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The role of crystallographic fabric in the generation of seismic anisotropy and reflectivity of high strain zones in calcite rocks

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Abstract—For a relatively pure calcite ultramylonite (grain size: 5 μm) from the Ivrea–Verbano zone of the the N.W. Italian Alps, the crystallographic preferred orientation was measured by X-ray texture goniometry. The fabric is characterized by a 3 times uniform, axisymmetric *c*-axis maximum, normal to the mesoscopic foliation. From this and available single crystal elastic properties of calcite, the expected variation of acoustic (P-wave) velocity with orientation can be calculated. This is compared with high pressure (up to 520 MPa at 20°C) ultrasonic velocity measurements made on seven different core orientations from the same rock, and good agreement obtained between the calculated and measured velocity distribution. Seismic velocity contrasts range up to 3.3% relative to an isotropically-textured protolith, sufficient to give rise to detectable seismic reflectivity. For normal incidence P-waves on a horizontal shear zone, crystallographic texture of the type observed maximises the obtainable seismic reflectivity. For a c-maximum fabric oriented obliquely to the plane of the high strain zone (as is observed in some other natural shear zones), or for a gently dipping shear zone, reflectivity may be either enhanced or weakened. Thus, visibility may be very sensitive to the local dip of a shear zone and the fabric orientation and intensity within it. © 1998 Elsevier Science Ltd.

INTRODUCTION

The propagation velocity of elastic waves through a zero porosity rock depends on the elastic properties of the constituent minerals, their relative (modal) proportions, their orientation distribution (texture), and the way that the different mineral phases are arranged spatially within the rock (microstructure). Given this information about a given rock, it is possible to calculate P and S wave velocities (V_p and V_s) as a function of orientation with respect to sample or geographic coordinates (e.g. Mainprice *et al.*, 1990). The essential methodology has been described by Mainprice and Nicolas (1989) and Mainprice and Humbert (1994), who have also provided computer programs for making such calculations. In a number of studies, velocity anisotropy has been measured directly in the laboratory on differently oriented rock samples (e.g. Christensen and Szymanski, 1988; Kern, 1990; Kern and Wenk, 1990) and related to seismic reflectivity. Seront *et al.* (1993) have made a detailed study of an anorthosite, relating seismic velocities calculated from the rock texture to laboratory measurements of ultrasonic velocity at high pressures in 24 different directions, and demonstrated good agreement. Such comparative experimental observations must be made at high hydrostatic pressures (typically above 200 to 300 MPa) so that cracks and pores become closed, and the variation of velocity with pressure is due solely to the effect of pressure on the elastic properties and densities of the constituent minerals.

For a given wave propagation direction in a rock in which there is no special microstructural arrangement of the constituent minerals, the modal proportion, combined with an averaging scheme for the effective elastic properties in that direction (Voigt, Reuss or Hill) allows the wave velocities to be calculated. The Voigt scheme, in which strain compatibility is assumed between all grains, tends to give the best agreement between calculated and measured velocity distributions (Seront *et al.*, 1993; Mainprice and Humbert, 1994). If different mineral phases are arranged into bands (such as in a gneiss), velocity anisotropy of the first arrival will arise, even if there is no crystallographic preferred orientation (CPO) in those bands. In the case of an isotropic microstructural arrangement, however, or in the case of a monomineralic rock, velocity anisotropy will arise only as a result of crystallographic preferred orientation.

Seismic reflectivity arises from contrasts in acoustic impedance in the wave propagation direction. Acoustic impedance (Z) is defined as $V_p\rho$, where ρ is the rock density, from which the reflection coefficient R for a P-wave at normal incidence to the boundary is defined as $(Z_1 - Z_2)/(Z_1 + Z_2)$, in which subscripts 1 and 2 refer to the rocks one either side of the interface. It is therefore to be anticipated that, for certain types of plastic strain-induced CPO, impedance contrasts may arise across the boundaries of planar high strain zones (such as plastic shear zones) sufficient to give rise to seismic reflectivity where otherwise none would exist. In this paper, we investigate the extent to which reflectivity may arise in pure (or nearly pure) calcite rocks containing a planar high plastic strain zone. The mineral calcite has a high degree of anisotropy of elastic properties, but the acoustic impedance contrasts that can be developed depend strongly on the types of CPO that can be developed. We have made ultrasonic velocity measurements at high pressure on a calcite mylonite and on Carrara marble (as an analogue for its protolith). The measured velocities are then compared with velocities calculated from measured CPO (texture), together with the known elastic properties of calcite.

