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A new assessment of the abundance of serpentinite in the oceanic crust

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Abstract. The 'gabbro' model of the composition of the oceanic crust has prevailed for more than two decades, but serpentinites are common along much of the Mid-Atlantic Ridge, and elsewhere, leading to renewed debate over the abundance of serpentinites in crust created at slow-spreading ridges. Based on data from both oceanic and ophiolite samples, it has also been suggested that serpentinites are not distinguishable from meta-gabbros and diabases by their seismic properties. We have made new statistical analyses of the relationship between V_S and V_P in oceanic gabbro and diabase samples and serpentinized peridotites, and compared them to in situ s-wave and p-wave velocities derived from Expanding Spread Profiles (ESPs) acquired in the Atlantic. Our findings demonstrate: (1) that there is some overlap of the properties of gabbroic samples taken from ophiolites with the properties of serpentinites, but (2) over the range of typical-layer 3 seismic velocities, the seismic properties of oceanic gabbros and diabases are distinctly different from the properties of serpentinites, and (3) that in situ seismic velocities are in excellent agreement with the properties of the gabbros, while the shear velocities in serpentinites are significantly lower. Partially-serpentinized peridotite is certainly present, but not abundant in 'normal' oceanic crust.

Introduction

Hess [1962, 1965] and Dietz [1963] proposed that the lower oceanic crust is composed of partially-serpentinized peridotite produced by hydration of the upper mantle. Others, notably Cann [1968], Christensen [1972] and Fox et al. [1973] argued for a lower crust composed of gabbro, the intrusive equivalent of the basalt that caps the crust. Apart from its obvious petrologic appeal, the 'gabbro' model (including gabbros, diabases and their metamorphic equivalents) has prevailed largely because seismic Vp/Vs ratios for the lower oceanic crust are consistent with the measured properties of meta-gabbros and meta-diabases, but not with the properties of partially-serpentinized peridotites [e.g., Christensen, 1972; Christensen and Salisbury, 1975; Spudich and Orcutt, 1980]. Still, serpentinites are common in Atlantic fracture zones, along the Mid-Atlantic Ridge and elsewhere [e.g., Juteau et al., 1990], and there is a growing conviction among some researchers that serpentinites must constitute a volumetrically-significant fraction of crust produced at slow-spreading ridges. Francis [1981], for example, reasoned that the lower crust (layer 3) along the Mid-Atlantic Ridge may be composed of serpentinized peridotite because the thickness of the 'magmatic' crust is limited by the low magma supply and because an appreciable volume of water must reach the mantle through the numerous faults that penetrate the thin basaltic section. More recently, Horen et al. [1996] have argued that serpentinized peridotites cannot, in fact, be distinguished from gabbros and diabases by their shear- and compressional-wave velocities, and hence that an abundance of partially-serpentinized peridotite in the crust is consistent with its seismic structure.

The gabbro and serpentinite models could hardly be more different in their implications for the composition and formation of the oceanic crust, but the Horen et al. study raises questions that go well beyond the issue of whether serpentinites are prevalent in parts of the oceanic crust, or what the volume fraction of partially-serpentinized peridotite might be. Most of our 'direct' knowledge of the structure of the oceanic crust derives from seismic p-wave data. For decades oceanic seismic velocity structure has been interpreted in terms of variations in the composition and physical state of a 'gabbroic' crust. What if we really cannot discriminate between gabbros and serpentinites, even in the few places where reliable shear- and compressional-wave velocities have been measured? Seismic data would then be largely useless for constraining models of the composition and evolution of the crust, and seismic velocities would be interpretable only in the light of a-priori knowledge or assumptions about the composition of the local crustal section. Whether seismic data can be used to distinguish between gabbros and serpentinites is thus a problem of primary importance. Consequently, we have undertaken a review and analysis of the measured properties of gabbros and diabases from ophiolites and the oceanic crust, partially-serpentinized peridotites, and seismic p- and s-wave velocities from Expanding Spread Profiles (ESPs) acquired in the Atlantic. Our primary objective is to determine whether the properties of both gabbros and serpentinites are consistent with reliable in situ shear- and compressional-wave velocities in crust created at slow-spreading ridges.

