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Seismic Velocity Anomalies beneath the New Hebrides Island Arc: Evidence for a Detached Slab in the Upper Mantle

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A remarkable gap in seismic activity exists between depths of about 300 and 600 km beneath the New Hebrides island arc. A detailed study of travel time residuals of *P* and *S* waves from deep earthquakes supports the idea that the deep earthquakes located at the northeast of the arc represent a detached piece of lithosphere. All except three of the deep earthquakes are located in a nearly horizontal zone between latitudes 12°S and 15°S. The earthquakes were relocated by using travel times to distant stations and excluding travel times to local and regional stations. Travel times for *P* waves from the deep earthquakes that travel through the dipping New Hebrides seismic zone are about 3 sec less than those for waves that travel through the probably normal mantle beneath New Caledonia. A three-dimensional seismic ray tracing program is used to compute *P* travel times for a velocity model beneath the New Hebrides arc. The model 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 mantle above the inclined seismic zone. The computed travel times for this model explain the observed travel time residuals along the New Hebrides arc.

An outstanding feature of the distribution of mantle earthquakes in the New Hebrides region is the lack of activity between depths of about 300 and 600 km. The deep earthquakes are concentrated in an area northeast of the arc (Figures 1 and 2). Only three deep earthquakes are located outside this area (earthquakes 38, 39, and 40 in Table 1). Deep earthquakes occur relatively infrequently: only about 40 earthquakes were detected during the past 12 years. Beneath the island arc the inclined seismic zone appears as a plane dipping at about 30° at shallow depths and about 70° at intermediate depths. The deep events are distributed in a nearly horizontal plane with perhaps a slight dip westward of 10°. *Isacks and Molnar* [1971] studied the focal mechanisms for two deep earthquakes (16 and 29 in Table 1). Their results suggest a nearly horizontal slab of lithosphere.

The main contribution of this study is a detailed analysis of *P* and *S* travel time residuals from the deep earthquakes and the implications of these data about the upper mantle structure beneath the New Hebrides arc. To eliminate errors in the determination of the parameters of the events, we have systematically relocated all the hypocenters, readings from possibly anomalous local stations being excluded. We assume the remaining errors in location, resulting from inhomogeneity of the lower mantle, anomalies beneath the distant stations, and a nonuniform distribution of recording stations, to be small in comparison with the effects of inhomogeneities in the upper mantle above the deep earthquakes [see *Mitronovas and Isacks*, 1971].

The station distribution in the New Hebrides area is relatively good. The Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) network is composed of eight stations, five in the New Hebrides arc, two in New Caledonia, and one in the Loyalty Islands (Figure 1). The upgoing ray paths from the deep earthquakes must pass through the dipping

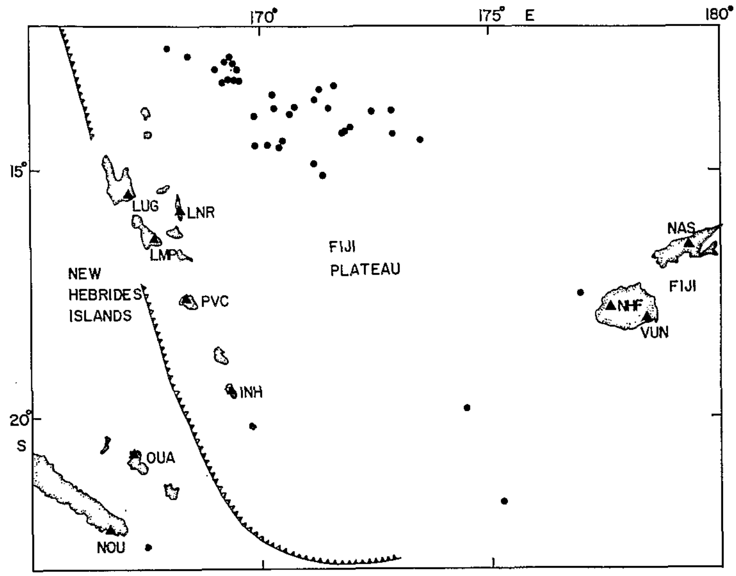

Fig. 1. Map of New Hebrides–Fiji area showing the local seismograph stations for which a detailed analysis of travel time residuals was made. The deep earthquakes are indicated by solid circles; New Hebrides trench is indicated (depth $\gtrsim$6 km).

