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SEISMIC REFRACTION STUDIES IN THE NEW HEBRIDES AND TONGA AREA

jacques jacques

B PONTOISE, G V LATHAM, J DANIEL, J DUPONT AND A B IBRAHIM

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ABSTRACT

Seismic refraction surveys have been conducted over the convergent plate boundaries of the New Hebrides and Tonga, in a joint programme by the Office de la Recherche Scientifique et Technique Outre-Mer (Centre de Nouméa) and the University of Texas (Institute of Marine Science). From 24 profiles taken during the EVA II, EVA IV and EVA VII cruises, it appears that

1. In spite of overall similarities, differences in the shallow structure of the two arcs can be seen. In the New Hebrides the low-velocity layers are much thicker than in Tonga, especially in the lower part of the inner slope of the trench. This difference in thickness can be correlated with the differences in thickness of the transition and oceanic layers of the crust of the dipping plate.
2. Refraction leaves uncertainty as to the structure at depth, particularly as to the joining of the arc and the back-arc basins. The existence of 7.6–7.7 km/s velocity layers complicates the interpretation in classical terms of crust and mantle. One possible interpretation of the evolution of the crust under the island arcs could be a thinning-down in time.

INTRODUCTION

Since 1976 a joint research programme has been operating in the Southwest Pacific, with the participation of the Office de la Recherche Scientifique et Technique Outre-Mer (Centre ORSTOM de Nouméa), Cornell University, the University of Texas (Marine Science Institute) and the National Ocean Survey of NOAA; the naval facilities used were provided by the Centre National pour l'Exploitation des Océans. Part of this programme involved seismic-refraction measurements across the convergent plate boundaries of the New Hebrides and Tonga (Fig. 1).

Together the two arcs form a double zone of convergence with to the west a dip eastwards and to the east a dip westwards under the Tonga arc. On the edge of the Australo-Indian plate, at the level of the area under study, lies a marginal basin, generally called the North Loyalty Plateau or Basin. Its age was determined from core samples JOIDES 286 (Andrews *et al.* 1975) and confirmed by the existence of magnetic anomalies (Lapouille 1978) as being Middle Eocene. The Pacific plate, which dips under the Tonga arc, is covered by an oceanic crust dating from Early Cretaceous (Burns *et al.* 1973). The two arcs also differ in age: it has been estimated that in the New Hebrides subduction began, in the present position, 5 m.y. ago (Carney and Macfarlane 1977), but in Tonga 45 m.y. ago (Gill 1976).

Earlier refraction measurements were taken during the expeditions *Capricorn* (1952) and *Nova* (1966-1967) of the Scripps Institution, the results of which were detailed by Raitt *et al.* (1955), Raitt (1956), and Shor *et al.* (1971). The measurements, taken during large-scale exploratory expeditions, dealt with greatly varying structures. It was therefore of interest to study the structures in more detail.

FIELD OBSERVATIONS AND DATA ANALYSIS

Twenty-four seismic refraction profiles were taken during the cruises EVA II, EVA IV and EVA VII from 1976 to 1978, 18 in the New Hebrides (Fig. 2) and six in the Tonga area (Fig. 3). The profiles were planned to parallel the structural units in such a way as to provide two cross sections of the New Hebrides trench system and one of the Tonga-arc trench system.

Three different sources were used: airguns (5- and 15-litre capacity), explosives, and Flexichoc. With the airguns, distances were obtained of 15–20 km (5-litre capacity airgun) and 40 km (15-litre capacity airgun). The

