pm$ 0.43	11.9 $\pm$ 10.6
3	37	13.45 $\pm$ 0.44	8.25 $\pm$ 0.27	7.7 $\pm$ 3.1	—	—	—
4	38	13.73 $\pm$ 0.13	8.09 $\pm$ 0.08	5.1 $\pm$ 0.5	—	—	—
5	40	13.88 $\pm$ 0.49	8.00 $\pm$ 0.28	4.8 $\pm$ 3.2	—	—	—
6	41	14.06 $\pm$ 0.37	7.89 $\pm$ 0.21	4.1 $\pm$ 2.4	—	—	—
7	41	13.74 $\pm$ 0.34	8.08 $\pm$ 0.20	4.6 $\pm$ 2.0	25.77 $\pm$ 1.37	4.31 $\pm$ 0.23	—
8	41	13.63 $\pm$ 0.49	8.14 $\pm$ 0.29	6.7 $\pm$ 3.2	—	—	—
9	44	14.05 $\pm$ 0.30	7.90 $\pm$ 0.17	3.6 $\pm$ 1.7	—	—	—
10	44	—	—	—	23.41 $\pm$ 0.82	4.74 $\pm$ 0.17	15.7 $\pm$ 5.5
11	50	13.77 $\pm$ 0.42	8.05 $\pm$ 0.25	2.9 $\pm$ 1.9	—	—	—
12	50	13.65 $\pm$ 0.46	8.12 $\pm$ 0.28	4.1 $\pm$ 3.3	—	—	—
13	52	13.38 $\pm$ 0.41	8.28 $\pm$ 0.26	8.1 $\pm$ 2.6	—	—	—
14	53	13.93 $\pm$ 0.30	7.95 $\pm$ 0.17	4.1 $\pm$ 2.0	—	—	—
15	63	—	—	—	24.35 $\pm$ 1.02	4.54 $\pm$ 0.19	15.5 $\pm$ 7.3
16	66	13.29 $\pm$ 0.70	8.32 $\pm$ 0.44	6.6 $\pm$ 3.8	—	—	—
17	69	13.23 $\pm$ 0.16	8.35 $\pm$ 0.10	—	—	—	—
18	74	13.67 $\pm$ 0.10	8.08 $\pm$ 0.06	5.4 $\pm$ 1.0	—	—	—
19	75	13.57 $\pm$ 0.35	8.13 $\pm$ 0.21	5.4 $\pm$ 2.6	—	—	—
20	79	13.31 $\pm$ 0.49	8.29 $\pm$ 0.31	7.6 $\pm$ 3.5	—	—	—
21	86	14.10 $\pm$ 0.26	7.82 $\pm$ 0.15	—	—	—	—
22	87	—	—	—	24.10 $\pm$ 0.16	4.57 $\pm$ 0.03	11.6 $\pm$ 1.2
23	96	13.97 $\pm$ 0.49	7.88 $\pm$ 0.28	—	—	—	—
24	97	—	—	—	23.34 $\pm$ 1.29	4.71 $\pm$ 0.26	13.1 $\pm$ 7.6
25	98	13.70 $\pm$ 0.58	8.03 $\pm$ 0.34	5.3 $\pm$ 5.3	23.69 $\pm$ 1.09	4.64 $\pm$ 0.22	10.8 $\pm$ 8.8
26	99	14.13 $\pm$ 0.18	7.78 $\pm$ 0.10	2.0 $\pm$ 1.4	—	—	—
27	102	—	—	—	23.39 $\pm$ 0.72	4.70 $\pm$ 0.15	14.3 $\pm$ 4.3
28	103	13.13 $\pm$ 0.29	8.37 $\pm$ 0.19	9.1 $\pm$ 2.3	24.01 $\pm$ 0.37	4.58 $\pm$ 0.07	11.2 $\pm$ 2.6
29	121	13.28 $\pm$ 0.49	8.25 $\pm$ 0.31	7.9 $\pm$ 4.0	—	—	—
30	130	13.31 $\pm$ 0.63	8.22 $\pm$ 0.39	8.3 $\pm$ 4.6	—	—	—
31	135	13.80 $\pm$ 0.61	7.92 $\pm$ 0.35	5.1 $\pm$ 3.6	—	—	—
32	140	13.72 $\pm$ 0.45	7.96 $\pm$ 0.27	4.4 $\pm$ 3.2	—	—	—
33	141	13.53 $\pm$ 0.51	8.07 $\pm$ 0.31	7.2 $\pm$ 4.0	—	—	—
34	164	13.37 $\pm$ 0.03	8.14 $\pm$ 0.02	7.5 $\pm$ 0.3	—	—	—
35	166	13.46 $\pm$ 0.08	8.08 $\pm$ 0.05	6.7 $\pm$ 0.6	23.42 $\pm$ 0.95	4.64 $\pm$ 0.19	17.3 $\pm$ 7.4
36	204	13.41 $\pm$ 0.33	8.06 $\pm$ 0.20	6.0 $\pm$ 3.1	—	—	—
37	205	—	—	—	23.78 $\pm$ 1.45	4.55 $\pm$ 0.28	17.1 $\pm$ 12.0
38	223	13.15 $\pm$ 0.43	8.19 $\pm$ 0.28	8.9 $\pm$ 3.6	23.50 $\pm$ 0.33	4.59 $\pm$ 0.07	18.0 $\pm$ 2.7
39	238	12.76 $\pm$ 0.26	8.43 $\pm$ 0.18	12.4 $\pm$ 2.2	—	—	—