seismic zone before reaching PVC and LUG, whereas the ray paths to the New Caledonia stations miss the seismic zone and therefore probably miss the large velocity anomalies associated with the descending slab. It is thus reasonable to determine the P and S travel time residuals relative to the stations in New Caledonia and thereby reduce the errors in travel time tables, hypocentral depths, and origin times. Evidence for a relatively normal mantle beneath New Caledonia is also indicated by the similarity of P travel time residuals of the

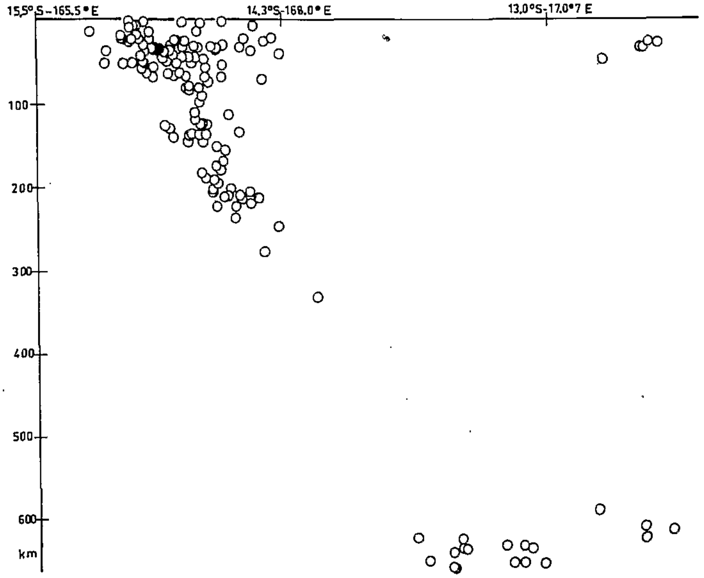

Fig. 2. Vertical cross section perpendicular to the New Hebrides arc showing earthquake distribution beneath the arc [from *Dubois*, 1971].

TABLE 1. Location Determinations for Deep Earthquakes in the New Hebrides Region

No.	Origin Time Date	Origin Time GMT	Latitude, °S	Longitude, °E	Depth, km	No. of Stations Used	Magnitude
1	Feb. 12, 1961	12h 57m 18.9s	13.18	171.60	598	27	
2	Aug. 28, 1961	17h 41m 26.6s	12.81	169.47	639	18	
3	May 11, 1962	12h 06m 42.3s	14.49	170.40	625	21	
4	Dec. 3, 1962	12h 50m 36.8s	12.91	169.22	632	22	
5	Jan. 13, 1963	13h 43m 42.1s	14.36	171.46	632	17	
6	Feb. 8, 1963	18h 18m 07.3s	12.93	170.20	626	11	
7	Mar. 14, 1964	15h 05m 54.2s	13.79	172.37	603	37	5.1
8	Jun. 26, 1964	13h 10m 31.1s	12.63	169.37	678	31	4.9
9	Jun. 30, 1964	17h 52m 35.2s	14.33	173.46	605	18	4.3
10	Sep. 17, 1964	15h 06m 13.1s	12.91	169.05	616	13	4.5
11	Jan. 21, 1965	21h 37m 27.6s	13.11	169.23	650	15	4.5
12	Jan. 25, 1965	01h 11m 53.8s	15.05	171.34	633	15	4.3
13	Jan. 30, 1965	17h 42m 11.6s	13.09	169.58	640	48	5.2
14	Jan. 30, 1965	18h 06m 21.8s	12.92	169.52	652	31	5.4
15	Feb. 3, 1965	18h 26m 05.3s	14.21	172.85	635	11	
16	Apr. 10, 1965	22h 53m 04.3s	13.41	170.28	641	52	6.2
17	Apr. 19, 1965	17h 01m 11.1s	13.66	170.30	659	10	4.9
18	Jun. 29, 1965	02h 07m 18.4s	13.83	170.62	638	11	
19	Dec. 13, 1965	16h 50m 17.5s	14.37	170.47	640	16	5.0
20	Apr. 24, 1966	03h 28m 52.0s	13.07	169.47	678	17	4.6
21	Jun. 4, 1966	08h 35m 15.7s	14.84	171.15	657	27	4.6
22	Feb. 14, 1967	05h 02m 38.7s	13.28	171.28	637	65	5.6
23	Mar. 16, 1967	17h 33m 06.9s	13.70	170.74	627	45	4.8
24	May 12, 1967	01h 59m 31.9s	13.89	169.90	621	18	4.1
25	Aug. 25, 1967	09h 09m 15.9s	14.47	170.14	631	9	4.0
26	Jan. 8, 1968	03h 17m 12.8s	13.70	171.45	631	86	5.2
27	Jan. 8, 1968	03h 56m 52.0s	13.50	171.17	656	12	4.2
28	Feb. 17, 1968	19h 46m 25.2s	13.79	172.83	625	26	4.5
29	Nov. 4, 1968	09h 07m 42.3s	14.15	171.84	628	41	5.8
30	Nov. 4, 1968	10h 36m 22.5s	14.09	171.96	606	13	4.8
31	Jan. 2, 1969	15h 47m 56.0s	12.82	169.03	639	23	4.7
32	May 30, 1969	15h 38m 53.9s	12.47	168.00	657	12	4.2
33	Oct. 15, 1969	06h 58m 21.7s	13.06	169.34	661	10	4.3
34	Jan. 12, 1970	10h 34m 37.1s	12.73	169.24	659	14	4.3
35	Mar. 1, 1970	05h 22m 29.1s	12.63	168.49	638	27	4.9
36	Mar. 2, 1970	08h 29m 16.4s	14.45	169.93	608	12	4.6
37	Apr. 22, 1972	13h 18m 20.5s	12.56	169.11	648	21	4.8
38	Oct. 1, 1965	13h 22m 28.5s	19.88	174.43	549	58	6.2
39	Jan. 28, 1966	04h 36m 45.4s	17.56	176.96	548	52	5.6
40	Nov. 18, 1970	16h 43m 14.6s	21.76	175.23	575	81	5.6