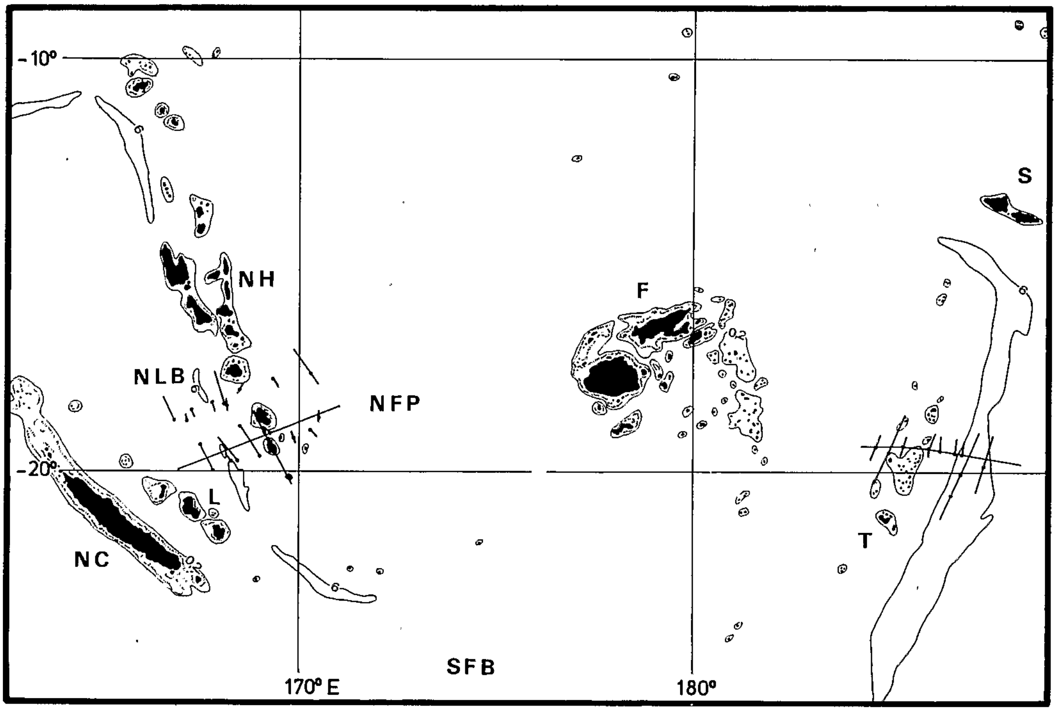


Figure 1. Location of refraction profiles. Bathymetric contours of 0.2 and 6 km. NC, New Caledonia; NLB, North Loyalty Basin; NH, New Hebrides; NFP, North Fiji Plateau; SFB, South Fiji Basin; F, Fiji; T, Tonga; S, Samoa.

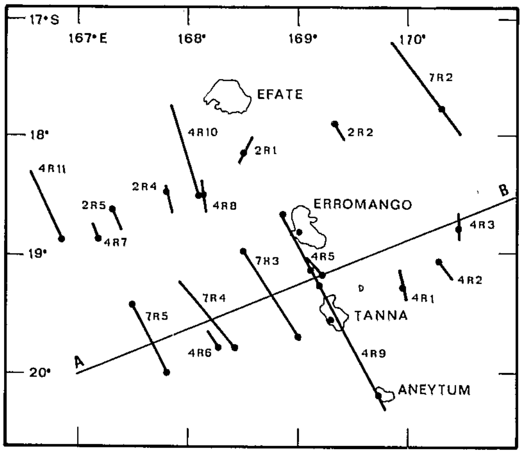


Figure 2. Location of the profiles across the New Hebrides subduction zone. All the profiles are projected on AB cross section (Fig. 5).

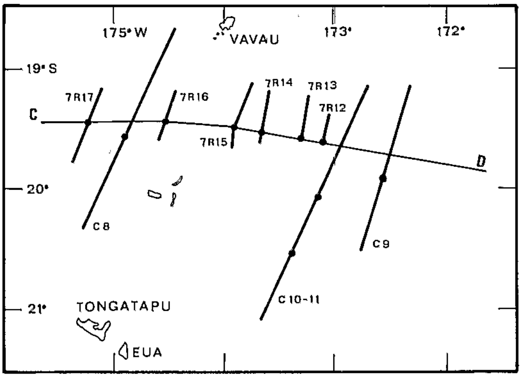


Figure 3. Location of the profiles across the Tonga subduction zone. All the profiles are projected on CD cross section (Fig. 6). C8, C9 and C10-11 profiles were shot on the Scripps Institution 1952 *Capricorn* Expedition.

Flexichoc, a high resolution implosion seismic source, developed by the Institut Français du Pétrole, is perfectly adapted to seismic reflection because of its bubble-effect free signal; however, the technique was found to be inefficient at the recording stations used and its range was only 8–9 km. For the explosives (gomme F 15), the charges varied between 1 kg and 200 kg according to the distance from the station. Calculations were made using the empirical experimental formula:

$$d = 22.1 \sqrt{P}$$

where P is the charge in kg and d the distance in km.

The stations used were the Ocean Bottom Seismographs (OBS) built by the University of Texas (Institute of Marine Science) and described by Latham *et al.* (1978) and Ibrahim and Latham (1978).

Four types of profiles were taken (Fig. 4):

Type (1): single profile, which has the advantage of being done quickly and with only one OBS. However, it gives no indication of the dip of the layers.

Type (2): split profile, which takes longer to do, but has the advantage of giving true velocities and of giving the dip of the layers assuming uniform velocity layers with constant dip.

Type (3): reversed profile, which is done with two OBS. It gives true velocities and the dip for the deep layers. If the velocity in the shallow layers varies from one OBS to another, it will be defined for plane horizontal layers only.

Type (4): compound profile, which gives the inclined shallow structure under each OBS.