METHODS EMPLOYED

The sample materials were characterized chemically and mineralogically by X-ray fluorescence (XRF), and by scanning electron microscopy (SEM) fitted with an energy dispersive analytical system. The microstructure was studied using ultrathin, double-polished thin sections, which allows ultrafine grained (*ca* 5 μm) calcite rocks to be imaged spectacularly well.

Preferred crystallographic orientations of calcite *c*-axes were measured optically using a universal microscope stage, but complete orientation distributions for both rock types were measured by X-ray texture goniometry. The X-ray textures were determined using a Scintag XDS2000 texture goniometer with CuKα radiation. Each pole figure was determined by a combination of reflection and transmission mode scans (Siddans, 1976). Seven pole figures [012 (*f*), 104 (*r*), 110 (*a*), 113, 202 (*h*), overlapping 024, 018 (*e*) and 116] were measured (see Rutter *et al.*, 1994 for crystallographic convention used). The standard harmonic method implementation of Casey (1981) was used to calculate the orientation distribution function (ODF). As the latter was used to calculate the centrosymmetric elastic properties, the indeterminacy of the odd expansion coefficients by the X-ray method does not present any problems.

Seismic P-wave velocity measurements were made at room temperature on dry cores, 15 mm in diameter and 40 mm long, at typically 20 confining pressures ranging from 20 MPa up to 520 MPa. A wait time of 10–15 min was allowed at each pressure before measurements were carried out, to allow adiabatic temperature fluctuations to dissipate. Conventional PZT (lead zirconium titanate) ceramic transducers were used at each end of the sample assembly, operating at 1 MHz. Time-of-flight measurements were made using a LeCroy 9310, 300 MHz, dual channel digital oscilloscope. A Thurlby TG1304, 13 MHz programmable signal generator was used to generate a single cycle sine wave to excite the driving transducer. Signal-averaging for noise cancellation was carried out on typically 2000 measurements at each pressure. The system was controlled from a microcomputer via an IEEE-488 bus link, and recorded waveforms were stored on disk so that first arrivals could be picked subsequently. Uncertainty in reported P-wave velocities is estimated to be $\pm 0.3\%$, and pressures are estimated to be correct to within 1 MPa.

MATERIALS STUDIED

The highly strained material is an ultrafine grained calcite mylonite from the Ivrea–Verbano zone (Northwest Italian Alps). An oriented block of about 5 kg was collected from the Cannobino river bed, 2 km SE of the village of Finero (grid ref. E686000, N105450, Carta Nazionale della Svizzera, 1:50 000 sheet 285). At this point, marbles of the Ivrea zone are transected by a number of shear zones, each a few metres wide. The protolith is a coarse-grained ($\geq$2 mm), mostly $>90\%$ calcite marble that has been metamorphosed in the upper amphibolite/granulite facies. A few isolated grains of diopside, tremolite, phlogopite, feldspar and forsterite are seen in the mylonite, in a matrix of ultrafine grained calcite (*ca* 5 μm). The calcite matrix has equant grains, devoid of twins, with straight grain boundaries (foam texture). The microstructure is virtually identical to that figured by Rutter *et al.* (1994) as typical of a dynamically recrystallized marble deformed by diffusion- plus plasticity-accommodated grain boundary sliding. From the grain size and the nature of the fabric, this deformation is inferred (based on experimental observations of Rutter, 1995) to have occurred when the rock was at about 300°C or cooler. In hand specimen the rock is foliated (060°/88°NW) and weakly lineated (plunge 05°/058°), and from mesoscopic shear sense indicators the displacement sense is inferred to be right lateral. The foliation and lineation are defined by faint colour banding and by trails of non-calcite phases, rather than by shape orientation of the calcite grains.

