Earth and Planetary Science Letters, 51 (1980) 171–180
Elsevier Scientific Publishing Company, Amsterdam – Printed in The Netherlands

[2]

ANOMALOUS CRUSTAL STRUCTURES IN OCEAN BASINS: CONTINENTAL FRAGMENTS AND OCEANIC PLATEAUS

R.L. CARLSON

Department of Geophysics and Geodynamics Research Program, Texas A & M University, College Station, TX 77843 (U.S.A.)

N.I. CHRISTENSEN

Department of Geological Sciences and Graduate Program in Geophysics, University of Washington, Seattle, WA 98195 (U.S.A.)

R.P. MOORE

Department of Geophysics, Texas A & M University, College Station, TX 77843 (U.S.A.)

Received January 28, 1980
Revised version received July 21, 1980

Plateau-like features in ocean basins exhibit crustal structures which differ markedly from the relatively simple, three-layer model which applies to most of the oceanic crust. While some plateaus are known or thought to be fragments of continental crust (e.g. Rockall Bank, Lord Howe Rise), others appear to be of oceanic origin (e.g. Shatsky Rise, Broken Ridge), and their seismic structures, though variable, are significantly different. Continental fragments are similar in structure to continental shield areas: Depth to Moho is typically about 30 km, and the lower crust consists of a 6.8–7.0 km/s layer, 14–18 km thick, overlain by a 5.8–6.4 km/s layer of variable thickness, while velocity structures are variable at upper crustal levels. By contrast, the Moho apparently occurs at shallower levels beneath oceanic plateaus, which are characterized by the presence of a 7.3–7.6 km/s layer, 6–15 km thick at the base of the crust. This basal layer is commonly overlain by units having velocities typical of oceanic layers 2 and 3. Refractors having velocities which correspond to layer 3 tend to occur at deeper levels in continental fragments than they do beneath oceanic plateaus.

That high-velocity basal layers have been detected at the base of normal oceanic crust and in some ophiolites suggests that oceanic plateaus are truly marine in origin. Upper and middle crustal levels probably consist of basaltic and gabbroic rocks, respectively. The nature of the basal layer is difficult to assess. Olivine gabbro, mafic garnet granulite, and epidote amphibolite all exhibit velocities in the appropriate ranges, as does a mixture of mafic and ultramafic lithologies. Partially serpentinized peridotite cannot be ruled out on the basis of shear and compressional wave velocities alone.

1. Introduction

Since Raitt [1] proposed his now-classic three-layer model for oceanic crustal structure, subsequent investigators have confirmed the remarkable uniformity of the oceanic crust with both layer models [2] and more sophisticated gradient models [3] and have shown that of the variations observed, many are systematic and related to aging of the lithosphere. Anomalous regions do exist, however: mid-ocean ridges and hot spots are well-known examples, and the numerous oceanic platforms such as Lord Howe Rise and Manihiki Plateau comprise yet another class of features having anomalous crustal structures.

These oceanic platforms are broad, high-standing, aseismic features, which are usually capped by thick accumulations of calcareous sediment. On the basis of

Texas A & M University Geodynamics Research Program Contribution 7.

their suspected origins they may be divided into two categories, those which are known or thought to be continental fragments, and those which originate in the ocean basins. The name "oceanic plateaus" generally includes both types of features. For convenience, we have chosen to apply the term "oceanic plateaus" exclusively to features of oceanic origin, thus restricting the usage of the general term.

Though the origins of continental fragments are self-evident, the processes which give rise to oceanic plateaus in an otherwise uniform oceanic crust are unknown. Hussong et al. [4] have suggested that the crustal structures beneath Ontong-Java, Manihiki, and Shatsky may be regarded as expanded sections of normal ocean crust. If this conclusion is correct, oceanic plateaus should be distinguishable from continental fragments on the basis of seismic structure. Furthermore, crustal structure and composition are significant in understanding the origins of oceanic plateaus and may lead to a better understanding of the processes by which normal oceanic crust is created at spreading centers. Our objectives in this study are to define and compare the crustal structures of oceanic plateaus and continental fragments, and to outline possible lithologic components corresponding to the seismic structures of oceanic plateaus in particular. We began by compiling a list of plateaus found in ocean basins, and assigning each plateau to one of the classes described above. The seismic data for eleven plateaus are summarized, with references 5–14, in Table 1. Their locations are shown in Fig. 1.

2. Continental fragments

Of the continental fragments listed in Table 1, three are known to be underlain by continental-type rocks. Rockall Island consists of Lower Eocene

