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RESEARCH NOTE

Cracked media, Poisson's ratio and the structure of the upper oceanic crust

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SUMMARY

Theoretical models of water-filled cracks within a solid are in general agreement, and indicate that the Poisson's ratio of the composite material will typically increase for thin cracks with aspect ratios less than $\frac{1}{200}$, but will decrease for thick cracks with aspect ratios between $\frac{1}{20}$ and $\frac{1}{2}$. Near-spherical pores cause little change in Poisson's ratio. This is true both for randomly oriented, isotropic crack models, and, at certain directions, for aligned crack models which predict seismic anisotropy. Observed anomalous values of Poisson's ratio in oceanic Layer 2 can often be explained using these models as an effect of cracks, and do not necessarily require the presence of rocks of unusual composition. In particular, the low Poisson's ratios reported by Spudich & Orcutt (1980) and Au & Clowes (1984) can approximately, but not always exactly, be fitted with a model consisting of thick cracks within higher Poisson's ratio rock more typical of the upper oceanic crust. However, this interpretation is near the limit of existing theories of cracked material, so other explanations for the anomalous observations must also be considered.

Key words: Cracked media, Poisson's ratio, upper oceanic crust

INTRODUCTION

Steep velocity gradients in the uppermost oceanic crust (Layer 2) are generally believed to be related to a decrease in porosity with depth within the layer (i.e. Whitmarsh 1978; Spudich & Orcutt 1980; Bratt & Purdy 1984). This interpretation is supported by analyses of borehole samples (i.e. Becker *et al.* 1982) which typically show a decrease in porosity with depth, and by studies of theoretical models of cracked and porous media, which predict a decrease in seismic velocities with increasing porosity (i.e. Whitmarsh 1978; Spudich & Orcutt 1980; Diachok *et al.* 1984). Cracks can also affect *P*- and *S*-wave velocities by disproportional amounts, and thus change the Poisson's ratio of a material. These variations in Poisson's ratio can be more diagnostic of material properties than *P*- or *S*-wave velocities alone. For cracks, such changes are related to the aspect ratio of the cracks as well as the effective crack density (Hyndman 1979). Observations of relatively high values of Poisson's ratio ($\sigma > 0.30$) near the surface of the oceanic crust have been interpreted as an effect of cracks and fissures within rock of lower Poisson's ratio (Hyndman 1979).

More puzzling are the apparent low Poisson's ratios at depths of 1–1.5 km which have been observed in several oceanic refraction experiments (Spudich & Orcutt 1980; Au & Clowes 1984), indicating anomalously high *S*-wave velocities compared to *P*-wave velocities. Figure 1 shows Poisson's ratio vs. depth within the oceanic crust for these experiments, compared with measurements of ophiolite samples (Salisbury & Christensen 1978; Christensen & Smewing 1981) and oceanic borehole observations (Wilkins, *et al.* 1983). At shallow depths (<0.5 km), the refraction experiments suggest high values of Poisson's ratio (0.32–0.38), which are associated with low velocities near the surface of the crust and can readily be explained as an effect of cracks and fissures associated with the high near-surface porosity.

However, at depths of about 1–1.5 km, anomalously low values for Poisson's ratio (0.20–0.25) are indicated by the refraction experiments. These values are much lower than those of ophiolite samples at similar depths (see Fig. 1), are difficult to explain as an effect of cracks (Spudich & Orcutt 1980), and have no generally accepted origin (Au & Clowes 1984). Understanding the cause of these observations is important, however, as they currently constitute a major exception to the ophiolite analogue to the oceanic crust.

My purpose in this note will be to compare the results of existing theories of cracked media, examine the dependence of Poisson's ratio on crack aspect ratio for these theories, and discuss possible explanations for the low Poisson's ratio observations in the oceanic crust. Although my emphasis will be on variations in Poisson's ratio, it is important to recognize that individual *P*- and *S*-wave velocity variations are also significant, a point which I will return to later.