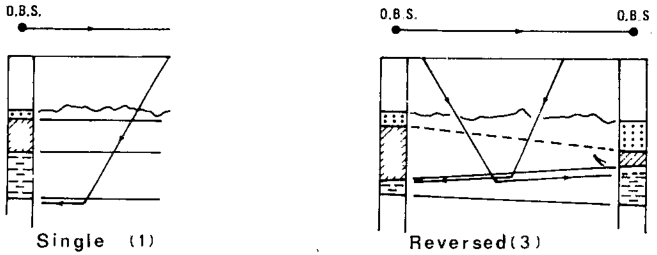
The characteristics of the different profiles and the results obtained are shown in Table I.

Data analysis techniques used were the classic ones: the sequences were played back on paper and collated according to a time fixed by the firing time, and for a distance either from the navigation if that was precise enough (radar and bearing) or from theoretical hodochrone of sound propagation in the water. The arrival times of correlatable phases were corrected for topographic effects by bringing the penetration points of the rays to the same depth as the OBS, using the classic formulae of plateau correction.

The arrival times observed were then linked by segments, the parameters of which were obtained by fitting to least squares. A model assuming uniform velocity in each layer was then constructed in accordance with the observations. In fact, the hodochrones obtained almost never had the curve characteristics of the hodochrones corresponding to layers with velocity gradient.

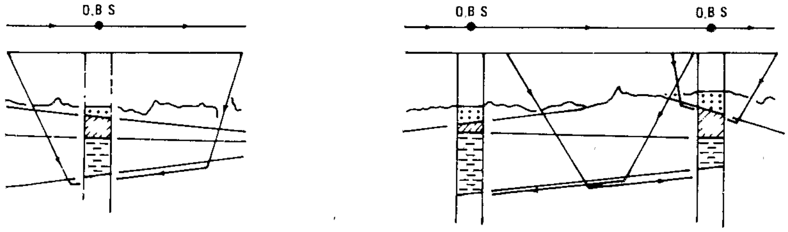
RESULTS AND DISCUSSION

The results obtained are shown on the two cross sections AB and CD (Figs. 2, 3, 5, 6). In fact, although in the New Hebrides the profiles were done on two cross sections, the results were plotted on a single profile. For ease of comparison, the Tonga cross section was reversed (east on the left). Below, the different



Single (1)

Reversed(3)



Split (2)

Compound (4)

Figure 4. Combinations of linear refraction profiles.

TABLE 1

Seismic Refraction Profiles

Note. For each group of refractors, V = apparent velocities, T = thickness, t = intercept; velocities marked * are defined either from second arrivals or on the corresponding multiple, those marked † are assumed.

					Sediment (1)				Transition (2)			Oceanic (3)			Mantle (4)	
Profile No. and Type ( )	Position of Recording Station	Source	Water Depth km	Az.	L km	V km/s	T km	t s	V km/s	T km	t s	V km/s	T km	t s	V km/s	T km
					NEW HEBRIDES (EFATE–ERROMANGO)											
2R1(2)	18°07.8 S	AG 5	0.81		14	1.8*	0.03	0.30	5.5		1.84					
	168°31.0 E					2.4	0.18	0.47								
						2.6	1.09	0.54								
						4.3	1.29	1.39								
2R2(1)	18°02.0 S	AG 5	2.61		13	2.2*	0.12	1.28				6.0		2.71		
	169°26.0 E					2.7	0.43	1.52								
						3.5	1.31	1.87								
2R4(1)	18°27.0 S	AG 5	4.32		14	1.9*	0.02	1.77	4.7		3.97					
	167°50.0 E					2.1*	0.60	1.98								
						4.1	3.00	3.20								
2R5(1)	18°36.0 S	AG 5	4.83		13	2.0*	0.30	2.08	5.4	0.48	4.37					
	167°20.8 E					2.4*	1.35	2.72	5.6		4.40					
4R7(2)	18°51.8 S	Flex.	4.31		12	2.0*	0.20	1.90	5.3		3.37					
	167°14.0 E					3.6	1.08	2.78								
4R8(2)	18°28.7 S	AG 5	2.80	N	17	2.9	0.60	1.59	5.2		2.62					
	168°09.8 E					4.1	1.60	2.04								
				S	18	3.2	1.39	1.67	5.3		2.52					
4R10(1)	18°30.8 S	Dyn.	2.86		100				5.1	3.91	2.95	6.1	8.06	3.91	8.1	6.05
	168°08.0 E															
4R11(1)	18°51.9 S	Dyn.	4.16		75	4	2.73	2.82				7.0	7.76	9.1	8.1	5.
	166°53.4 E															
7R2(2)	17°46.0 S	Dyn.	2.56	N	83	2.0*	0.55	1.13	5.3	0.85	2.30	6.7	5.75	2.57	7.81	3.58
	170°20.0 E	AG+15				4.2*	0.50	2.05								
				S	30	2.0*	0.55	1.13	5.2	1.55	2.30	6.3		2.70		
						3.9*	0.43	2.05								

NEW HEBRIDES (ERROMANGO–TANNA)