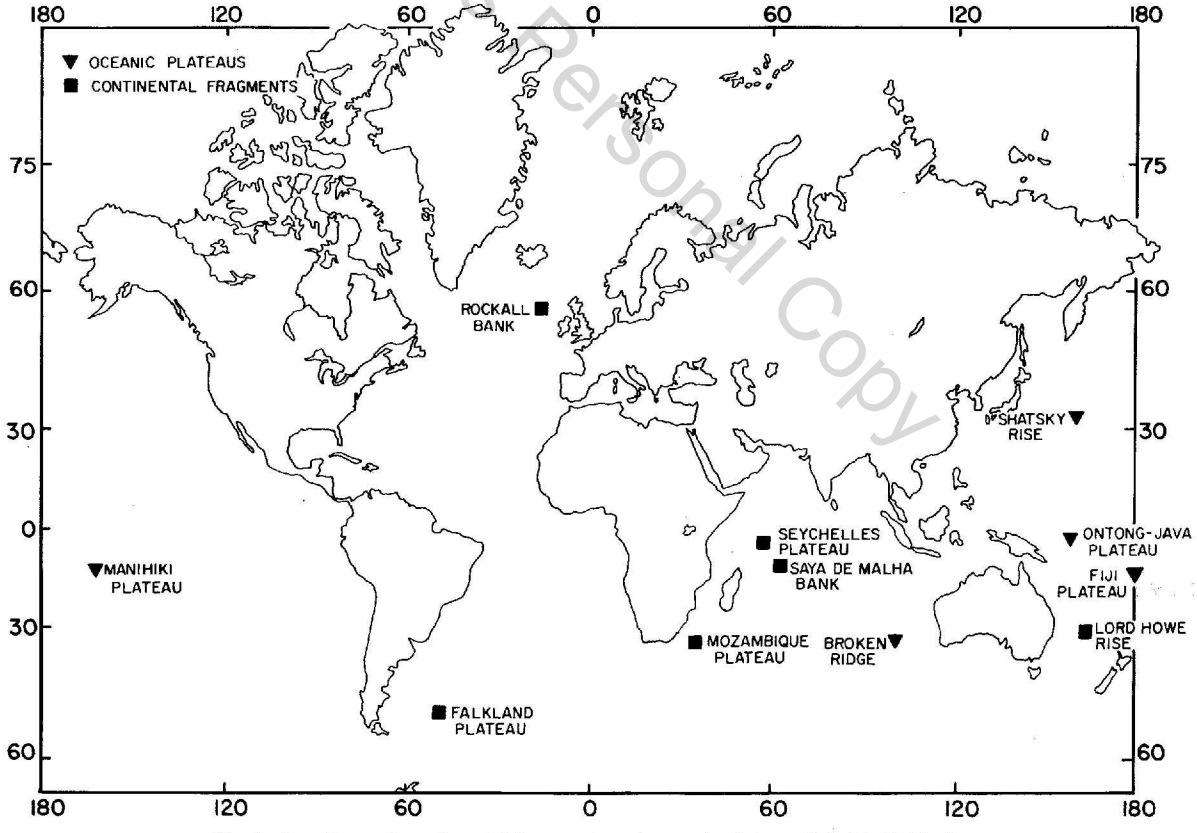

Fig. 1. Locations of continental fragments and oceanic plateaus listed in Table 1.

TABLE 1

Summary of plateau structures

	Water depth (km)	$v_p < 4.0$ km/s			$v_p = 4.0–6.3$ km/s			$v_p = 6.3–7.0$ km/s			$v_p = 7.0–8.0$ km/s			$v_p > 8.0$ km/s	
		d (km)	t (km)	v (km/s)	d (km)	t (km)	v (km/s)	d (km)	t (km)	v (km/s)	d (km)	t (km)	v (km/s)	T (km)	v (km/s)
Shatsky Rise [11]	4.1	4.1	0.3	2.0	4.4	0.7	4.9	7.3	6.0	7.0	13.3	11.4	7.5	24.7	8.2
					5.1	2.2	5.6								
Broken Ridge [12]	2.2	2.2	0.6	2.2	2.8	2.0	4.7	7.4	7.2	6.4	14.6	5.9	7.3	20.5	8.2
					4.8	0.9	5.8								
					5.7	1.7	6.1								
Fiji Plateau [13]	2.7	2.7	0.2	1.6	3.0	2.9	5.3	5.9	2.5	6.9	8.4	9.6	⩽7.8	18 *	8.2 **
		2.9	0.1	2.6											
Fiji Plateau [13]	3.0	3.0	0.3	1.6	3.3	2.4	5.6	5.7	1.3	6.6	7.0	11.0	7.4	18 *	8.2 **
Fiji Plateau [13]	3.1	3.1	0.2	1.6	3.6	0.8	4.9	6.2	2.3	6.9	8.5	9.5	7.5	18 *	8.2 **
		3.3	0.3	3.6	4.4	1.8	5.6								
Central Ontong-Java Plateau [14]	1.0	1.0	3.0	3.5	4.0	2.0	5.4	15.0	21.0	6.9				36	8.0
					6.0	9.0	6.1								
Northern Ontong-Java Plateau [14]	2.0	2.0	1.0	2.7	3.0	2.0	4.5	9.0	15.5	7.0	24.5	15.5	7.6	40.0	8.6
					5.0	4.0	5.9								
Manihiki Plateau [13]	2.6	2.6	0.1	1.5	3.4	0.3	4.9	13.5		6.9					
		2.7	0.3	1.9	3.7	4.4	5.4								
		3.0	0.4	2.3	8.1	1.9	5.6								
					10.0	3.5	6.1								
Seychelles Plateau [5]	0.05	0.05	0.3	2.0	0.35	3.3	5.7	13.1	19.0	6.8				32.0	8.1
					3.65	9.4	6.3								
Saya De Malha Bank [6]	0.1	0.1	0.4	1.7	1.7	3.1	4.4	9.0		6.8					
		0.5	1.2	3.3	4.8	4.2	5.6								
Mozambique Plateau [7]	2.7	2.7	3.3	2.0	6.1	4.8	5.3	22.0		7.0					
					10.9	11.3	5.8								
Rockall Bank [8]	0.0				0.0	6.0	4.8	6.0	9.0	6.4				31.0	8.2
								15.0	16.0	7.0					
Falkland Plateau [9]	2.7	2.7	1.3	2.2	4.0	2.4	4.2								
					6.4		5.9								
Lord Howe Rise [10]	1.2	1.2	0.3	2.2	2.4	13.4	6.0	15.8	13.2	6.8				29.0	8.0
		1.5	0.9	3.9											

v = compressional-wave velocity; d = depth below sea level; t = layer thickness; T = depth to Moho below sea level.
T = depth to Moho below sea level.
* Estimated depth to Moho.
** Assumed velocity.