Owing to its coarseness and heterogeneity of grain size, the protolith to the sheared rock at this locality was not well suited to seismic velocity and X-ray texture measurements, and therefore 99% calcite Carrara marble was taken as a reference protolithic material. The marble used came from the same block that was used by Rutter (1995) for experimental deformation studies. This rock has a mean grain size of 130 μm and was found by X-ray texture goniometry to be effectively isotropically textured (Fig. 1a).

The complete preferred crystallographic orientation pattern for the calcite mylonite was found by X-ray

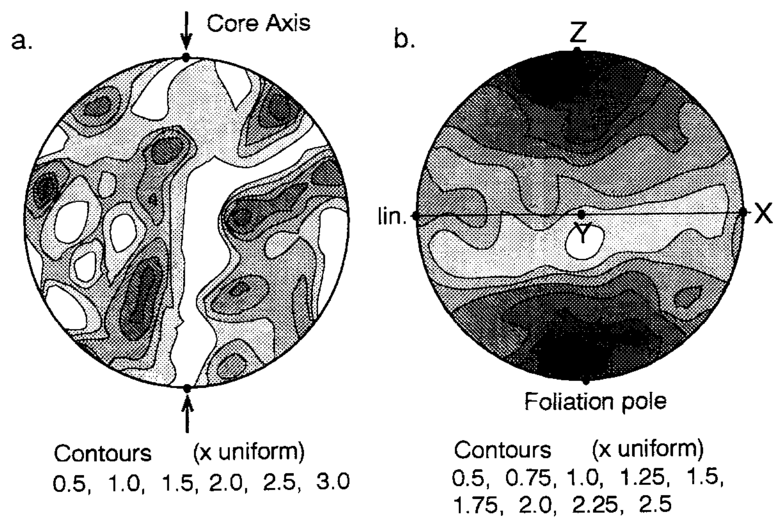

Fig. 1. Results of CPO measurements by X-ray texture goniometry. Complete orientation distributions were obtained for each rock, but only *c*-axis pole figures are shown here (upper hemisphere equal area projections, contours shown as multiples of a uniform distribution). (a) Carrara marble, with respect to core axis. (b) Ivrea–Verbano zone calcite ultramylonite, shown with respect to mesoscopic foliation and lineation, and a right-lateral sense of shear.

texture goniometry to be close to axisymmetric, with the axis of symmetry normal to the mesoscopic foliation. The *c*-axis pattern obtained by this method is shown in Fig. 1(b), with respect to the mesoscopic foliation and lineation, and agrees well with the pattern established by direct universal microscope stage measurements. This pattern has commonly been observed in studies on both experimentally and naturally deformed calcite rocks (e.g. Casey *et al.*, 1978, 1997; Schmid *et al.*, 1981, 1987; Wenk, 1985).

Rutter *et al.* (1994) established experimentally that such a pattern might be produced in the initial phase of deformation of the coarser protolith when twinning is active. Only 20–30% compression is required to produce a *c*-axis maximum on the order of 7 times uniform (Owens and Rutter, 1978). Subsequently, dynamic recrystallization would have reduced the grain size and obliterated evidence of any early twinning deformation. Much higher stress levels are required to produce twinning deformation in the finer grained mylonite than in the coarser protolith (Rowe and Rutter, 1990). The retention of an equant grain shape fabric suggests that continued deformation involved a mixture of diffusion- and plasticity-accommodated grain boundary sliding. Rutter *et al.* (1994) demonstrated that the early, pre-recrystallization fabric would survive dynamic recrystallization and subsequent deformation involving grain boundary sliding, but that it may become weakened. However, it is now known that this type of fabric can arise directly during experimental high strain flow by simple shear of an initially fine grained calcite rock when the deformation involves a mixture of grain boundary sliding and intracrystalline plasticity but without twinning (Casey *et al.*, 1998).