4R1(2)	19°17.0 S	AG 5	2.39	N	20	2.5	0.73	1.23	5.9		3.13					
	169°59.0 E					3.4	2.27	1.77								
				S	16	2.1*	0.33	1.10	5.9		3.13					
						3.6	3.00	1.65								
4R2(1)	19°05.5 S	IG 5	2.12		17	1.8*	0.32	0.72	5.5		2.93					
	170°17.0 E					2.4*	0.44	1.23								
						3.1	1.96	1.64								
4R3(2)	18°47.0 S	AG 5	3.01	N	18	2.0*	0.48	1.21	5.3	3.64?	2.89				7.6?	4.00?
	170°30.0 E					3.2	1.22	2.05								
				S	6	2.0	1.48	1.26	5.0		3.1					
4R5(1)	19°00.0 S	AG 5	0.97		18	2.0	0.60	0.44	5.0		2.28					
	169°10.0 E					3.4	2.66	1.06								
4R6(2)	19°47.5 S	AG 5	5.12	N	12	2.1*	0.21	2.26								
	168°18.6 E					2.8	0.66	2.96								
						4.1		3.60								
					18	2.1*	0.27	2.30								
						2.6	1.00	2.85								
						3.8		3.83								
4R9	(see Fig. 1)	Dyn.			170				5.0	4.11	2.28	6.6	18.5	3.48	7.9	7.08
7R3(4)	(N)18°57.2 S	Dyn. +	1.00	N	10	2.2*	0.2	0.52								
	168°30.0 E	AG 15				4.5		0.80								
				S	95	2.4*	0.2	0.52	5.3*	0.90	0.93	6.2	2.18			
						4.9	1.50	0.70	5.6	5.60	1.08					
	(S)19°42.0 S	Dyn. +	1.00	N	95	2.1	1.25	0.46	5.5	1.95	2.01	6.9	8.15	3.45	7.7	4.40
	169°03.0 E	AG 15				4.5*	0.62	1.65	5.8	3.82	2.30					
						4.9*	0.86	1.80								
				S	30	2.1*	1.22	0.46	5.2	1.30	2.01					
						4.4	1.12	1.75	5.6		2.60					
						4.7*	0.55	1.80								
7R4(1)	19°47.0 S	Dyn. +	5.30	N	82	2.5*	0.35	2.90				7.2	6.70	7.12	8.1	8.47
	168°27.0 E	AG 15				3.7*	0.72	3.54								
						4.7	8.75	3.96								
7R5(3)	(N)19°24.8 S	Dyn.	4.80	S	72	2.0	0.55	2.08	5.2	1.50	3.69	7.0	5.5	4.88	8.3	6.03
	167°30.9 E					3.7*	0.65	3.37	5.9	3.35	4.05					
	(S)19°59.5 S	Dyn.	4.50	N	70	2.8	0.54	2.54	5.4	2.08	3.75	7.0	7.63	4.46	8.3	5.81
	167°50.0 E					4.2	1.80	3.09								

TABLE 1 *(Contd.)*

						Sediment (1)			Transition (2)			Oceanic (3)			Mantle (4)	
Profile No. and Type ( )	Position of Recording Station	Source	Water Depth km	Az.	L km	V km/s	T km	t s	V km/s	T km	t s	V km/s	T km	t s	V km/s	T km
						TONGA										
7R12	19°37.3 S	AG 15	6.55		27	2.54	0.76	3.52	4.17	2.55	4.92					
	173°08.8 W								4.82	5.7						
7R13	19°35.9 S	AG 15	4.91		38	2.43	0.91	2.56	4.74	1.30	3.75	7.04		5.26		
	173°21.0 W								5.71	4.02	4.20					
7R14	19°35.2 S	AG 15	3.65		53	1.99	0.3	1.60	6.0	1.20	3.20	6.6	7.39	4.13		
	173°41.8 W					2.68	0.7	2.22				7.6		5.29		
						3.84	1.74	2.87								
7R15	19°27.8 S	AG 15	2.01	S	15	2.87	1.25		4.39	1.28	2.58					
	173°54.9 W					3.38	0.99		5.99		3.20					
			2.01	N	46	2.1	0.72	0.90	4.55	1.51	2.58	6.72	2.84	3.35		
						2.76	1.23	1.57	6.33	0.88	3.21	7.5		3.84		
7R16	19°23.7 S	AG 15	0.51	S	17	2 †	0.35	0.25	5.01		1.51					
	174°31.1 W					2.87	0.83	0.54								
						3.87	1.19	1.00								
			0.51	N	27	2 †	0.39	0.25	4.28	2.33	1.50	7.20		3.20		
						2.67	0.79	0.54	5.97	2.61	2.52					
						3.53	1.19	1.01								
7R17	19°25.5 S	AG 15	2.19	S	50	2.15†	1.46		5.83	1.88	2.68	6.9	2.57	3.08		
	175°12.9 W											7.6		3.50		
			2.19	N	35	2.15†	1.24		5.20	1.73	2.45	6.2	1.04	2.86		
												6.8	1.20	3.08		

structural units are examined by comparing the results obtained on each of the arcs.