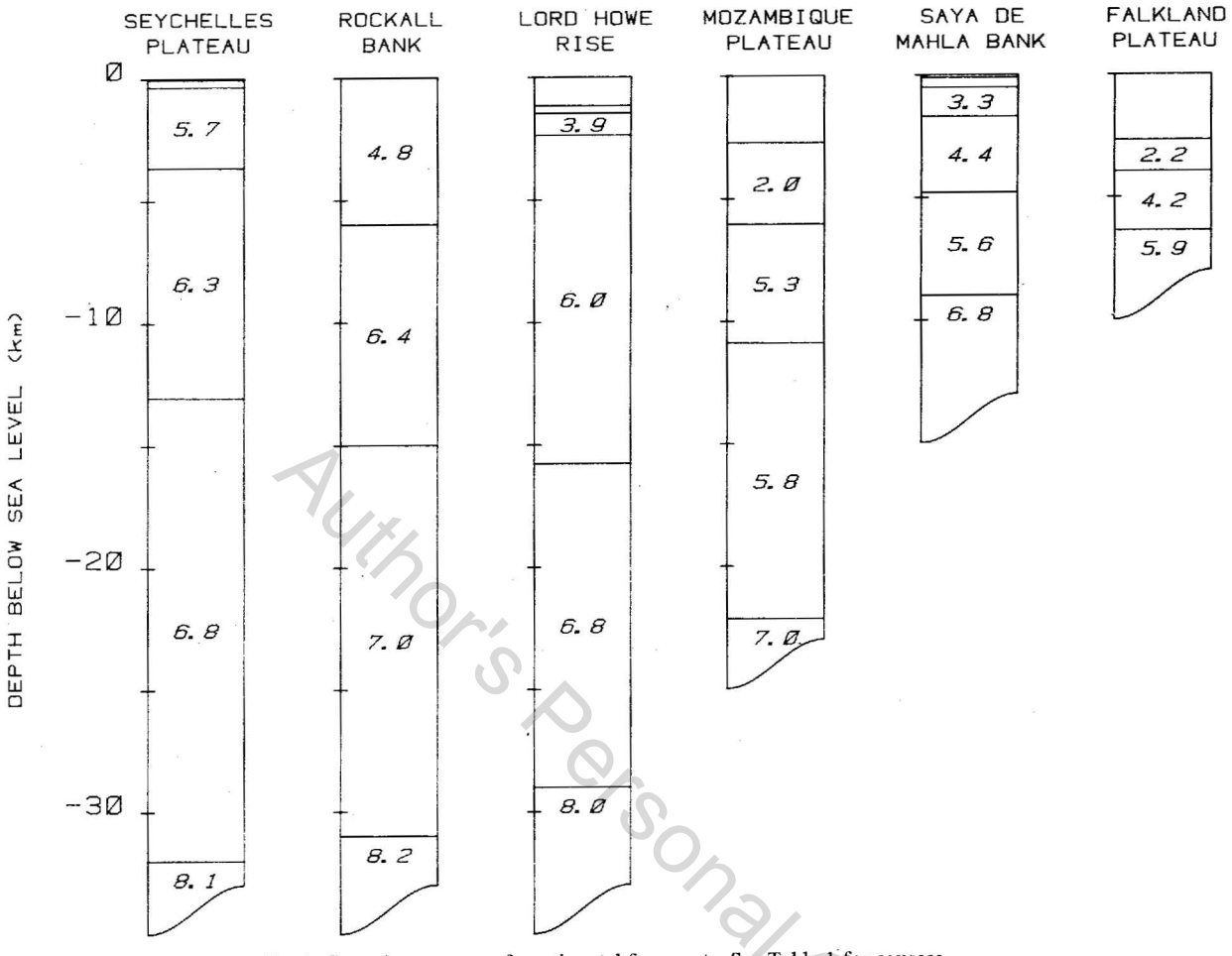

Fig. 2. Crustal structures of continental fragments. See Table 1 for sources.

granite [15], which is thought to have intruded continental crust. Granitic rocks are exposed in the Seychelles [16], and the continental nature of the basement underlying Falkland Plateau has been confirmed by the recovery of gneissic rocks at Site 330 of the Deep Sea Drilling Project [17]. Saya de Malha Bank is included in this class because of its proximity to the Seychelles and because it appears to be part of the same physiographic feature. Although no direct evidence of their continental nature exists, Lord Howe Rise is thought to be a fragment of the Australian Continent [18], and Mozambique Plateau is probably a displaced portion of Africa [19].

Fig. 2 shows velocity-structure columns for the continental fragments. Normal upper mantle velocities (8.0–8.2 km/s) have been detected at depths of about 30 km below sea level beneath the Seychelles, Rockall, and Lord Howe Rise. In each of these cases, the Moho is overlain by a 6.8–7.0 km/s layer which is 14–18 km thick. The deepest refractors detected beneath Saya de Malha Bank and Mozambique Plateau also have velocities in the 6.8–7.0 km/s range. Above this level the velocity structures of continental fragments are highly variable with velocities in the 5.3–6.4 km/s range commonly observed.