EXPERIMENTAL ULTRASONIC MEASUREMENTS

Ultrasonic P-wave velocity measurements were made from cores drilled in seven different directions from the block of calcite mylonite, at room temperature and up to 520-MPa confining pressure. The orientations are shown in Fig. 2(a), with respect to the kinematic frame defined by the foliation and lineation.

Figure 3 shows the results of the velocity measurements for each orientation. Each curve of velocity vs pressure is characterized by a rapid increase of velocity at low pressures, corresponding to the closure of cracks and pores, followed by a linear rate of increase above 200 MPa, corresponding to the effect of pressure on the elastic stiffnesses and density. In order to compare velocities calculated from elastic properties of calcite, density and CPO with the measured velocities, least-squares linear regression fits to the data above 200 MPa for each orientation were made, and the resulting straight line extrapolated to obtain the velocity intercept (V_0) at zero pressure. Thus in Fig. 2(a), the V_0 values in km s^{-1} are shown beside each core orientation.

The velocity–pressure relationship observed for Carrara marble is also shown in Fig. 3. As might be expected, the data lie in the middle of the cluster of curves for the much more highly textured calcite mylonite.

CALCULATED VELOCITIES

Comprehensive elastic stiffness measurements were reported for single crystals of calcite by Dandekar (1968a,b) and Dandekar and Ruoff (1968). From these

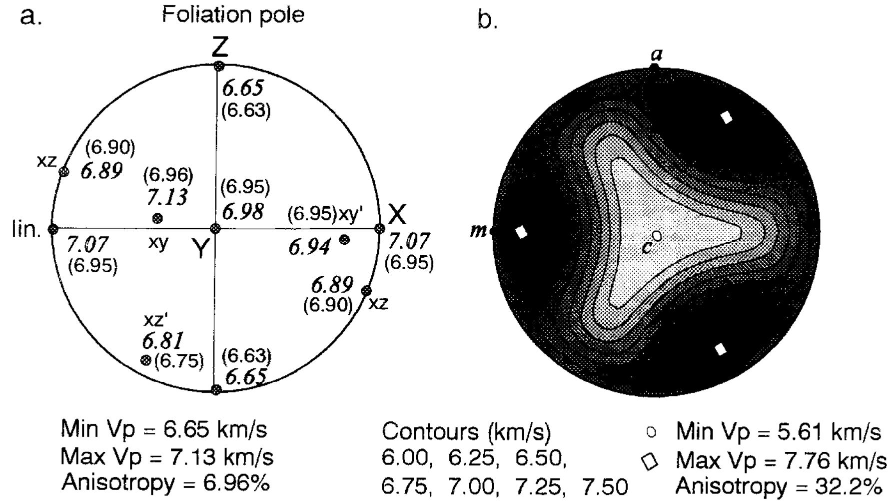

Fig. 2. (a) Lower hemisphere, equal area projection showing the seven core orientations from the calcite ultramylonite from which ultrasonic velocity measurements were made. Orientations of the mesoscopic foliation and lineation are shown; specimen oriented for right-lateral sense of shear. Numbers shown beside each point are measured P-wave (V_p) velocities (km s^{-1}), and also in parentheses are shown velocities calculated from the CPO of Fig. 1(b) and single crystal elastic properties. Letter codes beside each point identify the orientations for the velocity data shown in Fig. 3. (b) Equal area projection showing the variation of P-wave velocity with orientation calculated for a single crystal of calcite. *a*- and *c*-axis directions and pole to the *m* trigonal prism are shown for orientation reference.

data, and the density at room pressure and temperature, the variation of acoustic P-wave velocity at room pressure and temperature with crystallographic direction is easily calculated (Fig. 2b). The maximum velocity (7.76 km s^{-1}) lies near-normal to the *m* trigonal prism. The minimum velocity is in the *c*-axis direction (5.61 km s^{-1}). Defining anisotropy as $2(V_{max}-V_{min})/(V_{max}+V_{min})$, the maximum anisotropy is 32%, if all grains in a rock were to be similarly oriented. With realistic, imperfect textures, velocity anisotropy will generally be rather lower.