Outer oceanic basins (dipping plates)

Figure 7 presents the results for the New Hebrides on profiles 4R 7, 4R 11 and 7R 5, and for Tonga on profile C9 (*Capricorn* Expedition); also included is the structure of the standard oceanic crust of Ludwig *et al.* (1970). While the structure of the oceanic crust of the Pacific Basin near Tonga (T) is very similar to that of the standard oceanic crust (O), the crust of the North Loyalty Basin (NH) is considerably thicker, as the depth of the Moho there, in relation to sea level, can exceed 16 km (as against 12 km for the standard crust).

Comparing crust thickness in the North Loyalty Basin with that in the marginal basins of the West Pacific, it can be seen that some of the basins have quite thin crust, for example (as shown in Fig. 8) the Parece Vela Basin (PV) and the Philippine Basin (PH B) (Murauchi *et al.* 1968), in which the crust is thinner than the standard oceanic crust (O) and the depth of the Moho less than 10 km. In other basins, such as the South Fiji Basin (SFB), crust thickness exceeds 15 km. Further, the structure of the North Loyalty Basin crust is very similar to that of the South Fiji Basin, which supports the suggestion of Lapouille (1978) that there is just one basin. Another feature to be noted is that whereas the thickness of crust is greater near the New Hebrides than at Tonga (Fig. 7), the reverse is true for the lithosphere calculated by Dubois *et al.* (1977) from bulge parameters, i.e., 24 km in the North Loyalty Basin, but 34 km in the Pacific Basin near the Tonga Trench.

Inner wall of the trench

In the inner wall of each trench (Figs. 5 and 6) is a layer with velocity ranging from 4.7 to 5.3 km/s. The maximum thickness of this layer in the New Hebrides is 9 km, but only 3 km in Tonga. The difference in thickness parallels that of the two transition layers of the oceanic crust of the dipping plates: in the North Loyalty Basin the 5.3 km/s velocity layer is about 3 km thick, whereas the equivalent layer (5.1 km/s velocity) of the Pacific crust is only 0.5 km thick. This lends support to the hypothesis of accretion of material from the dipping plate on the inner wall of the trench, to a varying degree depending on the crustal structure.

The arcs themselves

In each arc there is a conspicuous rise in the deep layers (Figs. 5 and 6), 75 km from the trench axis in the case of the New Hebrides arc and 100 km away in Tonga. It could be said that the rise is in each case the limit of the arc, and it seems that the two morphologies are different. In the New Hebrides the rise can be seen even in the uppermost layers (4.9 km/s velocity); near Erromango there is even a frontal horst (the fore-horst of Dugas *et al.* 1977). In contrast, the uppermost layers in the Tonga arc are relatively regular; in particular, the rise of the basement is found well before the top of the arc (Fig. 6). It would therefore seem that in the New Hebrides vertical movements are more active.

The structure is also different under the arcs. Under the New Hebrides arc is an extensive layer, more than 15 km thick, of 6.6 km/s velocity. Under the Tonga arc the same layer is nowhere thicker than 10 km. In the New Hebrides on profiles 4R 9 and 4R 10 the velocity reaches 7.9 (4R 9) or 8 km/s (4R 10) under this layer. In Tonga the velocities are only 7.6 to 7.7 km/s. Reinterpreting the refraction measurements of the *Capricorn* Expedition (Raitt 1956) and taking into account gravimetric measurements, Talwani *et al.* (1961) evaluated the 7.6 km/s layer as having a thickness of 23 km, under which is found a 'normal' mantle. Our measurements did not reach the mantle, but it should be noted that all the profiles were shot with an airgun and therefore probably lacked power. According to this model the crust would be 36 km thick under the Tonga arc but 26 km, only, under the New Hebrides arc. As we may not completely exclude, from under the New Hebrides arc, the existence of a greater than 6.6 km/s layer (this layer could have been missed because of a velocity gradient), the two crustal structures could be comparable, the older arc (Tonga) having a thicker crust than the younger one (New Hebrides).