3. Oceanic plateaus

The oceanic plateaus differ from continental fragments in that they cannot be clearly related to nearby continents. Shatsky Rise, Broken Ridge, Manihiki

Plateau, and Ontong-Java Plateau, for example, all appear to be features of Mesozoic age and oceanic origin [20–23]. Indeed, with the exception of Broken Ridge, they are parts of the Pacific Plate, and cannot be associated with any continent by any reasonable reconstruction of plate motions. Sclater and Fisher [24], have suggested that Broken Ridge is a fragment of Kerguelen Plateau.

The velocity structures of the oceanic plateaus are illustrated in Fig. 3. While velocities typical of the upper mantle have been detected beneath Shatsky Rise, Broken Ridge, and Ontong-Java Plateau, mantle depths of 12.5–18 km beneath the Fuji Plateau are inferred from isostatic considerations [13]. Mantle velocities beneath the Fuji Plateau are assumed to be 8.2 km/s. Reported mantle depths range from 18 to 40 km (Fig. 3), and with the exception of the Ontong-Java Plateau profiles, depths to the Mohorovicic Discontinuity are less than 25 km. The lowermost crustal unit in the oceanic plateaus is a 7.3–7.6 km/s layer, 6–15 km thick, which is overlain by a unit having velocities typical of oceanic layer 3. Velocity structures in the upper crustal levels beneath these plateaus are variable and appear to be considerably more complex than the upper crustal portions of continental fragments.

4. Comparison of velocity structures

Of the 14 refraction profiles across 11 plateaus included in this study, all were obtained by conventional marine refraction methods except for the data for the Fiji and Manihiki Plateaus, where the Asper technique was used [13]. The following comparison is thus based largely on conventional refraction profiling results. An important objective of future seismic refraction studies of oceanic platforms should be the refinement of plateau crustal structures by using high-resolution methods.

In Fig. 4 the depth from the sea floor to each refractor is plotted against the refractor velocity for

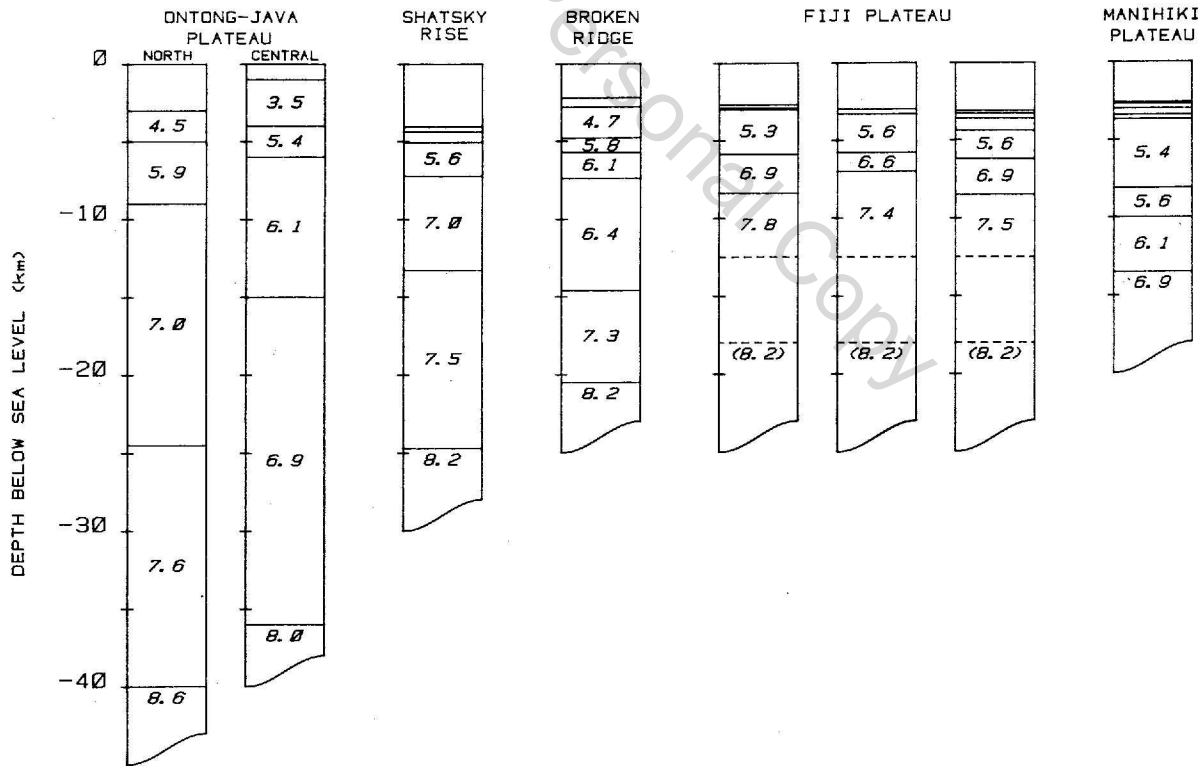

Fig. 3. Crustal structures of oceanic plateaus. See Table 1 for sources.

both oceanic plateaus and continental fragments. Rectangles represent typical ranges of depth and velocity for normal oceanic crust and continental shield areas, adapted from a compilation by Drake and Nafe [25]. We chose to compare the continental fragments with shield areas because the shields, like the fragments, are tectonically inactive. The excellent correlation between these structures does not imply that continental fragments are necessarily displaced portions of continental shields.