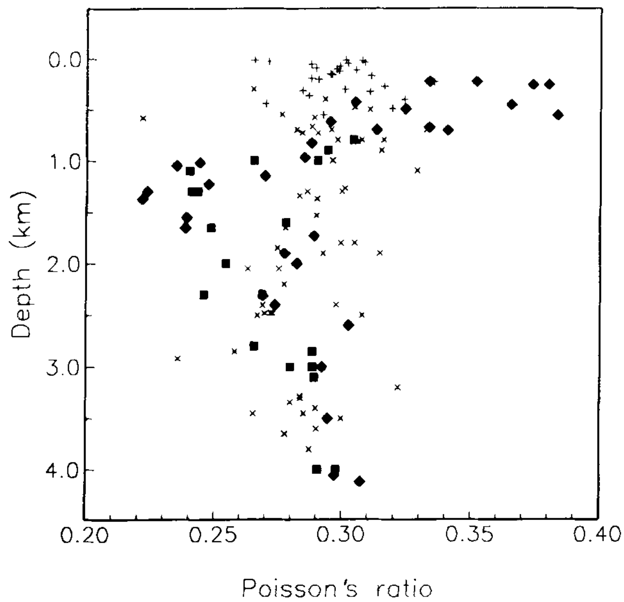

Figure 1. Poisson's ratio vs. depth within the oceanic crust for seismic refraction lines FF2 and FF4 (solid diamonds) from Spudich & Orcutt (1980) and lines EX2 and EX3 (solid squares) from Au & Clowes (1984), as compared with measurements of samples from an oceanic borehole (crosses) and ophiolites (X's). At shallow depths (<0.5 km), the refraction data indicate relatively high values for Poisson's ratio, while at depths of 1–1.5 km the data indicate anomalously low values of Poisson's ratio.

THEORETICAL CRACK MODELS

Many theories have been advanced to determine the effective elastic constants of a cracked material (see Watt *et al.* 1976, for a review). In this note, I will show results from the theories of Walsh (1969), Kuster & Toksöz (1974), O'Connell & Budiansky (1974, 1977), Garbin & Knopoff (1975), Watt *et al.* (1976) and Hudson (1980, 1981). These theories are typically valid only for low crack densities and restricted crack aspect ratios, and all should be considered approximate. The theories of Walsh (1969), Kuster & Toksöz (1974), and Garbin & Knopoff (1975) are to first order in crack density and neglect any crack–crack interactions. The self-consistent theories (Watt *et al.* 1976; O'Connell & Budiansky 1974) assume that the host matrix has the elastic properties of the final composite, are generally solved iteratively, and are claimed to give more accurate results at high crack densities than the first-order theories. Hudson's (1980) theory is not self-consistent, but includes second-order terms in crack density (correcting for some of the interaction between cracks). Most of these theories assume that the cracks are randomly oriented so that the composite material is effectively isotropic. The Hudson theory also includes a result for aligned cracks, for which the composite material is anisotropic. In order to determine the effect of cracks on Poisson's ratio, I examined the results of these theories for various crack aspect ratios and densities, both for isotropic and anisotropic models. In all cases, I assumed the cracks were water-filled ($\alpha = 1.5\,\mathrm{km\,s^{-1}}$, $\rho = 1.0\,\mathrm{Mg\,m^3}$), a likely situation in the upper oceanic crust.

The actual crack geometry in the oceanic crust is likely to be more complicated than these models, with cracks of varying degrees of alignment. Unfortunately, there is no independent evidence concerning the degree of crack alignment within the crust at the anomalous sites. Lacking such evidence, the two crack alignment models considered should be regarded as the limiting cases of no crack alignment (isotropic) and perfect crack alignment (anisotropic). Seismic properties of other models containing various degrees of partial crack alignment are likely to lie between these two cases.

ISOTROPIC RESULTS

For an example material ($\alpha = 6.0\,\mathrm{km\,s^{-1}}$, $\beta = 3.46\,\mathrm{km\,s^{-1}}$, $\rho = 2.8\,\mathrm{Mg\,m^{-3}}$, $\sigma = 0.25$), Fig. 2 shows the theoretical change in the P- and S-wave velocities (α, β) and the Poisson's ratio (σ) for the various theories as a function of crack aspect ratio (d), assuming that the crack density (ϵ) is held constant at $\epsilon = 0.05$. ϵ is a measure of the number of cracks per unit volume, and is defined as $\epsilon = Na^3/V$, where N is the number of cracks per volume V, and a is the crack radius. For ellipsoidal cracks, porosity (c) is related to ϵ by $c = \frac{4}{3}\pi d\epsilon$, and thus in Fig. 2 porosity scales with aspect ratio, increasing to 21 per cent at $d = 1$ (spherical pores). The theories of Walsh (1969), Hudson (1980), and O'Connell & Budiansky (1974) are valid only for small aspect ratios ($d \ll 1$) and are thus not shown above $d = 0.1$. The theory of Garbin & Knopoff (1975) applies to infinitely thin cracks, but for comparison is shown plotted at the left of Fig. 2. The self-consistent result for spheres (taken from Watt *et al.* 1976) is shown as a single point at $d = 1$. The Kuster & Toksöz (1974) theory is most useful, applying at all aspect ratios.

