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Crustal anisotropy in the vicinity of the Alpine Fault Zone, South Island, New Zealand

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Abstract Petrophysical measurements of rock samples collected within the Haast, Torlesse, and Alpine Fault Zone terranes of the South Island of New Zealand indicate significant seismic *P*-wave velocity anisotropy at pressures representing depths of up to 30 km. The percentage of anisotropy increases with increasing metamorphic grade and thus decreases with structural distance from the Alpine Fault. A maximum anisotropy of 17.3% was obtained from a drill-core sample located within the garnet-oligoclase zone schist, immediately adjacent to the Alpine Fault. Shear-wave splitting is another important property of the schists. For propagation parallel to foliation, split shear waves show velocity differences up to 1 km/s. At elevated pressures, the measured seismic velocity anisotropy is caused by preferred mineral orientation and is not due to the presence of cracks. The pronounced velocity anisotropy will significantly affect propagating seismic waves collected during both natural and active source seismic experiments; this effect must be incorporated into the analyses of such seismic data.

Keywords petrophysical measurements; Alpine Fault Zone; seismic anisotropy; shear-wave splitting

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INTRODUCTION

Recent studies to describe the crustal geometry and origin of the Southern Alpine orogen (South Island, New Zealand) suggest significant three-dimensional structural complexity for the thicknesses of the Pacific and Indo-Australian segments of the South Island crust (depth to Moho) and for the orientations, depths, and thicknesses of the important orogenic elements such as the Alpine Fault, Haast Terrane, and Torlesse Terrane. Uplift of the Southern Alps has been postulated to be a result of delamination of the South Island lithosphere into crustal and mantle components (Wellman 1979), or at the intracrustal level with or without critical wedge transpressional deformation as described by Reyners (1987), Koons (1989, 1990), and Norris et al. (1990). Wellman (1979) and Allis (1986) suggested models which require no Moho root, whereas those of Woodward (1979), Reyners (1987), Koons (1989, 1990), and Norris et al. (1990) require thickening of the crust beneath the Southern Alps. The Haast Terrane is upturned near the Alpine Fault (Sheppard et al. 1975; Adams & Gabites 1985; Cox 1991), which indicates variability in its gross-scale and internal configurations (Grindley 1963; Sibson et al. 1979; Grapes & Watanabe 1992; Kamp et al. 1992). The diversity in the structural orientation of the major orogenic elements and surface exposures of high-grade metamorphic rocks suggest the existence of significant anisotropy.

Effects of seismic velocity anisotropy are factors which must be considered when passive and/or active source seismic methods are used to identify the internal crustal structure of the Southern Alpine orogen. The results of this study quantify the amounts of velocity anisotropy in this orogen. Garrick & Hatherton (1973) provided velocity measurements obtained from seismic refraction studies and simple laboratory measurements; this study presents velocities measured from rock samples using a pressure range that represents depths of 0–30 km.

PETROPHYSICAL MEASUREMENTS

Six samples were selected for velocity measurements representing the Alpine Fault Zone, the Haast Schist Terrane, and the Torlesse greywacke terrane (Fig. 1). All samples were obtained from outcrop except for one (NZ-1) which was obtained from a borehole core located within the Alpine Fault Zone at Franz Josef. To investigate seismic anisotropy, three orthogonal cores (designated A, B, and C) were taken from each sample. The axes of the A cores were oriented normal to foliations and the B and C cores were cut perpendicular to one another with their axes in the foliation planes. When lineations were observed, the axes of the B cores were oriented parallel to the lineations. The cylindrical cores were weighed and measured to calculate bulk densities and jacketed with copper foil to exclude the pressure medium for velocity measurements as a function of pressure.

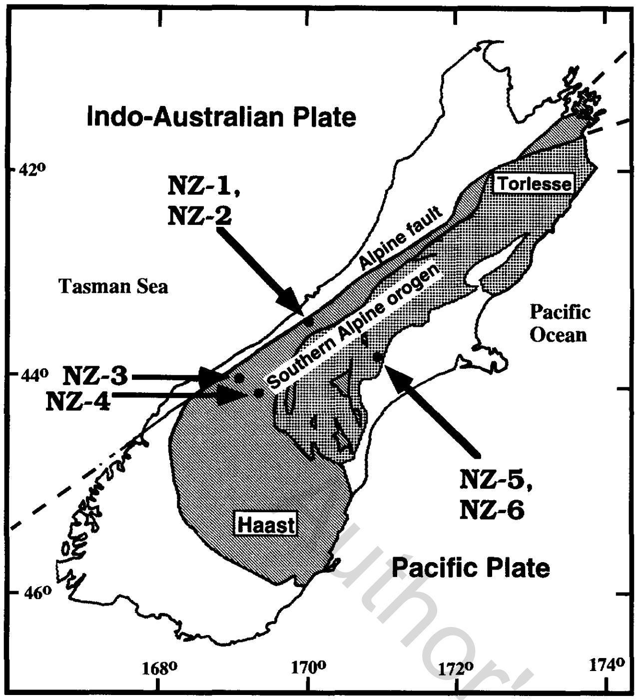

Fig. 1 Location of rock samples for which petrophysical measurements were taken. NZ-1 is from a core taken from a borehole in the Alpine Fault at Franz Josef. NZ-2 is a surface sample from the same locality. The Haast Schist Terrane is represented by NZ-3 and NZ-4; the Torlesse greywacke is represented by NZ-5 and NZ-6.