Serpentinized Peridotite

Compressional- and shear-wave velocities in partially-serpentinized peridotites [Christensen ,1966, 1972, 1978; Horen et al., 1996], are plotted in Figure 1. (For brevity, we use the term 'serpentinite' to refer to the full range of partially-serpentinized peridotites.) Two samples from Christensen's [1978] study were not used; though they have velocities that are consistent with the rest of the data, they have p-wave velocities that are inconsistent with their reported serpentine contents. The velocities reported by Horen et al. [1996] were measured at atmospheric pressure, while those reported by Christensen were measured at 200 MPa, a pressure that is

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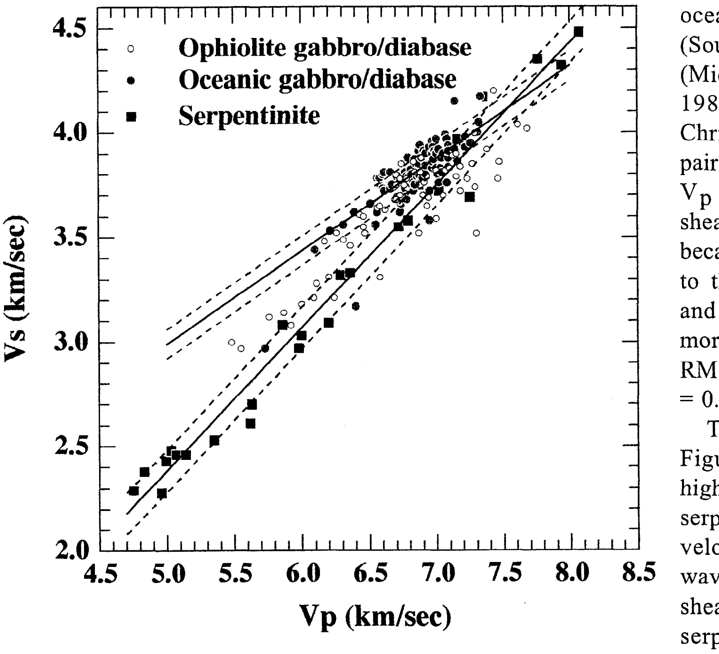

Figure 1. Laboratory shear- and compressional-wave velocities measured under water-saturated conditions at a confining pressure of 200 MPa. Solid lines indicate best fits to the oceanic gabbro/diabase and serpentinite data. Dashed lines indicate RMS errors.

roughly appropriate for the lower oceanic crust. Pressure affects both the velocities and the ratio of V_p to V_s, but (particularly at low pressures) does not significantly affect the V_p/V_s trend (i.e., increasing pressure has the effect of shifting the data points parallel to the trend shown in Figure 1). Hence, the two sets of velocities can be combined in an analysis of the dependence of V_s on V_p, even though the measurements were made at different pressures. The combined serpentinite data set includes 26 pairs of shear- and compressional-wave velocities. Experimental errors are small, ≤ 1 percent. The strong linear relationship between p- and s-wave velocities in partially-serpentinized peridotites reported by Christensen [1966, 1972] is evident; our fit of V_s on V_p has an RMS error of 0.10 km/s and $R^2 = 0.980$ (see Table 1). This data set does not include recently-acquired serpentinite samples from the ocean floor, but Miller and Christensen [in press] have documented the similarity of oceanic and ophiolitic serpentinites.