Using the methods of Mainprice *et al.* (1990) and Mainprice and Humbert (1994), the variations of V_p with direction in the calcite mylonite and in the Carrara marble were calculated ($=V_0$ at room pressure and temperature). The results are shown in Fig. 4. The results for the mylonite should be compared with the directly measured values in Fig. 2(a), in which the calculated velocities are shown in parentheses for each core orientation. The Voigt averaging procedure for summing the effects of the differently oriented grains was found to give the best agreement with the measured velocities. Using the Voigt average, the results of the two approaches agree within expected experimental uncer-

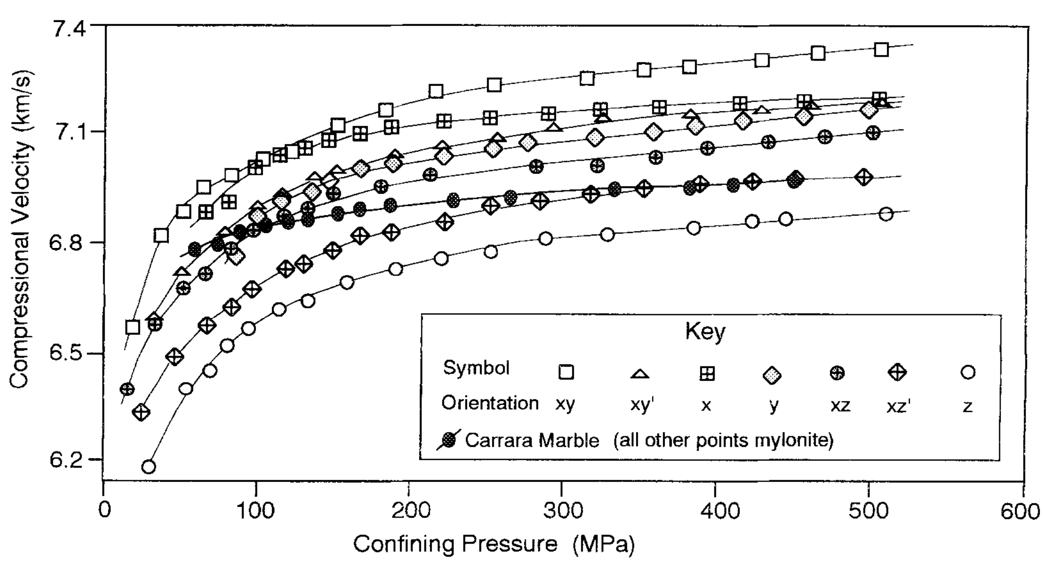

Fig. 3. Results of ultrasonic measurements of velocity vs pressure for the seven selected sample orientations in the calcite mylonite and for Carrara marble along the core axis shown in Fig. 1(a). Orientations for the mylonite cores are shown on Fig. 2(a).