Computer solutions using the Jeffreys-Bullen travel time tables with 'anomalous' stations deleted.

Longshot nuclear explosion for the New Caledonia, Fiji, and Australian stations [see *Mitronovas and Isacks*, 1971, Table 6].

The method of three-dimensional seismic ray tracing [*Jacob*, 1970] is used to construct a quantitative structural model for the New Hebrides island arc that includes a downgoing lithosphere of high velocity, a low-velocity wedge of mantle above the inclined seismic zone, and a detached piece of lithosphere (zone of the deep earthquakes). The thickness of the slab is taken to be 70 km.

DATA AND EARTHQUAKE RELOCATION

For the relocations we have used published arrival times of *P*, *pP*, *PKP*, and *pPKP* phases at seismic stations around the world. The arrival times were taken from the Earthquakes Data Reports and the Bulletins of the International Seismological Centre. The origin times and locations used as the initial input for the relocation program were taken from the same bulletins.

The permanent stations of the ORSTOM network include PVC, LUG, LMP, and LNR in the New Hebrides, OUA in the Loyalty Islands, and NOU and KOU in New Caledonia. Only the NOU and PVC stations have three components. The *S* waves are read on the vertical component of the other stations.

All earthquakes were relocated by the computer program originally developed by *Bolt* [1960] and modified by L. R. Sykes. It is the same program used by *Mitronovas and Isacks* [1971] for their study of the Tonga arc. The computer solutions are based on distant stations only ($\Delta > 30°$); the epicenters are determined by travel times along downgoing rays through the relatively homogeneous lower mantle to distant stations and are therefore relatively accurate. The anomalous local and regional stations were deleted manually before relocating any event. Most of the *pP* data come from the United States stations to the northeast at a distance of about 85° to 95° from the epicenters. The upgoing part of these rays reflects from the earth's surface northeast of the deep seismic zone in a relatively normal mantle; their travel times are therefore not affected by the anomalous upper mantle beneath the New Hebrides arc, and hypocentral depths are relatively accurate. The results are presented in Table 1. (For a detailed description of the above relocation method see *Mitronovas and Isacks* [1971].)