Gabbro and Diabase

We considered two sets of gabbro/diabase data (including meta-gabbros and meta-diabases), one consisting of samples from ophiolites and the other of samples recovered from the ocean floor by drilling at sites 504 (Costa Rica Rift), 735 (Southwest Indian Ridge), 894 and 895 (Hess Deep), and 923 (Mid-Atlantic Ridge/Kane Fracture Zone) [Christensen et al., 1989; Iturrino et al., 1991, 1995, 1996; Miller and Christensen, in press]. The oceanic data set includes the 98 pairs of velocities shown in Figure 1, with the best fit of V_s on V_p obtained by linear regression. The two samples having shear-wave velocities near 3 km/s were not included in the fit because they have velocities that are anomalously low relative to their densities. One is essentially a serpentinized dunite and the other is a highly-altered, Fe-rich gabbro. We note, moreover, that including them does not alter the results. The RMS error is 0.07 km/s and the coefficient of determination $R^2 = 0.657$; other statistics are summarized in Table 1.

The oceanic gabbro and serpentinite trends shown in Figure 1 are appreciably different. For p-wave velocities higher than about 7 km/sec, there is some overlap between the serpentinite and gabbro trends, but over the range of seismic velocities that is typical of layer 3 (6.7±0.2 km/sec), shear-wave velocities in oceanic gabbros are distinctly higher than shear-wave velocities in serpentinized peridotites. Partially-serpentinized peridotites are clearly distinguishable from oceanic gabbros and diabases based on p- and s-wave velocities measured in the laboratory.

The third data set shown in Figure 1 includes 66 gabbro and diabase samples from various ophiolite complexes, including the Bay of Islands and Semail [Christensen, 1978; Christensen and Salisbury, 1978; Christensen and Smewing, 1982]. Many of the ophiolite data, particularly those from Semail, fall below the trend of the oceanic samples, and overlap the serpentinite data. These data sets were used by Horen et al. [1996]; it would thus appear that their conclusion that gabbros and serpentinites cannot be distinguished by their compressional- and shear-wave velocities is based, at least in part, on the low shear velocities in some of the ophiolite samples. There is substantially less ambiguity between the properties of the serpentinites and the gabbro/diabase samples recovered from the oceanic crust. It is reasonable to suppose that the oceanic samples are more representative of gabbros and diabases in the oceanic crust than are samples from ophiolites because the latter often have approximately mafic-andesite compositions and a history of emplacement and alteration that they do not share with the oceanic rocks.

Seismic Velocities

Figure 2 shows shear- and compressional-wave velocities from several Atlantic ESPs (profiles 2, 3, 5, 12, 13 and 15 from NAT Study Group, [1985], Minshull et al., [1991] and Morris et al. [1993]) with the statistical models for the oceanic gabbro/diabase data and the serpentinite data. ESPs 5 and 12 are said to be of particularly high quality. The precision of the

Table 1. Summary of Regression Statistics, $V_s = a + bV_p$

Lithology	a (km/s)	b	R^2	n
Oceanic gabbro and diabase	0.77 ± 0.23	0.443 ± 0.033	0.657	96
Partially-serpentinized peridotite	-1.04 ± 0.12	0.683 ± 0.020	0.980	26