The theories agree extremely well for thin cracks ($d < 0.01$) but begin to diverge somewhat for thick cracks ($d = 0.1$), reflecting the inaccuracy of a thin-crack approximation in this case. The Kuster & Toksöz theory (not self-consistent) is accurate only for low porosities, and thus deviates from the self-consistent result for spheres (Watt *et al.* 1976) at a porosity of 21 per cent. However, the predicted Poisson's ratios for the two theories are in agreement, since the disagreements in P- and S-wave velocities are roughly proportional.

For thin cracks ($d < 0.005$), the S-wave velocity is reduced proportionally more than the P-wave velocity and the Poisson's ratio is increased. For thick cracks ($0.05 < d < 0.5$), the P-wave velocity reduction is more important, and the Poisson's ratio is decreased. For spherical cracks ($d = 1$), the Poisson's ratio is almost unchanged. This dependence of Poisson's ratio on crack aspect ratio was previously noted by Hyndman (1979).

Figure 3 illustrates the increase in Poisson's ratio for a thin-cracked material ($d = 0.001$) as a function of porosity, while Fig. 4 shows the decrease in Poisson's ratio for a thick-cracked material ($d = 0.1$). Note the difference in the porosity scaling – at a given porosity, thin cracks will have a much greater effect on elastic properties than thick cracks.

ANISOTROPIC RESULTS

If cracks are aligned in a particular direction, then the material becomes anisotropic and seismic velocities (and

