FORUM

Comment and Reply on "Seismic anisotropy due to preferred mineral orientation observed in shallow crustal rocks in southern Alaska"

COMMENT

Stuart Crampin, *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, Scotland*

Brocher and Christensen (1990) interpreted reflection-refraction profiles in the Chugach terrane of southern Alaska (Brocher et al., 1989) in terms of 20% P-wave velocity anisotropy. They identified this anisotropy with laboratory measurements of velocities in specimens of heavily foliated phyllitic schists from the Chugach terrane. They argued that because such foliated metamorphic rocks are common throughout the continental crust, the anisotropy-induced shear-wave splitting observed throughout much of Earth's crust is caused by mineral alignments and not the stress-aligned fluid-filled inclusions (known as extensive-dilatancy anisotropy, or EDA) suggested by Crampin (1987).

There are several features of that analysis that, I believe, invalidate these conclusions.

The assumption of strong velocity anisotropy in the field data is questionable. Most observations of seismic anisotropy (particularly EDA) in the crust are of shear-wave splitting (shear-wave birefringence). Shear waves carry much more information than P (compressional) waves, so that a few observations of shear-wave splitting are highly diagnostic of seismic anisotropy (Crampin, 1987). In contrast, because of the typically large scatter, reliable estimates of P-wave anisotropy from traveltime observations in the continental crust require unusually comprehensive datasets over 360° of azimuth. Few such experiments have been carried out. Kohler et al. (1982), as interpreted by Crampin et al. (1986), is the only one known to me.

The reflection-refraction line in the complicated Chugach terrane follows a wandering path containing two approximately straight-line sections oriented northeast-southwest and northwest-southeast. Brocher and Christensen (1990) based their evaluation of seismic anisotropy on selected source and receiver pairs from these orthogonal legs. Suitable pairs are strictly limited both in number and azimuth. Because the foliations of the phyllitic schists in this area are generally aligned east-west (Brocher and Christensen, 1990), approximately bisecting the northeast-southwest and northeast-southeast legs, if the velocity variations were primarily the result of foliations, as Brocher and Christensen suggested, the equally inclined orthogonal legs would be expected to have similar velocities. In fact, common shot gathers (Fig. 2 of Brocher, et al., 1989) for an explosion near the junction of the two orthogonal profiles show substantial traveltime differences between the orthogonal directions. The traveltimes for the northwest-southeast line are generally 30% (occasionally 50%) greater than those at equivalent distances along the northeast-southwest line. These variations of P-wave traveltimes with azimuth are much more likely to be caused by structural irregularities than by P-wave anisotropy, in this geologically and topographically complicated area.

Laboratory measurements of seismic velocity in intact specimens can be equated directly with field measurements. Cracks have significant effects on seismic velocities (Crampin, 1984), so that velocities in intact laboratory specimens are typically greater than those in conditions in situ where the rock is cracked. Specimens, when extracted, are destressed and new stress regimes imposed, with the potential for drastically modifying the most compliant elements of the rock mass—the fluid-filled inclusions. Merely restoring in situ stress, as Brocher and Christensen have done, does not necessarily restore the original inclusion geometry. Similarly, increasing pressure with depth of burial does not necessarily close isolated inclusions containing trapped pore fluids. These various difficulties are demonstrated by the velocities in the intact rock specimens (Brocher and Christensen, 1990), which are substantially greater at all pressures than the velocities at equivalent depths in the field.

A further misunderstanding in Brocher and Christensen (1990) is that P waves in cracked rock in situ necessarily have a cos 2θ variation (repeating every 180°) with a fast direction parallel, and a slow direction perpendicular, to the parallel cracks. Dry (empty) cracks, or liquid-filled cracks of large aspect ratio, do have a cos 2θ P-wave variation, but the liquid-filled cracks found in most rocks in situ, where the cracks are comparatively thin, have a cos 4θ P-wave velocity variation, repeating every 90° (Crampin, 1984).