However, the existence of low velocities in the uppermost part of the mantle under the

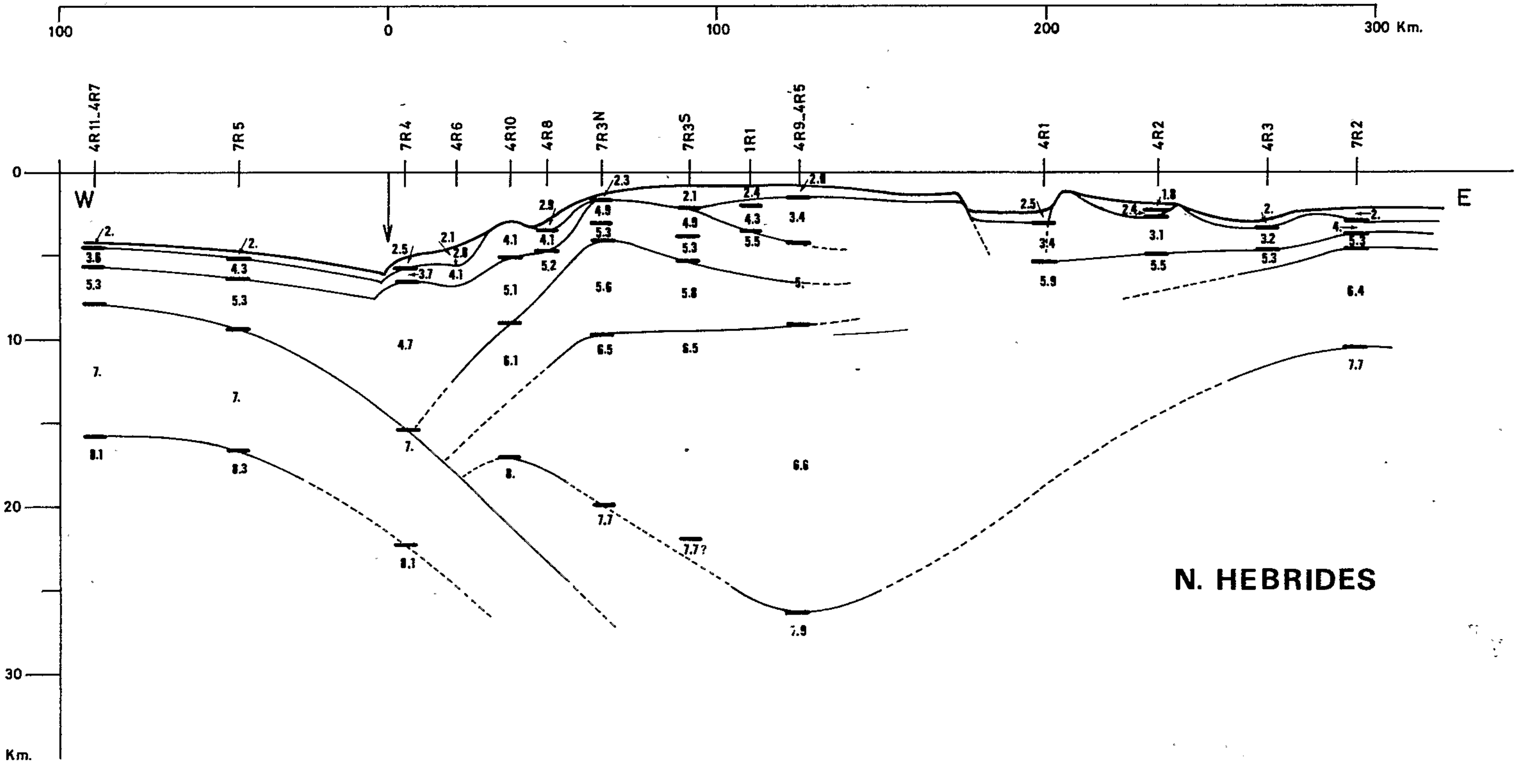


Figure 5. Structure section AB across the New Hebrides subduction zone.