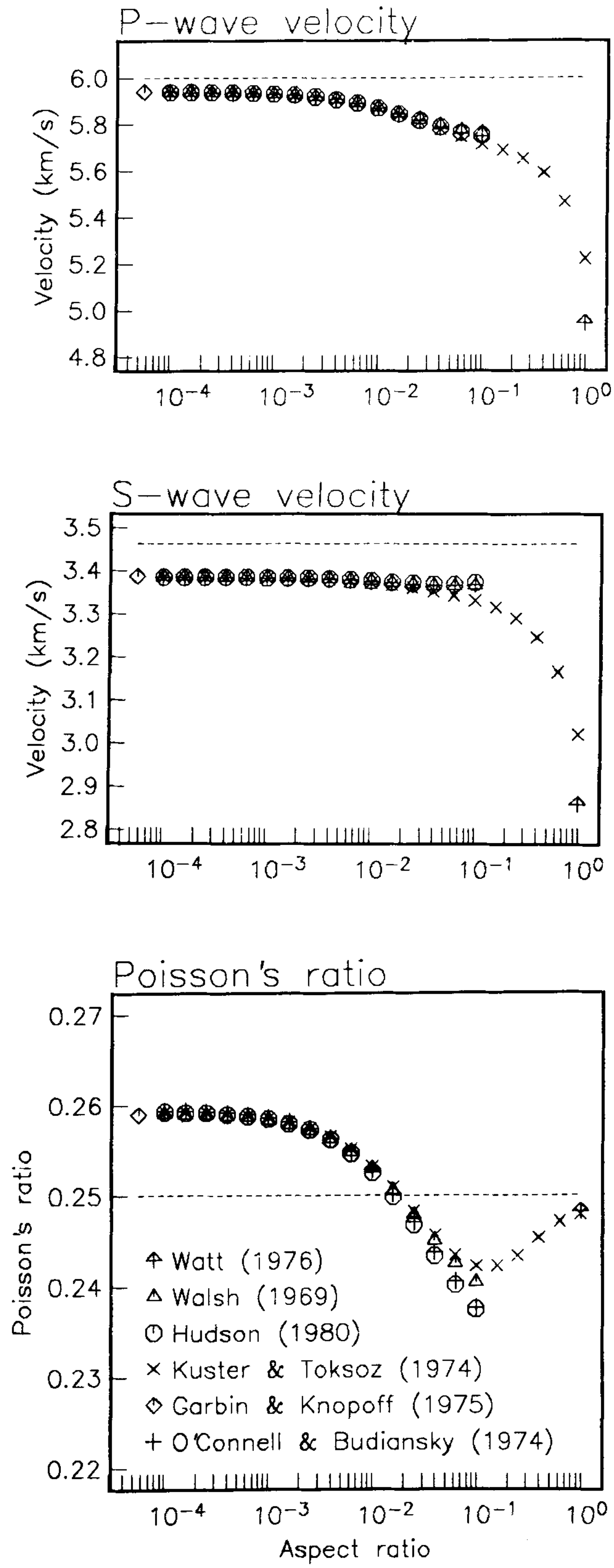

Figure 2. Theoretical *P*- and *S*-wave velocities and Poisson's ratios for a rock ($\alpha = 6.0\ \mathrm{km\,s^{-1}}$, $\beta = 3.46\ \mathrm{km\,s^{-1}}$, $\rho = 2.8\ \mathrm{Mg\,m^{-3}}$, $\alpha =$ 0.25) permeated with random, water-filled cracks. Crack density is constant ($\epsilon = 0.05$) while the crack aspect ratio (d) varies from 0.0001 (very thin cracks) to 1.0 (spheres). Elastic properties of unfractured rock are indicated by the dashed lines.

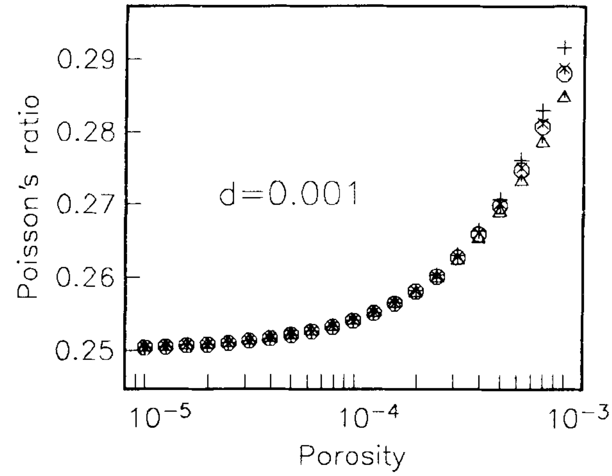

Figure 3. Poisson's ratio as a function of porosity for thin cracks ($d = 0.001$). Symbols are as in Fig. 2.

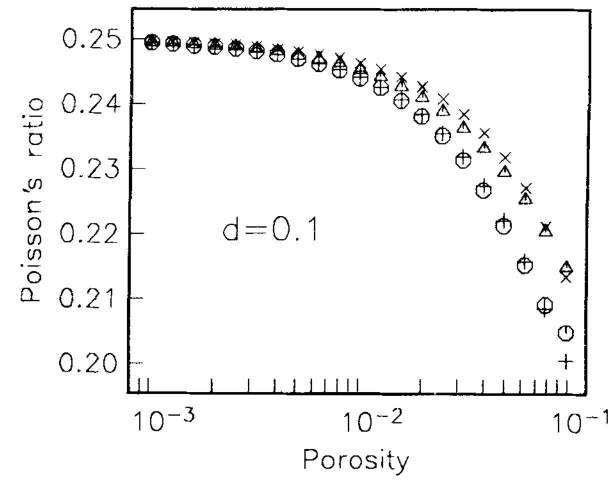

Figure 4. Poisson's ratio as a function of porosity for thick cracks ($d = 0.1$). Symbols are as in Fig. 2.

apparent Poisson's ratio) vary with the direction of wave propagation. Recently, several authors have suggested that such crack-induced anisotropy may be present in the uppermost oceanic crust (i.e. Stephen 1981, 1985; White & Whitmarsh 1984; Shearer & Orcutt 1985, 1986). Fig. 5 shows results of the Hudson (1980) theory for a system of parallel, vertical, water-filled cracks with constant crack density ($\epsilon = 0.05$) and varying aspect ratio. *P*- and *SV*-wave velocities and apparent Poisson's ratios are plotted for waves at azimuths of 0°, 45° and 90° from the crack direction.