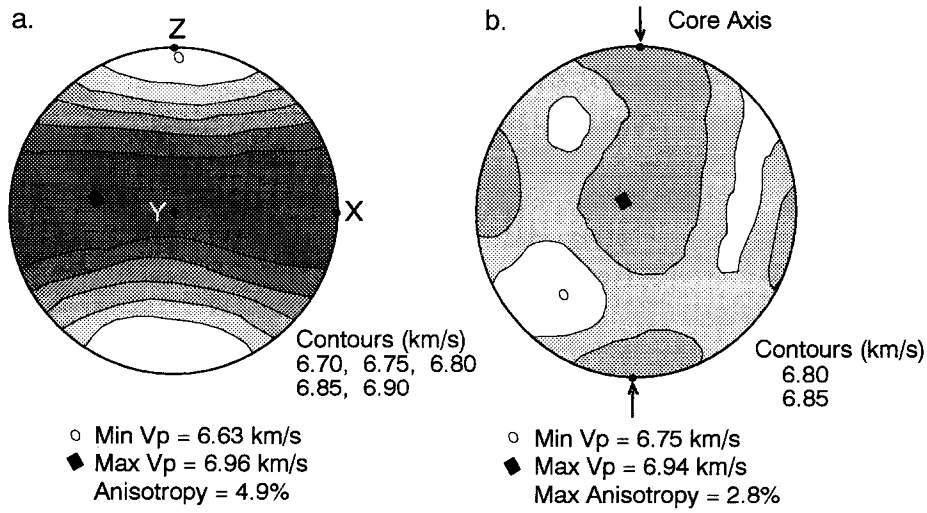

Fig. 4. Equal area, lower hemisphere projections showing the velocity distributions (contours in km s^{-1}) calculated from CPO and elastic properties of a single calcite crystal for (a) calcite mylonite (Z is normal to mesoscopic foliation; X is parallel to lineation; figure oriented for right-lateral shear sense), which should be compared with measured velocities shown in Fig. 2(a), and (b) Carrara marble.

tainty. The results demonstrate that the seismic anisotropy of this mylonite is due exclusively to its crystallographic preferred orientation, and also that reliable calculations of seismic velocity can be made from single crystal properties combined with petrofabric data. The elastic stiffness matrix C_{ij} ($\times 10^5$ MPa) calculated for the mylonite is given as follows, referred to the foliation plane normal $= z = 1$-axis and the lineation direction $= x = 2$-axis:

1.1865	0.5266	0.5274	−0.0012	0.0023	−0.0030
0.5266	1.3070	0.5494	0.0002	0.0012	−0.0045
0.5274	0.5494	1.3029	0.0008	0.0073	−0.0001
−0.0012	0.0002	0.0008	0.3836	−0.0002	0.0013
0.0023	0.0012	0.0073	−0.0002	0.3610	−0.0012
−0.0030	−0.0045	−0.0001	0.0013	−0.0012	0.3603

The isotropic Voigt average for a calcite aggregate yields the following non-zero terms: $C_{11} = 1.2677 \times 10^5$ MPa; $C_{44} = 0.3672 \times 10^5$ MPa and $C_{12} = 0.5333 \times 10^5$ MPa.

A maximum seismic anisotropy of 6.96% and 4.86% was obtained from the measured and calculated velocities, respectively, of the mylonite (using maximum and minimum values). Velocity distributions were calculated from X-ray texture goniometry-measured textures by Mainprice *et al.* (1990) for Alpine calcite mylonites with similar types and intensities of texture that have been observed in the present study, and entirely comparable seismic anisotropies were inferred. The average V_0 calculated here for Carrara marble was 6.85 km s^{-1}, and the maximum anisotropy was 2.8%, although the latter figure is not systematic and arises through the effects of random clustering of grain orientations, as would be expected from a random, but discrete, sampling from a uniform population of grain orientations.

DISCUSSION

Here, we consider the implications of the above results for the visibility of shear zones by seismic reflection profiling, as a result of their strain-induced crystallographic texture in isomineralic calcite rocks. For the purpose of the present discussion, it is assumed that a shear zone will be sufficiently thick to generate reflections at the wavelength used. It is recognized that quite major shear zones can be thin (less than a few metres) or comprise a braided network of smaller shear zones. Thin shear zones are likely to generate reflections only when their displacement juxtaposes rock types of sufficiently large acoustic impedance contrast. However, some thin shear zones are flanked by wide protomylonitic zones in which quite strong textures may be developed.