Several sources of anisotropy may contribute to the shear-wave splitting now widely observed in many areas of the crust in a wide variety of rocks, where foliated metamorphic rocks are absent: granite batholiths, sedimentary basins, poorly consolidated sediments, mixed tectonic regimes, etc. (Crampin et al., 1987). The similarities in the patterns of shear-wave splitting observed in almost all rocks worldwide suggest (although they do not prove) that a single source of anisotropy is everywhere present. The only source of anisotropy satisfying all observations, and common to all rocks where shear-wave splitting has been observed, is stress-aligned fluid-filled inclusions (EDA cracks) (Crampin et al., 1987). It is interesting to note that a few three-component observations of shear waves (from P to S conversions from explosions during the reflection-refraction profile, or from nearby earthquakes) would have provided critical information about the presence or absence of EDA cracks in the Chugach terrane.

REPLY

Thomas M. Brocher, *U.S. Geological Survey, MS 977, 345 Middlefield Road, Menlo Park, California 94025*
Nikolas I. Christensen, *Department of Earth & Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907*

We welcome this opportunity to expand upon our interpretation (Brocher and Christensen, 1990) of seismic reflection-refraction data from the Chugach terrane in southern Alaska as reported by Brocher et al. (1989). Although we argued that foliated metamorphic rocks are pervasive and can probably explain much of the seismic anisotropy observed in the continental crust, there clearly are regions where other mechanisms for anisotropy, including oriented cracks, must be sought. By stating that anisotropy "is not all that it's cracked up to be," we meant to suggest that other explanations, besides cracks, should be considered in many cases. The seismic reflection data reported by Brocher et al. (1989) were not recorded for the purpose of measuring anisotropy in P-wave velocities. When the anisotropy in P-wave velocity is as large as in southern Alaska, however, it is possible to recognize its presence and general orientation with the less than optimal dataset reported by Brocher et al. (1989). We do not agree with Crampin (Comment above) that there are several flaws in our analysis which invalidate our conclusions.

The observation of a large P-wave velocity anisotropy in the field data from southern Alaska is not an artifact of structural complexity. The geology of the Chugach terrane sampled by seismic waves used for the anisotropy analysis is relatively simple, as illustrated in our detailed geologic map (Brocher and Christensen, 1990). The study area consists of phyllites having a pervasive metamorphic foliation and orientation. These phyllites are covered with a thin veneer of Quaternary deposits whose velocity and thickness along the seismic line were well resolved by the two-dimensional forward modeling described by Brocher et al. (1989), using shotpoints every 2–3 km and receivers every 30 m. Although the surface topography is significant, the road along which the seismic data were acquired has less than 100 m of relief across the study area.

Furthermore, Crampin's argument that an asymmetry in traveltimes leads to the observed azimuthal variation in velocities cannot explain the data shown in Figure 13 of Brocher et al. (1989) for northeast-southwest orientations, which were all taken south of the big bend in the seismic line at km 27. The data in this figure show little scatter for reversing travel paths, and they show a consistent velocity at the farthest ranges. Variations in the thickness of Quaternary sediments located above the foliated metamorphic rocks do produce some traveltime delays north of km 27, but the traveltimes were corrected for these variations by using the structure of these deposits determined from forward modeling.

We disagree with the contention that laboratory measurements of seismic velocities can never be compared directly with field measurements. Each such comparison must be evaluated on its own merits, on the basis of such factors as rock type and crack density. For our study, the fact that these laboratory measurements, when combined with average strike and dip of the foliated rocks, can explain the field measurements from the Chugach terrane is a powerful argument favoring our interpretation.