As in the isotropic case, there is a significant difference in the behavior of thin cracks and thick cracks. At very small aspect ratios ($d < 0.001$), *P*-wave velocities exhibit a 4θ azimuthal dependence, with velocity maxima at angles both parallel and perpendicular to the crack direction. This saturated, thin-crack anisotropy was described by Crampin (1984). However, at larger-aspect ratios ($d > 0.02$), the *P*-wave velocities exhibit a 2θ dependence, with the maximum velocity parallel to the cracks and the minimum velocity perpendicular to the cracks. *SV*-wave velocities are not a function of the crack aspect ratio, and have a 2θ azimuthal dependence.

The effect of these changes in the P- and SV-wave velocities on the apparent Poisson's ratio can also be seen in Fig. 5. The Poisson's ratio is increased for very small aspect ratio, thin cracks ($d < 0.005$) and decreased for larger aspect ratio, thick cracks ($d > 0.05$), with the greatest changes occurring for directions perpendicular to the crack orientation. If these results are averaged over the different azimuths, it can be seen that they are in approximate agreement with the isotropic results shown in Fig. 2. However, for a given crack density and aspect ratio, much greater changes in elastic properties occur at certain azimuths for the anisotropic model than for the isotropic model. In particular, very low values of Poisson's ratio are possible in the direction normal to the cracks, an effect noted by Anderson *et al.* (1974).

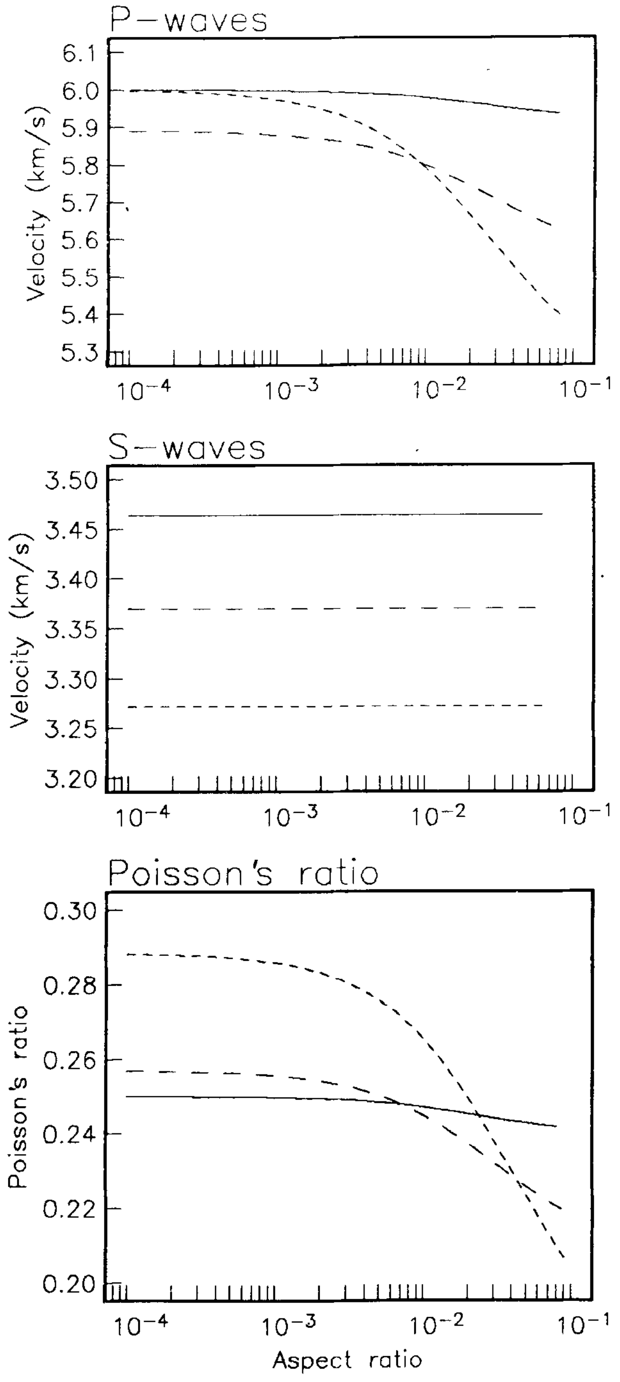

Figure 5. Theoretical P- and S-wave velocities and apparent Poisson's ratios for a rock ($\alpha = 6.0\,\mathrm{km\,s^{-1}}$, $\beta = 3.46\,\mathrm{km\,s^{-1}}$, $\sigma = 0.25$) containing aligned, vertical, water-filled cracks, using the anisotropic theory of Hudson (1980). Velocities vary with azimuth, and are shown at angles parallel to the cracks (solid), at 45° to the cracks (dashed), and perpendicular to the cracks (dotted). Crack aspect ratio varies from 0.0001 to 0.1, with crack density constant at $\epsilon = 0.05$.