per 100 km. On the other hand the S wave velocity from 40 to 220 km depth, increases linearly from 4.55 km/sec to 4.64 km/sec again with a very mild velocity gradient for S waves of only 0.04 ± 0.02 km/sec per 100 km.

3. Discussion

Upper mantle velocity structure for P and S waves in the New Hebrides island arc region as determined in the present study and shown as parts (a) and (b) in Fig. 6 is compared with the upper mantle velocity structure in the Tonga-Kermadec-New Zealand region determined by KAILA and KRISHNA (1978). Upper mantle velocity structure in

Fig. 4. (a) P wave velocity versus depth curve for the New Hebrides region. (b) $a_p (= T - p\Delta)$, at the inflection point, versus depth as a calibration curve for earthquake focal depth determination from P wave data in the New Hebrides region. In both figures — are the least squares fits obtained for the plotted points shown by $\circ$ and --- are the 95% confidence limits of their slopes. Truncated horizontal bars represent the standard deviations in the velocity and a_p values.

Fig. 5. (a) S wave velocity versus depth curve for the New Hebrides region. (b) $a_s (= T - p\Delta)$, at the inflection point, versus depth as a calibration curve for earthquake focal depth determination from S wave data in the New Hebrides region. In both figures — are the least squares fits obtained for the plotted points shown by $\circ$ and --- are the 95% confidence limits of their slopes. Truncated horizontal bars represent the standard deviations in the velocity and a_s values.

other regions of the earth due to KAILA *et al.* (1971, 1974), JEFFREYS (1939), SIMPSON *et al.* (1974) for P waves and HELMBERGER and ENGEN (1974) for S waves are also included in these figures for comparison. The P and S velocities at the top of the mantle in the New Hebrides seismic region as determined in the present study are 8.06 and 4.55 km/sec respectively. SHOR *et al.* (1971) from seismic refraction studies in the Melanesian Borderland along profile CD south of New Hebrides island and New Caledonia found P_n velocities of 7.8 km/sec under the Fiji plateau, and 7.7 to 8.0 km/sec under the Norfolk ridge. Our P velocity value of 8.06 km/sec at 40 km depth in the New Hebrides region is quite consistent with these findings.

Fig. 6. (a) P wave and (b) S wave velocity functions in the New Hebrides island arc region as determined in the present study along with velocity models for other regions of the Earth.