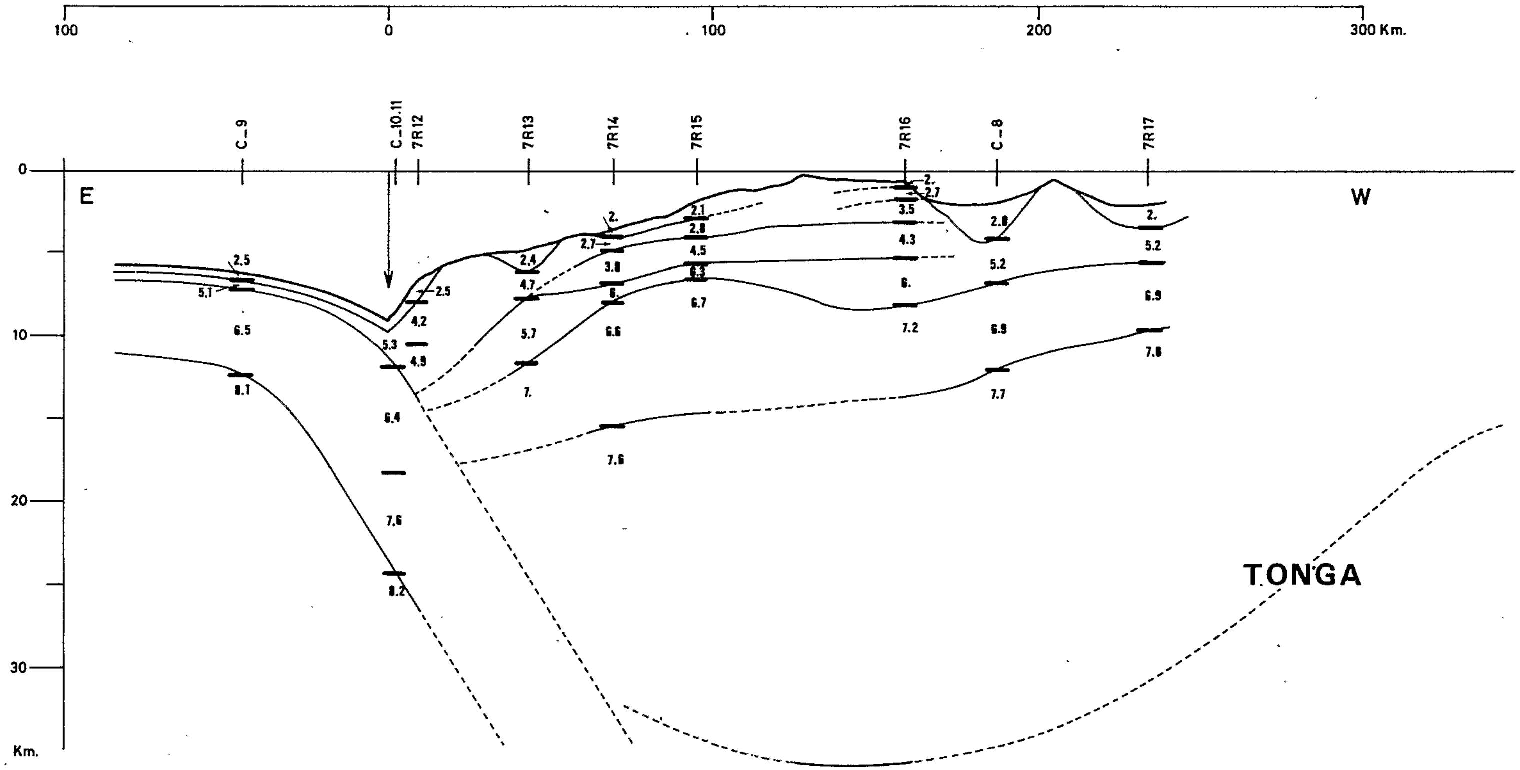


Figure 6. Structure section DC across the Tonga subduction zone.

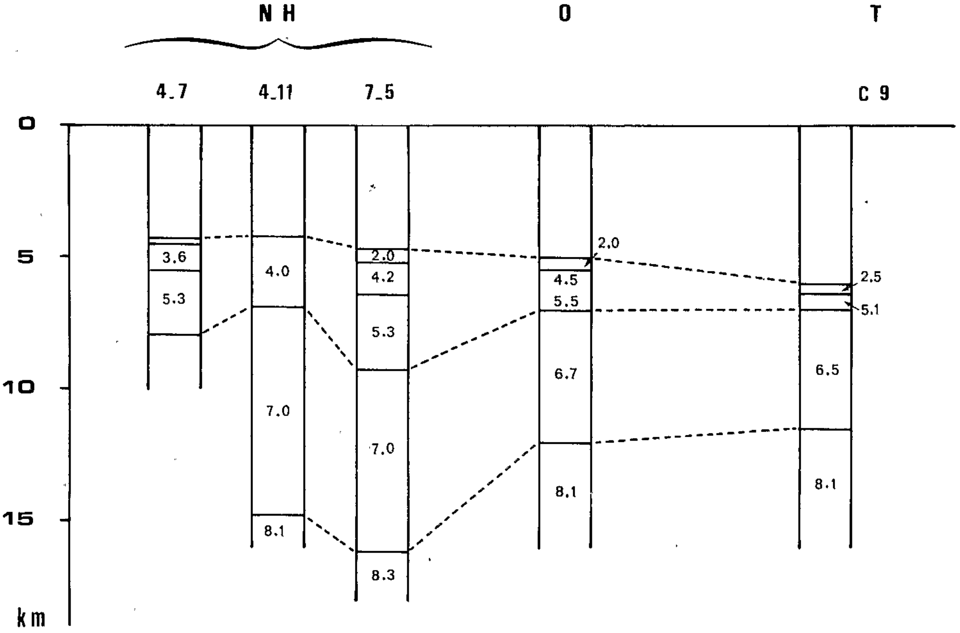


Figure 7. Structure sections of the crust of the dipping plate on the North Loyalty Basin (NH) and Pacific Basin (T) compared with standard oceanic crust (O) (from Ludwig *et al.* 1970).