DISCUSSION

For both the isotropic and anisotropic geometries, the physical reason for the difference between the theoretical seismic properties of saturated thin- and thick-cracked material can be seen in the behaviour of the shear modulus μ and bulk modulus κ ar different aspect ratios. At all small aspect ratios ($d < 0.1$), μ decreases by a fixed amount determined only by the crack density. In contrast, κ is unchanged for very thin cracks, but decreases with increasing crack thickness. Thus for thin cracks, the P-wave velocity, $\alpha^2 = (\kappa + 4\mu/3)/\rho$, decreases proportionally less than the S-wave velocity, $\beta^2 = \mu/\rho$, and the Poissons's ratio increases. However, for thicker cracks the decrease in κ becomes more important than the decrease in μ, and the Poisson's ratio decreases. At very large aspect ratios ($d > 0.1$), only the Kuster & Toksöz (1974) isotropic theory remains valid. In this region between very thick cracks and spherical cavities, the decrease in Poisson's ratio is reduced with increasing crack aspect ratio (see Fig. 2). For the material shown in Fig. 2, the Poissons's ratio is nearly unchanged for spherical cavities ($d = 1$).

These generalizations were inferred from results for a specific material ($\alpha = 6.0\,\mathrm{km\,s^{-1}}$, $\sigma = 0.25$) and crack density ($\epsilon = 0.05$) and should be expected to vary somewhat for other materials.

THE UPPER OCEANIC CRUST

Observations of low P-wave velocities near the surface of the oceanic crust have been explained as a result of cracks, fissures and other voids within higher-velocity basalt (i.e. Whitmarsh 1978; Spudich & Orcutt 1980; Bratt & Purdy 1984). If the observed Poisson's ratio is relatively high, then the cracks must be relatively thin (as noted above, and in Hyndman 1979). For instance, the Poisson's ratio of an oceanic basalt ($\alpha = 6.28\,\mathrm{km\,s^{-1}}$, $\beta = 3.41\,\mathrm{km\,s^{-1}}$, $\rho = 2.92\,\mathrm{Mg\,m^{-3}}$, example taken from Whitmarsh 1978) will change from 0.29 to 0.31 with the addition of 0.001 aspect ratio cracks at a porosity of just 0.06 per cent.

Spudich & Orcutt (1980) and Au & Clowes (1984) attempted to determine the most likely composition of the oceanic crust by comparing their observed P- and S-wave velocities with values from ophiolite samples. At most depths there was good agreement, but the low Poisson's ratios which they observed at 1–1.5 km depth are difficult to explain in this way, since the ophiolite rocks with the closest Poisson's ratio, the trondhjemites, are normally found at greater depths in the ophiolites. Spudich & Orcutt used the isotropic crack theory of O'Connell & Budiansky (1974) to