The most remarkable feature that can be noticed from Fig. 6 is the gross differences in the velocity structure between the two oppositely dipping inclined seismic zones, beneath the New Hebrides island arc and the Tonga-Kermadec-New Zealand regions. It can be seen from Fig. 6 that although P and S velocities at the top of the mantle in the New Hebrides region are comparable with the P and S velocities at the top of the mantle in the Tonga-Kermadec-New Zealand region, with increasing depth the velocity functions in the two regions show increasing divergence, the velocities in the Tonga-Kermadec-New Zealand region being substantially larger. At a depth of 240 km, the P velocity in the Tonga-Kermadec-New Zealand region is about 10% higher than that in the New Hebrides region at the same depth. Similarly, at a depth of 220 km, the S velocity in the Tonga-Kermadec-New Zealand region is also 6 to 7% higher than that in the New Hebrides region at a similar depth. We attribute this gross difference in the velocity structure between these two seismic regions of the southwest Pacific to large lateral temperature differences in the upper mantle extending to considerable depths. The velocities of both P and S waves are strongly affected by changes in pressure, temperature and chemical and mineralogical composition which may possibly extend to great depths. Inside the

earth both temperature and pressure increase with depth. The temperature gradient may be highly variable from place to place whereas the pressure gradient can be considered to be almost constant over various regions. The degree of compositional variation and its likely effect on the velocity structure in the two adjacent New Hebrides and the Tonga-Kermadec-New Zealand regions can be safely assumed to be negligible, the velocities in the uppermost mantle in the two regions being almost similar. Therefore the only possible explanation that can satisfactorily account for the gross difference in the velocity structure in the two regions, in our opinion, is the temperature differences prevailing in the upper mantle. The measurements of high temperature and pressure derivatives of elastic constants for a number of compounds appropriate for geophysical considerations as reported by ANDERSON *et al.* (1968) indicate that a temperature contrast of the order of $1,000^{\circ}\text{C}$ is needed to account for a 6% difference in the observed P velocities. Since, in the depth range from 40 to 240 km, the average P velocity difference between the New Hebrides and the Tonga-Kermadec-New Zealand regions is also about 6%, we therefore infer that there may be a temperature difference of about $1,000^{\circ}\text{C}$ between these two regions in this depth range. At a depth of 240 km, the temperature contrast required may be even much larger between the two regions to produce the observed 10% P velocity contrast at the pressures prevailing at that depth. However, it is quite possible that this temperature excess in the New Hebrides region, may cause a partial melting which would also decrease the velocity. KANAMORI (1968) found that a 2% partial melting would cause about 1% velocity decrease using the equation $V = V_0(1 - 0.58c)$ given by HASHIN (1962), where V is the P velocity in a material having a liquid inclusion of concentration c and V_0 is the velocity for $c=0$. Thus some component of the velocity contrast between the two regions, the New Hebrides and the Tonga-Kermadec-New Zealand may be also attributable to partial melting in the New Hebrides region and consequently the temperature contrast between the two regions may be somewhat smaller. It is therefore these high temperatures in the New Hebrides region which are primarily controlling the velocity gradients and thus keeping the P velocities more or less constant to a depth of 240 km.

Let us now investigate whether these large lateral temperature variations in the upper mantle between the New Hebrides and the Tonga-Kermadec-New Zealand regions will in any way correlate with the observed heat flow in the two regions. In Fig. 1, we have also shown the heat flow observations in the southwest Pacific region compiled by JESSOP *et al.* (1976). We have, however, classified the heat flow values only into 3 ranges as shown in Fig. 1, instead of 5 ranges given by JESSOP *et al.* (1976). It can be seen from Fig. 1 that the average observed heat flow value in the eastern north island of New Zealand and in the Tonga-Kermadec deep earthquake zone is much smaller than that in the New Hebrides seismic zone. Thus the distribution of the observed heat flow in the two regions is also quite consistent with our idea that the temperatures in the New Hebrides region are much larger than those in the Tonga-Kermadec-New Zealand region. These high temperatures in the New Hebrides region may also imply that the mantle material in this region down to at least 240 km is probably in a partially molten state and the chain of active volcanoes also nicely correlates with this idea (see Fig. 1).

In Fig. 6 we have also shown the P and S velocity functions for the southwest and central Japan regions determined by KAILA *et al.* (1971 and 1974). It is very interesting to note that the difference in the velocity structures between the southwest Japan and the central Japan regions is quite similar to that found by us between the New Hebrides and the Tonga-Kermadec-New Zealand regions. The velocity in the southwest Japan region

almost remains constant to the depth studied, about 255 km for P waves and about 170 km for S waves. On the other hand, although the velocities at the top of the mantle in the southwest and central Japan regions are comparable, the velocities of both P and S waves in the central Japan region increase with high velocity gradients in this depth range. Thus the velocity functions in the southwest and central Japan regions also show increased divergence with increasing depths. In our opinion, these velocity anomalies are also caused by only large lateral temperature contrasts between the southwest and the central Japan regions. KAILA *et al.* (1971, 1974) interpreted the constant P and S velocities in the upper mantle beneath the southwest Japan region as due to relatively high volcanic activity and probable existence of large magma chamber extending to about 250 km depth beneath southwest Japan.