Although there is disagreement whether P-wave velocity anisotropy can be adequately described when a 2θ variation is used, there likewise is not universal agreement that a 4θ variation should be assumed (Anderson et al., 1974). Furthermore, laboratory measurements of anisotropy in Chugach phyllite clearly show a 2θ variation (Fig. 1), supporting our assumption. In the Chugach terrane, we believe it is difficult to argue against the conclusion that oriented phyllosilicates within highly foliated phyllites would be expected to produce the observed anisotropy with the slow direction orthogonal to the foliation plane.

In supporting a model for crustal anisotropy due to stress-aligned fluid-filled inclusions, Crampin has chosen to explain shear-wave splitting observations by only one of the many potential mechanisms. Three-component observations alone, however, cannot be used to infer the origin of the anisotropy. Shear-wave splitting in crustal rocks was first observed during laboratory investigations (Christensen, 1966), and more recent laboratory investigations (e.g., Christensen, 1971; Christensen and Ramananantoandro, 1971), have demonstrated the presence of strong shear-wave splitting in a wide variety of rocks at hydrostatic pressures where cracks are closed. Petrofabric measurements have shown that this splitting originates from preferred orientation of anisotropic minerals. For this reason, we believe that integrated geological and seismological studies of anisotropy are important. Such integrated studies have been crucial to the Trans-Alaska Crustal Transect investigations of the crustal structure across Alaska. In our case, the detailed field mapping, seismic reflection and refraction profiling, and laboratory measurements of lithologic units *all* provide important support for our interpretation. Our laboratory measurements predict that significant shear-wave splitting will occur in the study area (Fig. 2), and we are therefore confident that three-component observations of shear waves will confirm our interpretation of the existing seismic data.

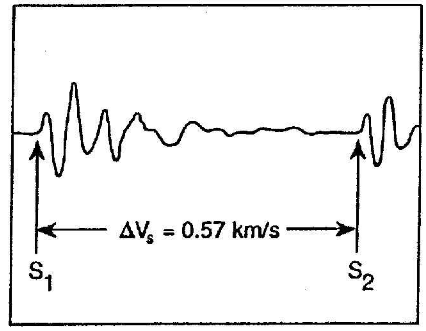

Figure 2. Shear-wave splitting at 200 MPa originating from preferred mineral orientation in Chugach phyllite for propagation parallel to foliation. Fast wave S_1 vibrates parallel to foliation, whereas slow wave S_2 vibrates normal to foliation.

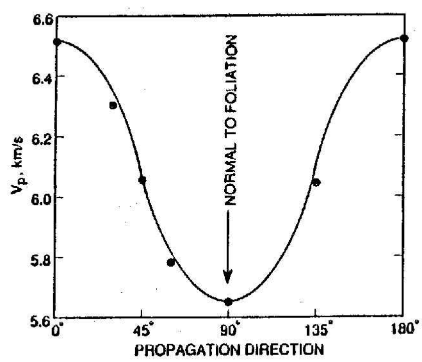

Figure 1. Compressional wave velocity as function of propagation direction relative to foliation plane. Measurements were made by using core samples cut at directions indicated from one rock sample. Note 2θ variation in compressional wave velocity.

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Comment on "U/Pb zircon and baddeleyite ages for the Palisades and Gettysburg sills of the northeastern United States: Implications for the age of the Triassic/Jurassic boundary"

Ajoy K. Baksi, *Department of Geology and Geophysics, Louisiana State University, Baton Rouge, Louisiana 70803*

Dunning and Hodych's (1990) high-precision U/Pb ages have repercussions for estimates of the age of the Triassic/Jurassic boundary, as well as the opening of the north-central section of the Atlantic Ocean. Their ages are not totally in agreement with $^{40}Ar/^{39}Ar$ data for these same intrusive bodies, nor with argon data for lava flows of the Newark Supergroup. Recent $^{40}Ar/^{39}Ar$ dating of mafic rocks indicates that, in general, plateau ages are older than K-Ar dates (Baksi and Farrar, 1990); this explains Dunning and Hodych's (1990) observation that their U/Pb ages are older than most of the K-Ar dates on equivalent rock units. However,