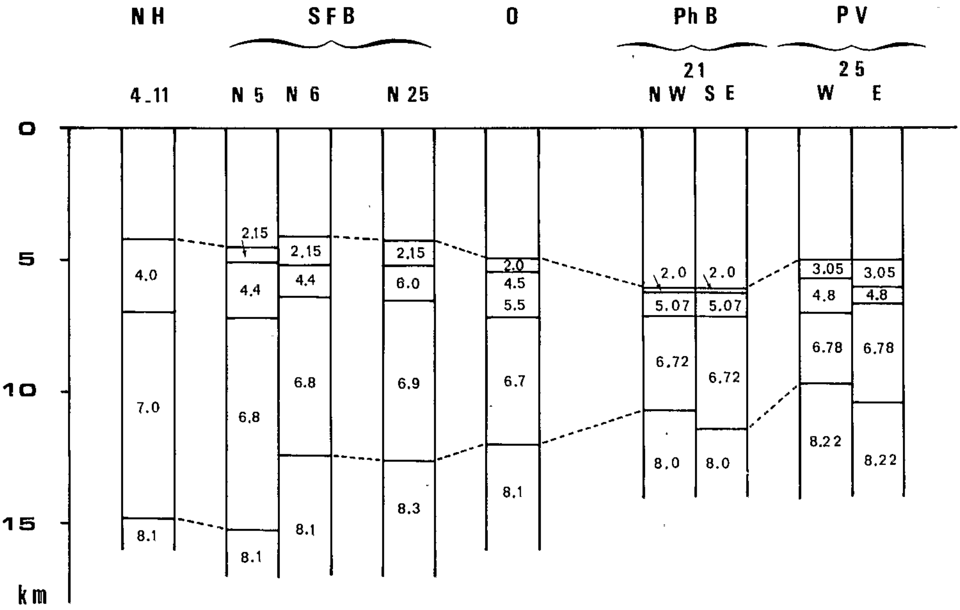


Figure 8. Structure sections of the crust of marginal basins compared with standard oceanic crust. NH, North Loyalty Basin on the dipping plate of the New Hebrides subduction zone; SFB, South Fiji Basin (Shor *et al.* 1971); O, standard oceanic crust (Ludwig *et al.* 1970); Ph B, Philippine Basin; PV, Parece Vela Basin (from Murauchi *et al.* 1968).

island arcs as well as under oceanic ridges is well known. Uyeda (1974) suggests that low velocity 'may be a characteristic of the mantle under island arc volcanic zones'. The 7.6 km/s layer under the Tonga arc could therefore be considered as uppermost mantle. The observed gravity anomaly should then be explained by a density variation with respect to the velocity-density curve of Ludwig *et al.* (1970). In this case, the crusts of the New Hebrides and Tonga arcs would be quite different: the crust of the older arc (Tonga) would be thinner (16 km) than that (26 km) of the younger one (New Hebrides), and the uppermost mantle velocity lower at Tonga (7.6 km/s) than in the New Hebrides (7.9 to 8 km/s).

Another problem is the structure of the crust in the troughs at the rear of the New Hebrides arc. These troughs were considered either as initial stages of marginal basins (where one could expect to find a much thinner crust than under the arc itself) or as extensional troughs (Dubois *et al.* 1975) associated in some way with intermediate and deep seismicity.

Seismic refraction gives no evidence of oceanic crust under the troughs (profile 4R 1, Fig. 5), and the structure of the upper layers is quite comparable to that on the arc. Furthermore, the observed gravity anomaly (J Y Collot, personal communication) leads to the supposition of a progressive joining between the arc (profile 4R 9) and the North Fiji Plateau (profile 7R 2). The possible existence of a 7.6 km/s layer above the Moho under the arc poses the problem of a joining, at the mantle level, with the North Fiji Plateau, where low-velocity uppermost mantle (7.6 km/s), characteristic of mid-oceanic ridges, can be observed.

CONCLUSION

The results obtained from seismic refraction on the New Hebrides and Tonga island arcs show that:

1. Although there are broad similarities in the two arcs, differences can be seen in the shallow structure. In the New Hebrides arc low-velocity layers are much thicker than in the Tonga arc, especially in the lower part of the inner slope of the trench. Further, differences in thickness can be correlated with differences in thickness of the transition and oceanic layers of the crust of the dipping plate.
2. Refraction leaves uncertainty as to the structure at depth, particularly as to the joining of the arc and the back-arc basins (North Fiji Plateau and the Lau Basin). The existence of 7.6–7.7 km/s velocity layers complicates the interpretation in classical terms of crust and mantle. One possible interpretation of the evolution of the crust under the island arcs could be a thinning-down in time.

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B Pontoise, J Daniel, J Dupont
ORSTOM
Centre de Nouméa
B.P. A5
Nouméa, Nouvelle-Calédonie

G V. Latham, A B Ibrahim
Marine Science Institute
University of Texas, U.S.A.