When there is no mineralogical change between the protolith and the shear zone, the seismic reflection coefficient is 0.5 × the velocity change across the interface for normal incidence P-waves. Thus, for a horizontal shear zone with a *c*-axis maximum normal to foliation ($V_0 = 6.63$ km s^{-1}), a velocity anisotropy relative to an isotropically textured protolith ($V_0 = 6.85$ km s^{-1}) of up to 3.3% is expected (reflection coefficient = −0.016). This is quite a low, but not wholly insignificant, reflection coefficient and is the largest normal incidence value likely to be generated for a shear zone in a calcite rock with a CPO maximum of strength about three times uniform. As the (vertical) incident wave deviates from normality to the foliation, however, such as when a non-zero dip is present on the shear zone, non-zero reflection coefficients can be enhanced if the texture is isotropic, but can be either enhanced or reduced when an anisotropic texture is present, depending upon its characteristics. Calcite rock

CPO maxima can be much stronger than that measured in the mylonite studied here, for example five or six times uniform (Rutter *et al.*, 1994), with a correspondingly increased value for the reflection coefficient.

In order to obtain an estimate of the effects of non-normal P-wave incidence, we have solved the Zoeppritz/Knott equations (Sheriff and Geldart, 1983) for the P-wave reflection coefficient (ratio of reflected P-wave amplitude to incident P-wave amplitude), simply treating the shear zone as isotropic but with a varying P-wave velocity according to the incidence angle θ with respect to the shear zone normal, and the fabric symmetry axis orientation ϕ with respect to the shear zone normal. The results are shown in Fig. 5. Reflectivity increases substantially with the amount of shear zone dip (increasing angle of incidence). The resultant reflectivity variations are usually greater than those due to variations in the orientation of the fabric symmetry axis with respect to the shear zone normal.

In natural calcite mylonites, the commonest crystallographic fabric is a c-axis maximum normal to the foliation plane or up to 45° to the foliation plane normal (e.g. the calcite ultramylonites at the base of the Morcles Nappe, Switzerland, Schmid *et al.*, 1981). For the first case, reflectivity increases from −1.6% to about −3% as dip increases from zero to 30°. For the second case, the reflectivity varies more markedly. If the fabric symmetry axis is rotated towards the vertical as a consequence of increasing dip, the reflectivity increases, and it decreases as the fabric symmetry axis is rotated away from the vertical. An asymmetry of the fabric with respect to the shear plane is generally interpreted in terms of the shear sense, with the fabric c-axis maximum rotating in a sense counter to the shear sense. Thus, a normal dip-slip sense of shear on a gently dipping shear zone should give rise to greater reflectivity than a reverse shear sense. For practical reflection profiling, incident waves that can be detected are unlikely to be >10° from normal incidence, irrespective of shear zone dip. In this case, only the orientation of the CPO with respect to the shear zone will give rise to reflectivity variations, and the c-axis maximum perpendicular to the foliation plane will produce the greatest reflectivity. In shear zones containing substantial proportions of oriented mica grains, reflectivity due to crystallographic fabric is greater than for calcite rocks ($R \approx 5\%$), and it is only in such rocks that significant reflectivity is likely commonly to arise from fabric effects alone (Law and Snyder, 1997).

An increase in temperature (as occurs with depth in the Earth) produces a decrease in seismic velocity that tends to counteract the increase in velocity with pressure. However, based on the available data relating elastic constants to temperature (Dandekar, 1968a), we have no reason to believe that the anisotropy will be significantly affected by temperature. It may also be noted that, in Fig. 3, the rate of change of velocity with pressure (at high pressures) is not constant for different core orientations. This means that the details of the variations of velocity with orientation will be different at high pressures from that calculated at atmospheric pressure. However, the differences will not be large, and the differences between the fastest and slowest orientations will be least affected of all.

The inference that changes in the intensity of preferred orientation of calcite can give rise to seismic reflectivity in pure calcite rocks may also apply to other monomineralic rock types, although the calcite single crystal displays a relatively high degree of anisotropy of physical properties. However, where polyphase rock types (especially involving phyllosilicates, mineralogically banded protoliths, the possibility of metamorphic reactions and changes in modal proportions) are involved in the formation of localized high strain zones, the nature of velocity contrasts may be much more complex and difficult to predict, and the presence of CPO may serve either to enhance or weaken reflectivity arising from other causes.