Fig. 4 illustrates several marked differences between oceanic plateaus and continental fragments. For refractor velocities up to 6.4 km/s, the distribution of velocity with depth is essentially the same in both structures. At deeper levels of the crust, the distinction becomes more apparent. The structures of continental fragments correlate remarkably well with continental shields, whereas oceanic plateau structures do not. Further, velocities typical of oceanic layer 3 are observed in both types of plateau structures but tend to occur at deeper levels in continental fragments. An important distinguishing characteristic of oceanic plateaus is the existence of a basal layer with velocities in the 7.1–7.6 km/s range. No such layer has been detected in continental fragments.

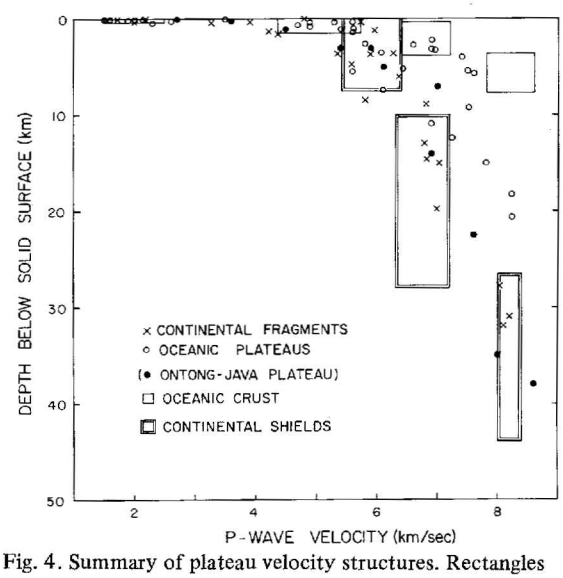

Fig. 4. Summary of plateau velocity structures. Rectangles represent typical ranges of velocity and depth for continental shield areas and normal oceanic crust adapted from Drake and Nafe [25]. Solid circles represent data from Ontong-Java Plateau.

Finally, the crust beneath continental fragments may be 5–10 km thicker than that beneath plateaus of oceanic origin.

The crustal structure of Ontong-Java is peculiar in a number of respects (see Fig. 4). The central part of the plateau has characteristics of a continental fragment, differing only in that the Moho is depressed by a thick basal layer. By contrast, the crust beneath the northern flank of Ontong-Java is similar to that of other oceanic plateaus except that the layers corresponding to layer 3 and the high-velocity basal layer are substantially thicker. These conditions suggest that Ontong-Java Plateau is a composite consisting of both continental and oceanic elements, that it represents an entirely different type of feature or that the high-velocity layer is present but undetected beneath the central plateau as suggested by Hussong et al. [4].

5. Composition of oceanic plateaus

Knowledge of the crustal composition beneath oceanic plateaus is essential to an understanding of their origins. The upper crustal layers beneath oceanic plateaus with velocities similar to oceanic layers 2 and 3 are likely to be composed of basaltic and gabbroic rocks, respectively, but the nature of the thick, high-velocity basal layer of oceanic plateaus is problematical. Relatively thin, high-velocity basal layers, which may be analogous to those associated with oceanic plateaus have been detected in normal oceanic crust of the Pacific and Atlantic ocean basins [4] and are likely to occur in some ophiolites [26].

During the past two decades velocities have been measured as a function of confining pressure for a wide variety of igneous and metamorphic rocks (e.g. [27]). A review of the rock velocities produces the significant conclusion that only a limited number of rock types has compressional wave velocities in the range of 7.3–7.6 km/s at pressures appropriate for the lower regions of oceanic plateaus (2–6 kbar). At present geophysical data are not sufficient to allow speculation as to which composition or compositions discussed below are most probable for the lower crustal sections. The following considerations also apply to high-velocity basal layers in normal oceanic crust.

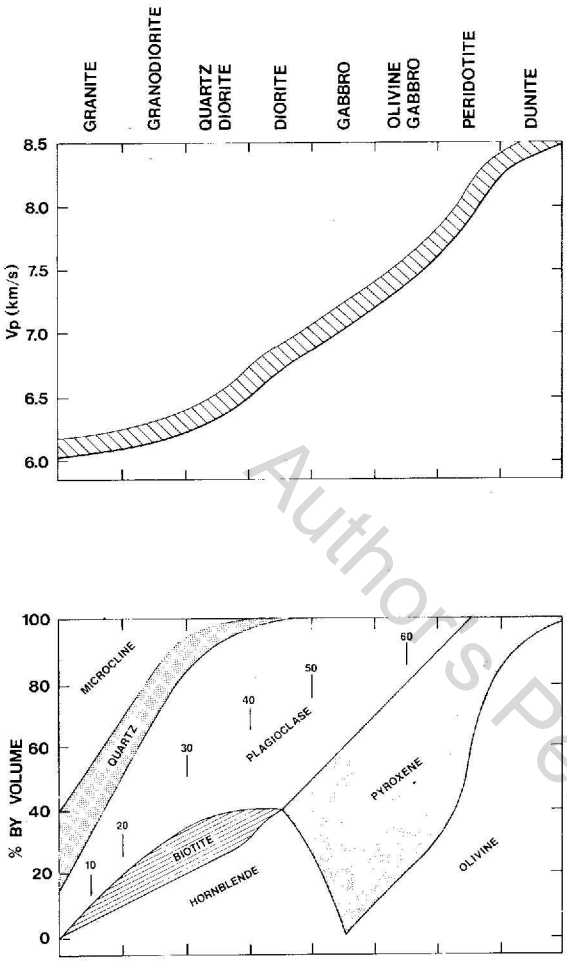

Fig. 5. Compressional-wave velocity in the pressure range of 2–6 kbar, versus composition for common igneous rocks, and corresponding mineralogy. Plagioclase compositions (in % anorthite) are shown in the plagioclase field. Adapted from Christensen [31].