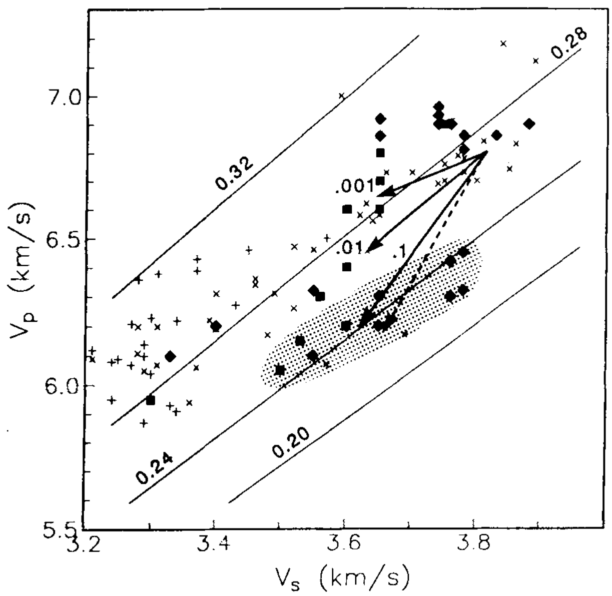

Figure 6. *P*-wave velocity vs. *S*-wave velocity for seismic refraction lines FF2 and FF4 (solid diamonds) from Spudich & Orcutt (1980) and lines EX2 and EX3 (solid squares) from Au & Clowes (1984), as compared with measurements of samples from an oceanic borehole (crosses) and ophiolites (*X*'s). Lines of constant Poisson's ratio are also shown. The stippled region indicates the area of anomalously low values of Poissons' ratio which are indicated by the refraction data at depths of 1–1.5 km. The arrows show the effect of water-filled cracks on the velocities of a reference material with elastic properties near many of the ophiolite samples. Each arrow corresponds to a different crack aspect ratio and shows the change in the seismic velocities for a crack density of $\epsilon = 0.1$. A crack aspect ratio of $d = 0.1$ comes closest to explaining the anomalous observations. The dashed arrow shows the change in seismic velocities in the direction perpendicular to the cracks for an anisotropic model of aligned cracks with crack aspect ratio $d = 0.1$ and crack density $\epsilon = 0.038$.

show that rocks which could be fractured to exactly match their observations have elastic properties well removed from any of the ophiolite samples, most of which have Poisson's ratios of 0.27–0.28 (see Fig. 22, Spudich & Orcutt 1980). The problem is not simply the low Poisson's ratio itself, but that the observed *S*-wave velocities (3.5–3.75 km s^{-1}) are close to the *S*-wave velocities of the ophiolite samples, but the observed *P*-wave velocities (6.0–6.4 km s^{-1}) are significantly less than the ophiolite *P*-wave velocities. Thus, it is important to consider both the *P*-and *S*-wave velocities individually, and not simply their ratio.

This is illustrated in Fig. 6, which plots *P*-wave vs. *S*-wave velocity for the refraction data and measurements of ophiolite and oceanic borehole samples to a depth of 4 km. This type of plot, first popularized by Spudich & Orcutt (1980), also shows lines of constant Poisson's ratio. The refraction data points are taken directly from velocity models calculated for lines FF2 and FF4 (Spudich & Orcutt 1980) and EX2 and EX3 (Au & Clowes 1984). Because these data are unsmoothed, the refraction data exhibit more scatter in this plot than similar plots of smoothed data in Spudich & Orcutt (1980) and Au & Clowes (1984). The stippled region in Fig. 6 shows the area of anomalous observations, in which the Poisson's ratios are significantly less than those of ophiolite and borehole samples.

The addition of cracks to a sample shown in Fig. 6 will reduce both *P*- and *S*-wave velocities and move its position diagonally to the lower left. The arrows in Fig. 6 illustrate this for a reference point with seismic velocities typical of ophiolite samples ($\alpha = 6.8$ km s^{-1}, $\beta = 3.82$ km s^{-1}, $\sigma = 0.27$). Assuming a constant crack density of $\epsilon = 0.1$, each arrow shows the effect of a particular crack aspect ratio on the velocities of the composite material. As expected, Poisson's ratio is increased by thick cracks and decreased by thick cracks. Much of the anomaly represented by the stippled region in Fig. 6 could thus be modelled as an effect of water-filled thick cracks ($d = 0.1$) on material of higher Poisson's ratio. In this case, the velocities of the composite material are $\alpha = 6.21$ km s^{-1}, $\beta = 3.82$ km s^{-1} ($\sigma = 0.24$), with a porosity of 4.2 per cent. However, as shown in Fig. 2, a crack aspect ratio of about 0.1 represents the maximum effect possible on lowering Poisson's ratio, and thus the points at the right side of the stippled region (from FF2 and FF4) cannot be fitted with a crack model of this type.