P AND *S* TRAVEL TIME ANOMALIES FROM DEEP EARTHQUAKES

Table 2 presents average *P* and *S* travel time residuals (observed minus Jeffreys-Bullen) for the stations of the ORSTOM network. The *P* residuals are close to normal: slightly negative at the New Hebrides stations and positive at the New Caledonia stations. The scatter of the data can be reduced by first comparing the *P* and *S* residuals of the New Hebrides stations with those of NOU in New Caledonia for each event before averaging. Secondly, the effect of the paths' not being perpendicular to the arc can be investigated by separating the residuals in groups according to the source-to-station azimuths. Table 3 presents the residuals from the stations PVC, LUG, and LNR taken relative to NOU. The standard deviation decreases appreciably for these residuals. We have also compared the *P* and *S* residuals relative to PVC (see Table 3). The results of LUG-PVC and LMP-PVC are small relative to those of LNR-PVC, probably because the ray paths to LUG and LMP are more similar to those to PVC than to those to LNR (see Figure 1).

Table 4, listing the *P* residuals from deep earthquakes for PVC relative to NOU as a function of azimuth, shows that azimuth in this case is an important factor. The deep earthquakes are divided into four groups from northwest to southeast direction. Ray paths to PVC from the northwestern group pass closest to and through the inclined seismic zone. These paths have the largest negative residuals, about 3 sec. Ray paths from the southeasternmost group pass above the inclined seismic zone, and the residuals are small.

In a similar study for the Tonga island arc, where seismic activity is continuous to depths of about 650 km, *Mitronovas and Isacks* [1971] found that *P* travel times of the Tonga deep events are about 5 sec less at Tonga stations relative to travel times at Fiji stations. They explained the approximately 6% higher velocity paths to Tonga by the presence of a cool lithospheric slab that descends beneath the Tonga arc along the dipping seismic zone. The comparison of the magnitude of the velocity anomalies in Tonga and New Hebrides arcs suggests that the gap in seismic activity between depths of 300 and 600 km beneath the New Hebrides arc corresponds also to a gap in the descending lithospheric plate. This conclusion is also supported by evidence from seismic wave attenuation that the descending slab beneath the New Hebrides is not continuous between depths of 300 and 600 km [*Barazangi et al.*, 1973].

Table 5 shows that *P* residuals are close to normal at regional stations from the New Hebrides deep earthquakes. The negative residual of 1.4 sec at WEL may be due to the slab's descending beneath New Zealand.

VELOCITY MODELS FOR THE NEW HEBRIDES ARC

Jacob's [1970] method of three-dimensional ray tracing allows us to compute *P* residuals for several models and compare them with the observed residuals. In the models we adopt the hypothesis of a dipping lithospheric slab associated with the seismic zone beneath the New Hebrides arc, and we assume that no slab is present in the gap in seismicity between 300 and 600 km. Our structural model for the New

TABLE 2. *P* and *S* Travel Time Residuals (Observed minus Jeffreys-Bullen) for Local Stations in the New Hebrides Area from Deep Earthquakes

		P Residuals, sec			*S* Residuals, sec		
Station	Region	Mean	Standard Deviation	No. of Observations	Mean	Standard Deviation	No. of Observations
			Earthquakes with Latitudes <15°S				
PVC	New Hebrides	-0.9	1.6	29	1.7	1.5	17
LUG	New Hebrides	-0.6	1.7	17	2.0	0.8	7
LNR	New Hebrides	0.0	1.4	14	1.7	2.6	7
LMP	New Hebrides	-0.1	1.3	7			
NOU	New Caledonia	1.2	1.5	28	4.6	1.3	15
KOU	New Caledonia	1.0	1.5	19	4.1	0.3	4
OUA	Loyalty Islands	-0.5	1.1	10	3.2	0.6	4
			Earthquakes with Latitudes >15°S				
PVC	New Hebrides	0.9	0.9	3	4.6	0.7	3
LUG	New Hebrides	0.6	0.6	3	6.9		2
NOU	New Caledonia	0.9	0.3	3	3.0	0.8	3

TABLE 3. *P* and *S* Travel Time Residuals (Observed minus Jeffreys-Bullen) for Local Stations in the New Hebrides Area from Deep Earthquakes