If we compare the velocity structure in the New Hebrides and the southwest Japan regions we can find that although the velocities remain constant in both the regions, the velocities in the southwest Japan region are about 3% lower for P waves and about 4% lower for S waves than those in the New Hebrides region. This may imply that the temperature at the top of the mantle beneath the New Hebrides may be smaller than that in the southwest Japan region. However, the temperature gradients in the two regions may be comparable because the velocities remain almost constant upto about 240 km. Of course, we cannot rule out the possibility that some component of the observed velocity anomaly between these two regions, the New Hebrides (in the southwest Pacific) and the southwest Japan may be also due to some compositional change, the two regions being so wide apart. However, the compositional change, even if it exists to some extent in the uppermost mantle immediately below Moho, may not be able to account for the observed velocity anomaly at large depth, which can be only explained by temperature differences between the two regions.

JEFFREYS (1939) velocity curves for both P and S waves are also shown in Fig. 6. The P velocities in the New Hebrides region to a depth of about 160 km are found to be comparatively higher and they are somewhat lower between 160 to 240 km than those given by JEFFREYS (1939). On the other hand, the S velocities are also relatively higher in the New Hebrides region than those given by JEFFREYS (1939) throughout the depth range of 220 km studied. The P velocity model SMAK I for northeastern Australia given by SIMPSON *et al.* (1974) also reveals very small velocity gradient comparable with the P velocity gradient for the New Hebrides region determined in the present study. It may be mentioned here, that the source region involved in deriving the SMAK I model is New Guinea, New Britain and Solomon islands region which is also an active volcanic region and a region of high heat flow (see Fig. 1) as the New Hebrides region. These observations again substantiate our idea that the temperatures may be considerably higher in these regions therefore the velocity gradients in both the regions are very small. In fact the mantle material in the entire region, beneath the New Hebrides, Solomon islands, New Britain and the New Guinea regions may be in a partially molten state as evidenced by intense volcanism and high observed heat flow in these regions. Therefore, the velocity gradients in these regions are extremely small. However, since some correction to remove the source effect to some extent, is applied by SIMPSON *et al.* (1974) the SMAK I model is therefore revealing somewhat higher velocities than our P velocity curve for the New Hebrides region in the depth range from 90 to 240 km. BROOKS (1962) determined P velocities to a depth of 500 km in the New Guinea-Solomon Islands region from the analysis of travel times using GUTENBERG's (1953) graphical method, and presented evidence

for the existence of a low velocity zone in the region. According to him, the minimum velocity reached may be as low as 7.6 km/sec at a depth of about 150 km and the decrease in velocity in that region is much more pronounced than reported by other workers and that shadow zones for the arrival of direct P waves exist in the area. The S velocity model SHR 14, given by HELMBERGER and ENGEN (1974), applicable for the western United States has a low velocity layer between depths of 80 to 100 km and it reveals somewhat lower velocities than our S velocity curve for the New Hebrides region.