Mafic compositions. Approximate ranges of velocities for common igneous rocks (Fig. 5) illustrate several important conclusions. First, igneous rocks of granitic through dioritic composition and their metamorphic equivalents cannot be major constituents in the lower crustal regions of oceanic plateaus, because their velocities are less than 7 km/s. Furthermore, velocities in common gabbro are lower than 7.1 km/s [27]. Olivine-rich gabbros on the other hand, have velocities similar to those observed in the lower crustal regions of oceanic plateaus. The presence of abundant olivine gabbro in these regions would result from magmatic activity, perhaps associated with large magma chambers.

Metamorphic rocks of gabbroic composition also have velocities in the 7.3–7.6 km/s range. Mafic garnet granulites have velocities in this range [28,29]; however, these rocks may not be stable under the *P-T* conditions likely within oceanic plateau crustal regions [30]. Christensen [31] reported velocities for two epidote amphibolites of 7.39–7.66 km/s and 7.32–7.60 km/s at pressures from 2 to 6 kbar. Epidote apparently exhibits extremely high acoustic velocities, since common plagioclase-hornblende amphibolites have velocities approximately 0.5 km/s lower than the epidote-rich varieties [31]. In support of the possible presence of epidote in the lower oceanic crust, epidote has been reported in ophiolites [32,33] and abundant epidote was found in cores recovered from a depth of approximately 2 km in a hole drilled near Reydarfjordur, eastern Iceland, in 1978 [34]. The hydration which produces epidote at such depths apparently results from the seepage of seawater downward through joints and fractures in the overlying rocks. Since the high-velocity basal layers beneath oceanic plateaus occur at relatively deep levels within the oceanic crust, a hydrous metamorphic origin implies deep hydrothermal circulation.

Ultramafic compositions. Peridotite and dunite have velocities higher than the basal layer of oceanic plateaus (Fig. 5). However, Christensen [34], has shown that the physical properties of these ultramafic rocks are dramatically affected by their degree of serpentinization as illustrated in Fig. 6. Thus, partially serpentinized peridotites having compressional-wave velocities in the 7.3–7.6 km/sec range contain 18–23% serpentine by volume and have shear-wave velocities ranging from 3.8 to 4.1 km/s [35]. Poisson's ratio for these rocks is approximately 0.30. Because these values compare favorably with the properties of some gabbros and their metamorphic equivalents [36], it is not possible to discriminate between mafic and ultramafic compositions for lower regions of oceanic plateaus using Poisson's ratio calculated using compressional and shear wave velocities from seismic refraction surveys.