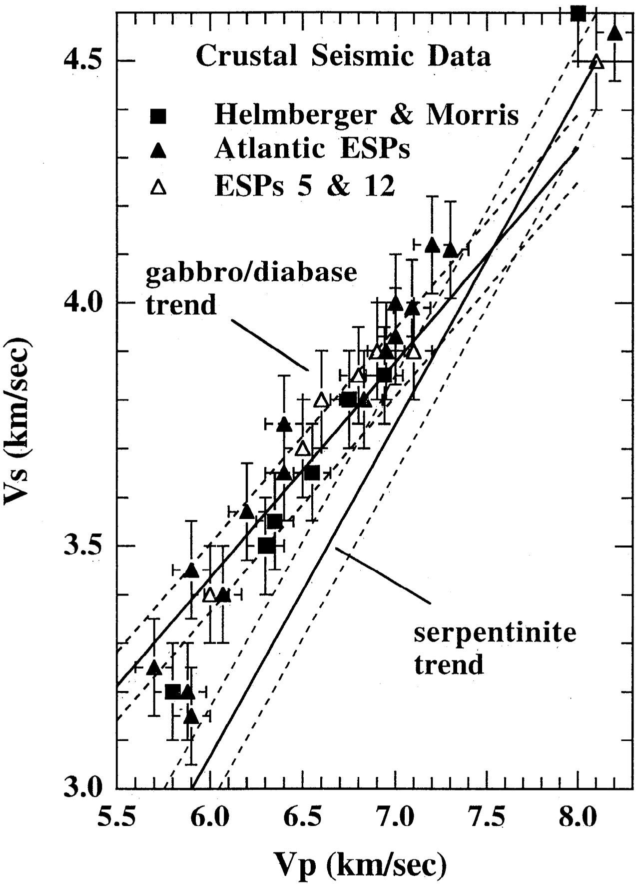

Figure 2. In situ seismic velocities compared with linear models relating shear- and compressional-wave velocities in oceanic gabbro/diabase and serpentinite samples measured in the laboratory. Solid lines indicate best fits, dashed lines indicate RMS errors, and error bars indicate one standard deviation.

estimated velocities is about 0.1 km/s [Minshull et al., 1991]. We have been careful not to include shear velocities calculated from the p-wave velocities by assuming a value of Poisson's ratio, because the Poisson's ratios used for this purpose are usually taken from the measured properties of gabbros [e.g., Minshull et al, 1991], and therefore yield shear velocities that agree with the gabbro model. It is for this reason as well that we have included the p- and s-wave velocities estimated by Helmberger and Morris [1970]. The fact that these velocities also agree with the data for oceanic gabbros is particularly important because Helmberger and Morris analyzed their data before the properties of gabbros from ophiolite suites had been measured, and long before the first gabbroic rocks (diabases) from the crust were sampled by drilling at site 504. There are a few data points in Figure 2 that fall below the gabbro/diabase trend, but their p-wave velocities are characteristic of layer 2B, where cracks are likely to have a significant influence on the seismic properties of the crust. Where the in situ p-wave velocities are higher than 6 km/s (i.e., in 'layers' 2C and 3), the seismic data are coincident with the gabbro/diabase trend to a remarkable degree, and except where the two trends meet near 7.2 km/s, the in situ velocities are not even remotely consistent with a partially-serpentinized peridotite lower-crustal composition. Furthermore, in situ velocities do not commonly occur within the region of overlap between the gabbro and serpentinite data sets (Figure 2). The Atlantic ESP data are in excellent agreement with the oceanic gabbro/diabase data, but fail to support a serpentinite model.

From Figure 2 it is evident that the linear relationship between s- and p-wave velocities in partially-serpentinized peridotites (Figure 1, Table 1) systematically and uniformly underestimates in situ shear-wave velocities. Another illustration of this point is shown in Figure 3, where we have plotted the observed shear-wave velocity profiles and shear-wave velocities calculated from the gabbro and serpentinite models for ESPs 5 and 12 [NAT Study Group, 1985]. ESP 5 is located on magnetic anomaly M0 (118 MA) southwest of Bermuda, and ESP 12 is located on 10-million-year-old crust east of the Mid-Atlantic Ridge. In both cases, the velocities estimated from the oceanic gabbro model are in good agreement with the observed shear velocities. Except for the deepest part of the ESP 12 profile, the serpentinite model significantly underestimates in situ shear-wave velocities in the lower crust. The results for other profiles are much the same. It is thus evident that partially-serpentinized peridotite cannot be a primary constituent of 'normal' lower oceanic crust in the Atlantic Basin.