DUBOIS *et al.* (1973) from the study of P and S times from shallow earthquakes between the New Hebrides and Fiji found that in the centre of the Fiji plateau the velocities for P and S waves in the uppermost mantle are 7.70 and 4.30 km/sec respectively. They have also found that along the seismically active margins of the plateau P velocities are only 7.30–7.40 km/sec. According to DUBOIS *et al.* (1973) the zone of low velocity beneath the Fiji plateau has its boundaries which seem to coincide with a high seismic wave attenuation zone that exists in the uppermost mantle between the Fiji and the New Hebrides islands. BARAZANGI *et al.* (1974) studied 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. They found significant variations in the amplitudes and frequencies of the waves. Their data defined zones of anomalously high seismic wave attenuation in the uppermost mantle beneath the Fiji plateau and the Woodlark basin south of the Solomon islands. BARAZANGI and ISACKS (1971) also mapped in detail a zone of anomalously high seismic wave attenuation under the Lau basin. All these areas are also the sites of variable but generally high heat flow (SCLATTER *et al.*, 1972; 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). All these results suggest that hot and probably partially melted upper mantle material exists beneath these areas. It is also evident from our Fig. 1 that the observed heat flow in the Fiji plateau and other anomalous regions is considerably higher. BARAZANGI *et al.* (1974) also found that the high attenuation zone extends to depths of at least 300 km beneath the Fiji plateau. This implies that the temperatures of the mantle material beneath the Fiji plateau to a depth of about 300 km are relatively much higher than those in the surrounding mantle. It is quite possible that, the high temperatures probably prevailing to great depths of about 300 km beneath the Fiji plateau are even affecting the northeasternly dipping New Hebrides seismic zone to a considerable extent and that the temperatures in the dipping seismic zone are also very high. That is why the velocity gradients of P and S waves in the New Hebrides seismic zone as determined by us are extremely small thus the P and S velocities are also much lower in the New Hebrides region as compared to those in the Tonga-Kermadec-New Zealand region at comparable depths.

BARAZANGI *et al.* (1973) studied the seismic wave propagation in the mantle beneath the New Hebrides island arc and presented evidence for the detachment of lithospheric slabs in the upper mantle beneath the New Hebrides arc. They interpreted the remarkable gap in the seismic activity between deep and intermediate depth earthquakes at the northern part of the arc as due to a gap in the lithospheric slab descending beneath the arc, and the deep earthquakes as due to a detached piece of lithosphere. They found that predominantly low frequency (about 0.5 Hz) S waves are recorded at PVC and LNR stations in the New Hebrides from the deep earthquakes north of 15°S. New Hebrides deep earthquakes located at the western part of the deep zone produced attenuated, low

frequency S waves at PVC. The ray paths pass just beneath the dipping seismic zone. BARAZANGI *et al.* (1973) found that frequencies greater than 1 Hz are absent and the amplitude of the S phase is generally less than that of P phase. As OLIVER and ISACKS (1967) and BARAZANGI and ISACKS (1971) showed, this can be explained by a transmission through an attenuating low Q zone. BARAZANGI *et al.* (1973) also found that in contrast, S waves recorded at NIU station on the Tonga island arc from Tongan deep earthquakes have predominant frequencies of 3–4 Hz and the amplitude of S are generally larger than those of P. They interpreted the observation of low frequency S waves at PVC and LNR to be mainly the result of attenuation along the path. According to them the attenuation is chiefly below 300 km. BARAZANGI *et al.* (1973), on the basis of all these observations, suggested that there is absence of lithospheric slab material between depths of about 300 and 600 km, and the deep earthquakes of New Hebrides therefore represent a detached slab in the upper mantle. In our opinion, the very high temperatures reached at about 300 km depth in the surrounding mantle have probably affected the New Hebrides seismic zone to such an extent that the material in the seismic zone also has lost its strength substantially and no stresses can be accumulated in it. FARBEROV and GORELCHIK (1971) studied the focal distribution of subcrustal earthquakes and the dynamic features of seismic wave propagation under some volcanic areas of Kamchatka. They found that under active volcanoes there are aseismic areas of anomalous attenuation of seismic waves. As one of many possibilities, they suggested the presence of low viscosity zones under volcanoes in which there are no concentration of sufficient stresses to generate earthquakes and that these zones extend down to the focal layer. Since the volcanic activity in the New Hebrides region is also quite extensive the large temperatures there might have also reduced the viscosity of the mantle material at depths considerably. Thus beyond the depth of about 300 km there seems to be a gap in the seismic activity in this region. Again at depths greater than 600 km, due to increased pressure, built up by the usual pressure gradient, the material in the seismic zone might have recovered the necessary strength again to accumulate the stresses and therefore there are earthquakes occurring at these depths. Therefore, if we view the properties of the seismic zone in the light of this argument there is no necessity to imagine a gap in the lithospheric slab between depths of 300–600 km and a detached piece of lithosphere at about 600 km depth. The lithospheric slab in the New Hebrides may as well be continuing down to the usual depth of its penetration, i.e., probably the 650 km velocity discontinuity in the mantle. It may be only because of the anomalously high temperatures attained at depths beyond about 300 km, that the seismic activity is not continuing between 300–600 km depths. This does not necessarily mean that there is a gap in the lithospheric slab itself. The gap according to us, is only the change in the physical properties of the lithospheric slab but not its existence as such.