An ultramafic composition consisting of partially

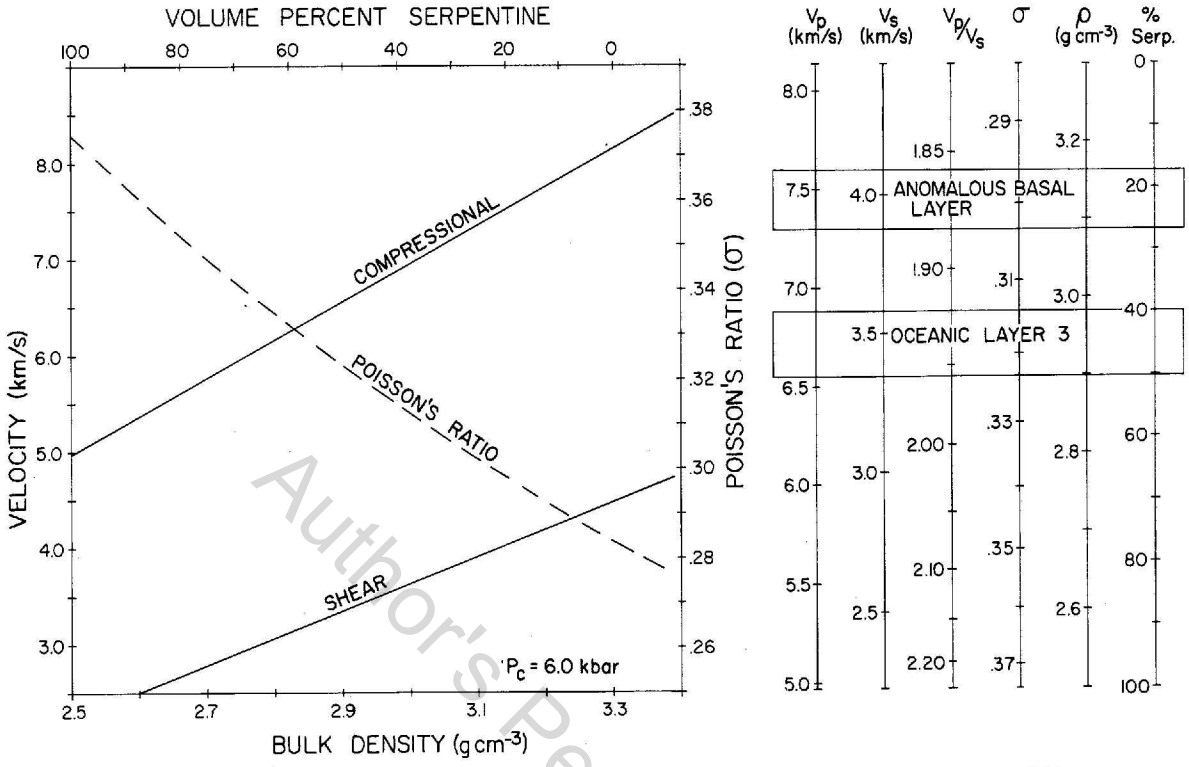

Fig. 6. Elastic properties of partially serpentinized peridotites, adapted from Christensen [35,36].

serpentinized peridotite for lower crustal regions of oceanic plateaus would likely originate from serpentinization of mantle rocks. Such an origin would be attractive because volume increases associated with the serpentinization would help to explain the relatively high elevations of many oceanic plateaus. A critical test for such an origin would be a seismic refraction experiment designed to detect anisotropy within the basal layer. Gabbros have low anisotropy [27], whereas moderately serpentinized mantle ultramafics generally retain much of their fabric and should consequently mimic the anisotropy of the underlying upper mantle.

Ultramafic-mafic mix. A third possibility for the petrologic nature of the lower crustal regions of oceanic plateaus comes by analogy with ophiolites. The Blow-Me-Down massif of the Bay of Islands complex contains a 1-km-thick basal crustal layer consisting of interlayered anorthositic gabbro, olivine gabbro, troctolite and plagioclase peridotite. Based on laboratory measurements, average compressional and shear wave velocities for the lower crustal layer are 7.4 and 3.9 km/s, respectively, and Poisson's ratio is 0.31 [37].

As in the Bay of Islands ophiolite, we have recently established from laboratory measurements the presence of a high-velocity (~7.5 km/s) crustal basal layer in the northern portion of the Semail ophiolite of Oman [38]. This high velocity originates from a 1- to 2-km thick zone of interlayered banded gabbro and peridotite. These rocks are clearly cumulate in origin.

6. Conclusions

The number of plateau-like features for which complete velocity structures are known is admittedly small, and to that extent our conclusions regarding their distinguishing characteristics must be regarded as tentative. Nevertheless, the crustal structures of

continental fragments and oceanic plateaus appear to differ significantly in a number of respects:

(1) The crustal structures of continental fragments correlate remarkably well with the structure of continental shields, whereas the structures of oceanic plateaus do not.

(2) Velocities in the 6.5–6.9 km/s range are common to both types of plateaus, but are observed at deeper levels in continental fragments.

(3) The high-velocity (7.3–7.6 km/s) basal layer of the oceanic plateaus is not observed in continental fragments.

(4) The crust beneath continental fragments appears to be 5–10 km thicker than that beneath oceanic plateaus.

The composition of the basal layer found in oceanic plateaus is likely to consist of gabbroic rocks, epidote amphibolite, interlayered mafic and ultramafic cumulates, or partially serpentinized peridotites. Poisson's ratio cannot be used to discriminate between these possibilities, but modestly serpentinized mantle ultramafics may be expected to mimic upper mantle anisotropy, while gabbroic rocks are expected to be essentially isotropic.

Acknowledgements

We gratefully acknowledge the contribution of D.A. Fahlquist in the early stages of this research. The project was supported by Office of Naval Research Contract N-0014-75-C-0502 and NSF grant OCN-7817919.