	P Residuals, sec			*S* Residuals, sec		
Stations	Mean	Standard Deviation	No. of Observations	Mean	Standard Deviation	No. of Observations
			Residuals Relative to NOU			
PVC-NOU	-2.0	1.0	26	-2.8	1.2	10
LUG-NOU	-1.7	0.8	10	-2.4	1.9	4
LNR-NOU	-1.0	1.2	10			
			Residuals Relative to PVC			
LUG-PVC	0.0	1.5	11			
LNR-PVC	1.2	0.7	9			
LMP-PVC	0.6	0.9	5			

Hebrides island arc consists of an inclined lithospheric slab of high-velocity material that reaches a depth of 300 km, a wedge of low-velocity material above the dipping slab, and a detached, horizontal piece of lithosphere at a depth of 600 km and located north of 15°S. We have not included the effect of possible anomalies associated with the deep earthquakes located south of 15°S.

TABLE 4. *P* Travel Time Residuals (Observed minus Jeffreys-Bullen) for PVC Relative to NOU (PVC-NOU) from Deep Earthquakes as a Function of Azimuths

	P Residuals, sec		
Region	Mean	Standard Deviation	No. of Observations
12.0°S to 13.3°S 168.0°E to 170.0°E	-2.9	0.7	7
13.8°S to 15.0°S 169.8°E to 171.0°E	-2.5	0.5	5
13.0°S to 15.0°S 170.2°E to 172.2°E	-1.5	0.4	8
13.7°S to 15.0°S 172.3°E to 174.0°E	-0.6	0.3	4

The hypocenters of all the earthquakes that occurred in the New Hebrides area from 1961 to 1971 and that were reported by NOAA are used to draw isodepth contours. Table 6 shows the different parameters of the five velocity models considered. The velocity distribution of *Herrin et al.* [1968] was used to compute the theoretical travel times and distances of different rays emerging from the deep hypocenters. To compare the computed and observed travel times, we corrected our results to compare with the tables of Herrin et al. Also we slightly modified the computer program of

TABLE 5. Average P Travel Time Residuals from Deep Earthquakes in the New Hebrides Region for Regional Stations

Station	Region	Location	Average Distance, deg	Average Azimuth, deg	P Residuals, sec Mean	Standard Deviation	No. of Observations
BRS	Australia	27.39°S, 152.78°E	20	230	0.4	0.6	17
CTA	Australia	20.09°S, 146.25°E	25	250	-0.3	0.5	21
RIV	Australia	33.83°S, 151.16°E	28	220	0.1	0.6	10
CAN	Australia	35.32°S, 148.99°E	30	220	0.1	0.5	21
ADE	Australia	34.97°S, 138.71°E	35	230	0.6	0.4	18
KRP	New Zealand	37.92°S, 175.53°E	25	170	-0.3	0.7	17
WEL	New Zealand	41.28°S, 174.77°E	28	170	-1.4	0.6	9
ROX	New Zealand	45.48°S, 169.32°E	30	180	-0.8	0.3	8
VUN	Fiji Islands	18.05°S, 178.46°E	9	120	-0.5	0.5	6
HNR	Solomon Islands	9.45°S, 159.95°E	11	290	0.2	1.2	19
AFI	Western Samoa	13.91°S, 171.78°W	15	90	-0.9	1.2	16

Klaus Jacob to include the detached piece of lithosphere.

We separate the P travel time residuals of the deep earthquakes into different groups according to the azimuths from the earthquakes to the recording stations. The groups are as follows.

Group 1. An assumed hypocenter is located at 13.0°S, 169.5°E at a depth of 650 km. Two directions of propagation are considered: an azimuth of 220° to LUG and an azimuth of 200° that passes between the stations LNR, LMP, and PVC.

Group 2. An assumed hypocenter is located at 13.8°S, 170.9°E at a depth of 630 km with two directions of propagation (azimuths of 245° and 220°).

Group 3. An assumed hypocenter is located at 14.4°S, 171.9°E at a depth of 630 km with two directions of propagation (azimuths of 240° and 260°).

Group 4. An assumed hypocenter is located at 13.8°S, 173.0°E at a depth of 630 km with two directions of propagation (azimuths of 240° and 255°).