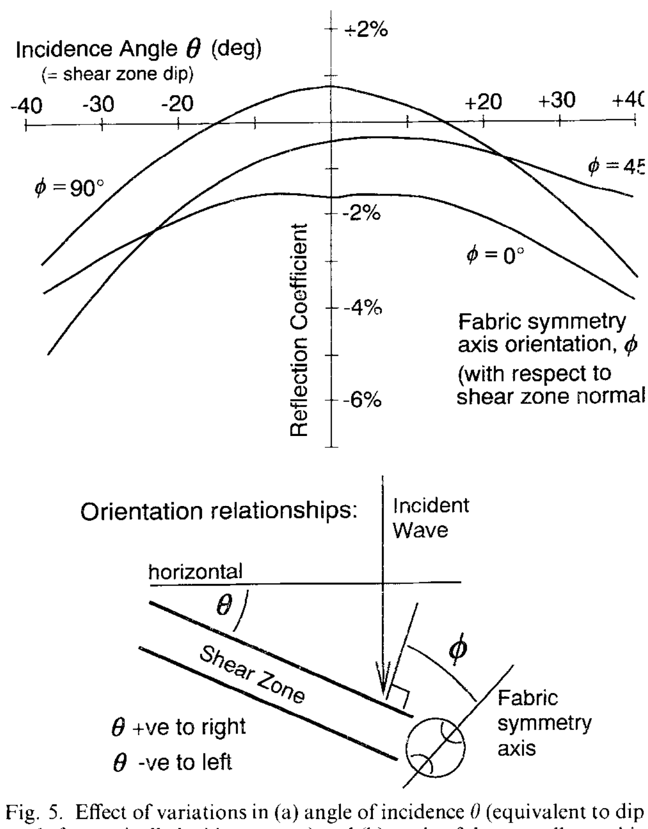

Fig. 5. Effect of variations in (a) angle of incidence θ (equivalent to dip angle for vertically incident waves) and (b) angle of the crystallographic fabric symmetry axis ϕ with respect to the shear zone normal, on the P-wave reflectivity of a shear zone in an otherwise isotropic calcite protolith. The CPO maximum corresponds in strength to that measured for the mylonite studied here. Here, ϕ is always taken as positive (clockwise), but negative and positive incidence angles θ correspond to the shear zone dipping to the left and to the right, respectively (reverse and normal shear sense). The shear zone normal, the crystallographic fabric symmetry axis and the incident wave direction are all taken to be coplanar. The asymmetry of the CPO maximum shown here with respect to the dipping shear zone corresponds to a left-lateral (reverse dip-slip) shear sense.

CONCLUSIONS

The variation of seismic P-wave velocity with direction in a calcite mylonite, calculated from the crystallographic preferred orientation and published elastic properties of single crystals of calcite, agrees well with laboratory measurements of ultrasonic P-wave velocity measurements. The CPO type for this calcite mylonite is a moderate (three times uniform) *c*-axis maximum, normal to the mesoscopic foliation of the rock and to the shear zone walls. For normal incidence waves, this is expected to give rise to a small, but detectable, seismic reflectivity ($R \approx -0.016$) at the contact between an isotropically textured protolith and a shear zone of the fabric type described here. Deformed calcite rocks can display fabric strengths at least twice as strong as in the mylonite studied here, with a correspondingly increased potential for reflectivity generation.

For oblique incidence waves, the reflectivity is expected to become strengthened for the commonly occurring *c*-axis maximum crystallographic fabric types, when the fabric maximum is normal to the foliation plane. For a fabric maximum about 45° to the normal to the foliation plane, as observed in some natural calcite shear zones, the normal incidence reflectivity would be weakened to the point of insignificance. For gently dipping shear zones with fabric maxima oblique to the shear zone, normal dip-slip shear zones would be more reflective than reverse dip-slip shear zones. The presence of a CPO in a shear zone may add to, or subtract from, other causes of reflectivity, such as the presence of some proportion of oriented phyllosilicates or mineralogical contrasts with the host rock arising from metamorphic reactions.

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