References

1 R.W. Raitt, The crustal rocks, in: The Sea, M.N. Hill, ed. (Wiley, New York, N.Y., 1963) 85.
2 N.J. Christensen and M.H. Salisbury, Structure and constitution of the lower oceanic crust, Rev. Geophys. Space Phys. 13 (1975) 57.
3 S.J. Malecek and R.M. Clowes, Crustal structure near the Explorer Ridge from a marine deep seismic sounding survey, J. Geophys. Res. 83 (1978) 5899.
4 D.M. Hussong, L.K. Wipperman and L.W. Kroenke, The crustal structure of the Ontong-Java and Manihiki oceanic plateaus, J. Geophys. Res. 84 (1979) 6003.
5 T.J.G. Francis, D. Davies and M.N. Hill, F.R.S., Crustal structure between Kenya and the Seychelles, Philos. Trans. R. Soc. London, Ser. A, 259 (1966) 240.
6 T.J.G. Francis and G.G. Shor, Jr., Seismic refraction measurements in the northwest Indian Ocean, J. Geophys. Res. 71 (1966) 427.
7 A.L. Hales and J.B. Nation, A crustal structure profile on the Agulhas bank, Bull. Seismol. Soc. Am. 62 (1972) 1029.
8 D.G. Roberts, Marine geology of the Rockall plateau and trough, Philos. Trans. R. Astron. Soc. 278 (1975) 447.
9 J.I. Ewing, W.J. Ludwig, M. Ewing and S.L. Eittreim, Structure of the Scotia Sea and Falkland Plateau, J. Geophys. Res. 76 (1971) 7118.
10 G.G. Shor, Jr., J.K. Kirk and H.W. Menard, Crustal structure of the Melanesian area, J. Geophys. Res. 76 (1971) 2562.
11 N. Den, W.J. Ludwig, S. Murauchi, J.I. Ewing, H. Hotta, N.T. Edgar, T. Yoshii, T. Asanuma, K. Hagiwara, T. Sato and S. Ando, Seismic-refraction measurements in the northwest Pacific basin, J. Geophys. Res. 75 (1969) 1421.
12 T.J.G. Francis and R.W. Raitt, Seismic refraction measurements in the southern Indian Ocean, J. Geophys. Res. 72 (1967) 3015.
13 G.H. Sutton, G.L. Maynard and D.M. Hussong, Widespread occurrence of a high-velocity basal layer in the Pacific crust found with repetitive sources and sonobuoys, in: The Structure and Physical Properties of the Earth's Crust, J.G. Heacock, ed., Am. Geophys. Union, Geophys. Monogr. 14 (1971) 193.
14 A.S. Furumoto, W.A. Wiebenga, J.P. Webb and G.H. Sutton, Crustal structure of the Hawaiian archipelago, northern Melanesia, and the central Pacific basin by seismic refraction methods, Tectonophysics 20 (1973) 153.
15 P.A. Sabine, Rockall – an unusual occurrence of Tertiary granite, Proc. Geol. Soc. London 51 (1965) 16.
16 B.H. Baker and J.A. Miller, Geology and geochronology of the Seychelles islands and structure of the floor of the Arabian Sea, Nature 199 (1963) 346.
17 P.F. Barker, I.W.D. Dalziel et al., Initial Reports of the Deep Sea Drilling Project, Vol. 36 (U.S. Government Printing Office, Washington, D.C., 1976).
18 R.E. Burns, J.E. Andrews et al., Initial Reports of the Deep Sea Drilling Project, Vol. 21 (U.S. Government Printing Office, Washington, D.C., 1973).
19 A.S. Laughton, D.H. Matthews and R.L. Fisher, The structure of the Indian Ocean, in: The Sea, A.E. Maxwell, ed. (Wiley, New York, N.Y., 1971).
20 R.L. Larson, R. Moberly et al., Initial Reports of the Deep Sea Drilling Project, Vol. 32 (U.S. Government Printing Office, Washington, D.C. 1975).
21 T.A. Davies, B.P. Luyendyk et al., Initial Reports of the Deep Sea Drilling Project, Vol. 26 (U.S. Government Printing Office, Washington, D.C., 1974).
22 S.O. Schlanger, E.D. Jackson et al., Initial Reports of the Deep Sea Drilling Project, Vol. 33 (U.S. Government Printing Office, Washington, D.C., 1976).
23 J.E. Andrews, G. Packham et al., Initial Reports of the Deep Sea Drilling Project, Vol. 30 (U.S. Government Printing Office, Washington, D.C., 1975).

24 J.G. Sclater and R.L. Fisher, Evolution of the east central Indian Ocean, with emphasis on the tectonic setting of the Ninetyeast Ridge, Geol. Soc. Am. Bull. 85 (1974) 683.
25 C.L. Drake and J.E. Nafe, The transition from ocean to continent from seismic refraction data, in: The Crust and Upper Mantle of the Pacific Area, L. Knopoff, C.L. Drake and P.J. Hart, eds., Am. Geophys. Union, Geophys. Monogr. 12 (1968) 174.
26 N.I. Christensen, Ophiolites, seismic velocities and oceanic crustal structure, Tectonophysics 47 (1978) 131.
27 F. Birch, The velocity of compressional waves in rocks to 10 kilobars, 1, J. Geophys. Res. 65 (1960) 1083.
28 M.H. Manghnani and R. Ramananantoandro, Compressional and shear wave velocities in granulite facies rocks and eclogites to 10 kbar, J. Geophys. Res. 79 (1974) 5427.
29 N.I. Christensen and D.M. Fountain, Constitution of the lower continental crust based on experimental studies of seismic velocities in granulite, Geol. Soc. Am. Bull. 86 (1975) 227.
30 A.E. Ringwood and D.H. Green, An experimental investigation of the gabbroeclogite transformation and some geophysical implications, Tectonophysics 3 (1966) 383.
31 N.I. Christensen, Compressional wave velocities in metamorphic rocks at pressures to 10 kilobars, J. Geophys. Res. 70 (1965) 6147.
32 I.G. Gass and J.D. Snewing, Intrusion, extrusion and metamorphism at constructive margins – evidence from Troodos Massif, Cyprus, Nature 242 (1973) 26.
33 H. Williams and J. Malpas, Sheeted dikes and brecciated dike rocks within transported igneous complexes, Bay of Islands, western Newfoundland, Can. J. Earth Sci. 9 (1972) 1216.
34 I.L. Gibson, ed., Crust of oceanic affinity in Iceland, Nature 281 (1979) 347.
35 N.I. Christensen, Elasticity of ultrabasic rocks, J. Geophys. Res. 71 (1966) 5921.
36 N.I. Christensen, The abundance of serpentinites in the oceanic crust, J. Geol. 80 (1972) 709.
37 M.H. Salisbury and N.I. Christensen, The seismic velocity structure of a traverse through the Bay of Islands ophiolite complex, Newfoundland, an exposure of oceanic crust and upper mantle, J. Geophys. Res. 83 (1978) 805.
38 N.I. Christensen and J.D. Smewing, Seismic structure of the northern portion of the Semail Ophiolite, Oman, Trans. Am. Geophys. Union 60 (1979) 964.