TABLE 6. Model Parameters [see *Jacob*, 1970, Figure 2]

Model	a, km	b, km	c_0, km	d, km	δv_{AB} 0 to 300 km	δv_{AB} 600 to 670 km	δv_{AC}
NEH 001	20	50	170	150	4	0	-6
NEH 002	20	50	170	150	6	0	-6
NEH 003	20	50	170	150	6	6	-6
NEH 004	20	50	170	150	6	6	-4
NEH 005	20	50	250	200	6	6	-4

$a + b$, horizontal thickness of dipping plate perpendicular to island arc; c_0, width of low-velocity wedge at the earth's surface perpendicular to island arc; d, depth of low-velocity wedge; δv_{AB}, P velocity deviation in percentage in the slab from tables of Herrin et al. (in the slab and in the detached part of the slab); δv_{AC}, P velocity deviation in percentage in the low-velocity wedge from tables of Herrin et al.

Figure 3 shows the corresponding travel time curves, calculated by using the ray tracing program for the assumed hypocenter of group 1. For a 200° azimuth it is clear that there is no influence of the high-velocity dipping slab at epicentral distances less than about 4°. The ray paths penetrate the high-velocity slab at a depth of 250 km and emerge at PVC with an angle of incidence of about 18°. This explains the size of the P travel time residual obtained at PVC relative to NOU for this group (Table 4). In the case of LUG, the direction of propagation is nearly perpendicular to the boundaries of the slab (azimuth of 220°). The ray paths penetrate the high-velocity slab at a depth of about 200 km and emerge at LUG with an

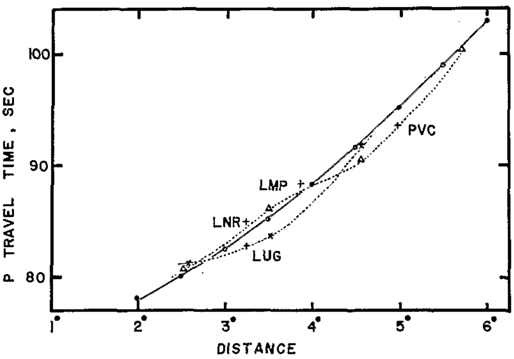

Fig. 3. Computed travel times (dotted lines) using the ray tracing program for model NEH 005 (Table 6). The solid line with open circles gives the travel times of *Herrin et al.* [1968]. The observed travel times at the New Hebrides stations are plotted as plus signs. The dotted line through triangles is obtained for an azimuth of 200° and through crosses for an azimuth of 220°.

angle of incidence of about 20°. The computations showed that a velocity inside the dipping slab and inside the deep detached slab that is 6% higher than normal provides a suitable residual pattern that best explains our observations (model NEH 005 in Table 6). The data, of course, do not permit a unique solution, and velocity models different from those considered in Table 6 could possibly explain our observations. However, we think that model NEH 005 is the simplest model that not only explains the observed velocity anomalies but also is supported by the attenuation structure beneath the New Hebrides arc [*Barazangi et al.*, 1973].

CONCLUSIONS

The travel time residuals for the New Hebrides stations produced by the nearby deep earthquakes suggest that the gap in seismic activity between depths of 300 and 600 km beneath the New Hebrides arc corresponds to a similar gap in the descending lithospheric slab. This conclusion is based on the observation that travel times of *P* waves from the deep earthquakes traveling through or just beneath the dipping New Hebrides seismic zone are about 3 sec less than travel times of *P* waves that travel through the aseismic and relatively normal mantle beneath the New Caledonia island to the west of the New Hebrides arc. A similar study in the Tonga island arc, where the dipping seismic zone is continuous to a depth of about 650 km, revealed a 5-sec difference in the travel times of *P* waves recorded at Tonga relative to those recorded at Fiji [*Mitronovas and Isacks*, 1971]. The above conclusion is also supported by evidence from seismic wave attenuation [*Barazangi et al.*, 1973].

A velocity model for the upper mantle beneath the New Hebrides arc with 6% higher velocity descending slab associated with the intermediate-depth earthquake zone, a 6% higher velocity detached piece of lithosphere at a 600-km depth, and a 4% lower velocity wedge above the inclined seismic zone explains the *P* residuals pattern observed along the New Hebrides arc.

The horizontal extent of the New Hebrides deep earthquakes suggests that the detached slab descending into the upper mantle is unable to penetrate the presumably worldwide boundary at a depth of about 650 km. Thus the lower boundary of the asthenosphere may extend to a 650-km depth in the New Hebrides region.

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