For some of the anomalous points, a slightly closer fit can be obtained with much less required porosity if we assume that the cracks are aligned and the material is anisotropic. The dashed arrow in Fig. 6 shows the composite velocities in the direction perpendicular to the cracks for $d = 0.1$ and $\epsilon = 0.038$ (porosity of 1.6 per cent). However, this model seems unlikely because three of the four seismic refraction profiles involved (EX2, FF2, FF4) were shot perpendicular to the fossil-spreading direction, while most seismic evidence for anisotropy in the uppermost crust (i.e. Stephen 1985; Shearer & Orcutt 1986) indicates that cracks are aligned parallel to the original spreading ridge. This implies that the most probable orientation of cracks for these refraction lines is parallel, not perpendicular, to the shooting direction. The limited data available at the anomalous sites do not permit the resolution of any possible anisotropy. The Shearer & Orcutt (1986) observation of upper-crustal anisotropy in the SW Pacific indicated that the Poisson's ratio within the anisotropic region was about 0.28–0.30, with little azimuthal variation – values in approximate agreement with ophiolite measurements.

Spudich & Orcutt (1980) attempted to model their low Poisson' ratio observations (from line FF2 and FF4), using the crack theory of O'Connell & Budiansky (1974), and showed that exact agreement with ophiolite sample velocities was not possible. My results confirm this, and show that no crack aspect ratio or anisotropic alignment is capable of exactly fitting the most anomalous of the FF2 and FF4 data points with an ophiolite model. Although Spudich & Orcutt did not explicitly consider crack aspect ratio in their analysis, aspect ratio d is included in the O'Connell & Budiansky (1974) parameter $\omega = K'/Kd$, where K'/K is the ratio of the fluid to host matrix bulk moduli. For the reference ophiolite sample point shown in Fig. 6, $\omega = 0.3$ for water-filled cracks with aspect ratio $d = 0.1$.

Although an exact fit to all of the anomalous points shown in Fig. 6 is not possible with existing crack theories, it is possible to explain much of the anomalous effect. One could argue that the points within the stippled region represent observational scatter, and that a model of a thick-cracked material ($d = 0.1$) is adequate to reconcile the observations with the ophiolite samples. However, this explanation is not wholly satisfactory for several reasons:

(1) It is *ad hoc*; there is no independent evidence that the oceanic crust is permeated with thick cracks at depths of 1–1.5 km. The known factures, cracks and voids in the very shallow oceanic crust (<0.5 km) appear to *increase* the Poisson's ratio; thus the nature of the cracking must change (i.e. to thicker cracks) at depth.

(2) The anomalous points most closely fit at an extreme of the crack aspect ratio ($d = 0.1$), and some of the observations cannot be exactly fitted.

(3) The required porosity may be higher than that present in the oceanic crust at depths of 1–1.5 km since borehole measurements indicate a porosity of 1 per cent at only 1.2 km depth in the oceanic crust (Becker *et al.* 1982).

Thus, other explanations for the anomalous observations should also be considered. These include:

(1) Unfractured low Poisson's ratio rock is present at depths of 1–1.5 km in the oceanic crust, and the ophiolites are not representative of the oceanic crust at these sites. Spudich & Orcutt (1980) suggested the possibility that trondhjemites, which have low Poisson's ratio due to their relatively high quartz content, might be responsible for the observations. Trondhjemites have been observed in ophiolites, but at greater depths and not in large abundance (Salisbury & Christensen 1978; Christensen & Smewing 1981).

(2) Existing crack theories do not accurately describe the effect of cracking for these observations. The only theory valid at crack aspect ratios between 0.1 and 1.0 (Kuster & Toksöz 1974) is not self-consistent and is thus suspect at high crack densities. At very high crack densities, even the self-consistent and second order crack theories may not be accurate.

(3) Although Spudich & Orcutt (1980) and Au & Clowes (1984) took great care in their synthetic seismogram modelling, it is not inconceivable that the low Poisson's ratio result is an artifact of the processing. There is a trade-off between fitting different parts of velocity models, and if near-surface *S*-wave velocities were underestimated, this could lead to models with unrealistically high *S*-wave velocities at depth. Lateral heterogeneity is now recognized as a significant complication in analysis of the oceanic crust (i.e. Bratt & Purdy 1984), and might be causing bias in these 1-D models.

The existing data are not adequate to discriminate between these explanations, and more work is needed. Particularly helpful would be more-detailed seismic refraction surveys at sites with anomalous Poisson's ratio observations, with the aim of increasing the resolution of the seismic velocities and resolving the effects of any lateral heterogeneity and/or anisotropy as indicated by azimuthal velocity variations or *S*-wave splitting. Also useful would be theoretical or experimental studies of the effect on seismic velocities of very thick cracks ($0.05 < d < 1.0$) at high crack densities ($\epsilon > 0.1$).

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