Conclusions

Our analysis of shear- and compressional-wave velocities in diabase, gabbro and partially-serpentinized peridotite samples, and in situ seismic velocities from Atlantic Expanding Spread Profiles leads us to the following conclusions:

1. The measured shear- and compressional-wave velocities of gabbro and diabase samples from ophiolites are more scattered than the velocities of the oceanic samples, and overlap the serpentinized-peridotite trend. Thus, by using the ophiolite samples, one might reasonably conclude that gabbros, diabases and serpentinites should be difficult to distinguish from their seismic properties. We suggest that it is more

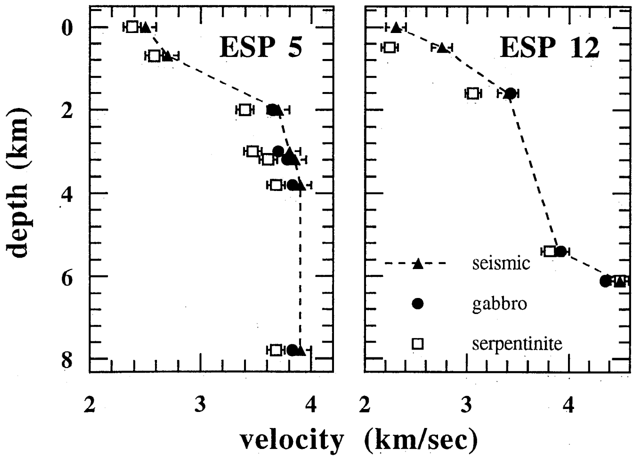

Figure 3. In situ shear velocities compared with shear-wave velocities calculated from linear models relating shear- and compressional-wave velocities in oceanic gabbro and diabase, and partially-serpentinized peridotite. Upper crustal velocities were not calculated from the gabbro/diabase model because that would require applying the model outside the range of the data. Error bars indicate one standard deviation.

reasonable to base our conclusions on oceanic samples because the ophiolite samples have different chemical compositions and have suffered the effects of emplacement and alteration.

2. Statistical relationships between s-wave and p-wave velocities in oceanic gabbros and diabases and partially-serpentinized peridotites demonstrate that these rocks have distinctly different seismic properties; for p-wave velocities characteristic of seismic layer 3 (6.7±0.2 km/sec), the gabbro/diabase samples have significantly lower Vp/Vs ratios (higher s-wave velocities and lower Poisson's ratios). For p-wave velocities higher than about 7 km/sec, there is some overlap of the gabbro and serpentinite V_p/V_s trends. Thus, seismic data might fail to distinguish between gabbro and serpentinite compositions only where seismic p-wave velocities are greater than 7 km/sec, usually in the deepest levels of the oceanic crust.

3. In situ shear- and compressional-wave velocities from ESPs in the Atlantic are in excellent agreement with measured velocities in oceanic gabbros and diabases; the seismic structure of 'normal' crust is well explained by the 'gabbro' model. In contrast, the seismic shear velocities are markedly higher than the shear velocities in serpentinized peridotites, and s-wave velocities calculated using the serpentinite model are systematically and uniformly lower than the in situ seismic velocities.

We must note, however, that this conclusion may not apply to crust produced in or near fracture zones, where the seismic structure is anomalous relative to 'normal' crust and reliable s-wave velocities are exceedingly rare [e.g., White et al., 1984]. Based on ESP data, Minshull et al. [1991] have proposed that the lower crust beneath the Blake Spur Fracture Zone is composed of partially-serpentinized peridotite. Similarly, Dick [1996] has argued that serpentinites may be abundant in the vicinity of the Southwest Indian Ridge.

Nevertheless, based on evidence that was not available more than two decades ago, we are lead to reaffirm the conclusion previously reached by Christensen [1972] that '... serpentinite is not abundant in the oceanic crust... An oceanic crust composed primarily of mafic igneous rocks and their metamorphosed equivalents is in better agreement with comparisons of laboratory measured elastic properties with seismic refraction data.'

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