BARAZANGI *et al.* (1973) found that one of the three deep earthquakes occurred south of 15°S at about 18°E and 173°E produced large amplitude, high frequency S waves at PVC station in the New Hebrides. According to them this observation is quite clear and may imply the continuity of descending slab in the southern part of the New Hebrides arc. ISACKS and MOLNAR (1971) suggested that the gaps in seismic activity as a function of depth can be explained by two models. In the first the stress inside a continuous slab varies from downdip extension at intermediate depths to downdip compression at greater depths, and thus is near zero between these depths. In the second a piece of descending lithosphere breaks off, sinks into the upper mantle and leaves a gap between the piece and the plate

to which it was attached. SYKES (1966) studied the seismic activity versus depth for several island arcs. He found that in all island arcs studied the activity decreases in the upper 100 to 200 km approximately exponentially as a function of depth with a decay constant of about 100 km. ISACKS *et al.* (1968) found that there is an approximate correlation of the decrease in seismic activity versus depth with a similar general decrease in seismic velocities, Q and viscosity in the upper 150 km. They stated that these effects may be related to a decrease in the difference between the temperature and local melting temperature.

ISACKS *et al.* (1968) have plotted in their Fig. 12 the annual number of earthquakes per 25 km depth intervals as function of depth for several island arcs, the data being taken by them from SYKES (1966) and from KATSUMATA (1967) for the Japan region. If we scrutinize these curves carefully, we can find that there is either a broad minimum between depths of about 200 to 400 km or there are some gaps in certain depth ranges. We can notice broad minima for the Japan and the Tonga-Fiji-Kermadec regions in almost the same depth range where the P velocity functions reveal reduced velocity gradients in these regions (KAILA *et al.*, 1971; KAILA and KRISHNA, 1978). In our opinion, this is a nice correlation between the zones of less seismic activity and zones of reduced velocity gradients. Both these phenomenon can be easily explained by means of very high temperatures and/or temperature gradients in these depth ranges. Therefore, it is also quite possible that in a region like the New Hebrides which is surrounded by anomalously hot regions of the mantle there may be actual gap in the seismic activity in certain depth range like 300–600 km. In our opinion, this gap in the seismic activity however, does not necessarily mean a gap in the lithospheric slab. The slab may be actually continuing right to its maximum depth of penetration which may be the 650 km seismic discontinuity with variable physical properties throughout its length as explained above.

4. Conclusions

From the present study of the travel times of P and S waves in the New Hebrides island arc region we can make the following conclusions regarding the upper mantle structure in that region.

1) The P and S velocities are almost constant in the upper mantle to a depth of about 240 km. These velocities, although are comparable at the top of the mantle, they are however, much lower, by as much as 10% for P waves and 6–7% for S waves at a depth of about 240 km as compared to those at similar depths in the Tonga-Kermadec-New Zealand region. A temperature contrast of about 1,000°C between these two regions is needed to account for these velocity anomalies on the average.

2) The lower velocities observed in the New Hebrides seismic zone, are primarily due to anomalously high temperatures prevailing even at great depths in the upper mantle surrounding the New Hebrides region. In fact, the mantle material in the entire region beneath the New Hebrides, Solomon islands, New Britain and New Guinea regions may be in a partially molten state as revealed by very mild velocity gradients, high heat flow and intense volcanism in these regions.

3) The remarkable gap in the seismic activity observed in the New Hebrides region between depths of 300–600 km need not necessarily mean a gap in the lithospheric slab descending beneath the New Hebrides island arc. It is only due to the anomalously high temperature, prevailing in this region that the descending slab also has probably lost its

strength considerably and therefore cannot take sufficient stresses to accumulate and subsequently release through the earthquakes. At depths of about 600 km again the material in the slab has probably recovered its strength and therefore there are deep earthquakes at these depths. Therefore, we conclude that the lithospheric slab descending beneath the New Hebrides region is not broken between 300–600 km depth and may be continuing with varying physical and thermal properties right to the maximum depth of its penetration which may extend upto the 650-km seismic discontinuity.

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