The travel times of compressional and shear waves were measured using a pulse transmission technique (Christensen 1985), and velocities were calculated from these travel times and sample lengths. Natural resonant frequencies of the compressional and shear-wave transducers were 1 MHz. Measurements were made at elevated hydrostatic confining pressures using a single-stage intensifier pressure generating system connected to a pressure vessel with an internal working space 15 cm long and 4.5 cm in diameter. Velocities were recorded at 0.1 kbar increments up to 1 kbar and 1 kbar increments at higher pressures. The pressure medium was hydraulic oil. The velocity measurements are estimated to be accurate to better than 1%.

The compressional (*P*-wave) velocities as functions of pressure are shown in Fig. 2 for samples from the Alpine Fault Zone, the Haast Schist, and the Torlesse greywacke. Results for all three orthogonal directions are shown for these samples at pressures between 0 and 10 kbars. All velocity measurements increase slowly between 2 and 10 kbars; from 0 to 2 kbars the velocities increase sharply due to closure of cracks. The samples from all three major orogenic terranes show significant velocity anisotropy. The direction normal to exhibited foliation (A cores) is slowest, whereas the directions within the plane of foliation (B and C cores) are fast and similar to each other, with the direction parallel to lineation (B cores) being the faster of the two. This behavior is observed in studies of similar highly foliated rocks at other localities (Christensen 1965; Christensen & Salisbury 1979; Christensen & Szymanski 1988; Wang et al. 1989).

A summary of the amount of velocity anisotropy is shown in Fig. 3. The velocities of the three core directions are shown for all six samples at a pressure of 5 kbars (c. 15 km depth). Within the Alpine Fault Zone, NZ-1 and NZ-2 exhibit 12.9 and 17.3% anisotropy when computed using the formula $(V_{\max} - V_{\min})/V_{\text{ave}}$; in the Haast Schist, samples NZ-3 and NZ-4 have 7.6 and 17.3% anisotropy, respectively. Sample NZ-5, from the Torlesse greywacke, is relatively isotropic at 2.1%.

In addition to compressional wave anisotropy, shear-wave splitting is another important property of these rocks. This is illustrated in Fig. 4 for propagation parallel to the foliation of the Alpine Fault Zone mylonite NZ-1. The fast shear wave vibrates parallel to the foliation. At elevated pressures, the two shear velocities have a velocity difference of nearly 1 km/s. A teleseismic shear wave travelling upward through 20 km of similar mylonite with vertical foliation will exhibit shear-wave splitting with nearly 1 s of separation. Although shear-wave splitting has recently been attributed to mantle structure (e.g., Silver & Kaneshima 1993) a significant portion in the South Island may be due to intracrustal effects (e.g., Gledhill 1991).

DISCUSSION: IMPLICATIONS FOR SEISMIC STUDIES

The effects of the observed velocity anisotropy are significant for seismic studies in the Southern Alpine orogen because of the physical distribution and tectonic prominence of the Alpine Fault and Haast Terrane. Primary effects are due to seismic wave propagation which will exhibit different travel times in different directions. These effects will occur at different scales of rock orientation and are, in part, related to the type of seismic experiment.

At a gross scale, if the Haast and Torlesse Terranes were situated with their overall foliations and lineations oriented in a uniformly subhorizontal position, then travel-time differences would be observed for horizontally propagating seismic waves travelling parallel and normal to the Alpine Fault (strike and dip directions). Velocities will be fast parallel to lineations (B directions). Discrepancies when integrating the results of both strike and dip lines would be apparent. In a similar manner, coincident seismic reflection and refraction profiles will produce arrival time mismatches. For example, a wide-angle *PmP* (Moho) reflection will travel using the B–C velocities, whereas the vertical-incident Moho reflection will travel at the slower A velocity; the reflection Moho will appear deeper than the refraction Moho.

In a hypothetical illustration of this reflection/refraction mismatch, if the crust were composed solely of the uniformly subhorizontal Haast Schist, the observed reflection Moho travel time would be $t_{refl} = 2\, z_{true}/V_a$ where z_{true} is the Moho depth and V_a is the vertical, slow A-direction (perpendicular to foliation) velocity. Conversion of this observed Moho travel time normally would use the crustal velocity provided by a refraction study; in this case, the faster V_b or V_c direction so that, for example, $z_{calc} = .5 t_{refl}\, V_c$. The interpreted Moho depth is thus $z_{calc} = z_{true}\, V_c/V_a$. From Fig. 2, representative velocity values are $V_a = 5.8$ km/s and $V_c = 6.8$ km/s, so that the interpreted Moho depth will be 17% too deep; for a 30 km crust, this represents a mismatch of c. 5 km. Such calculations are heavily dependent on the amounts and orientations of anisotropic material; a 30 km crust of solely Haast Schist is not realistic, which indicates that the degree of reflection/refraction mismatch will be less severe.

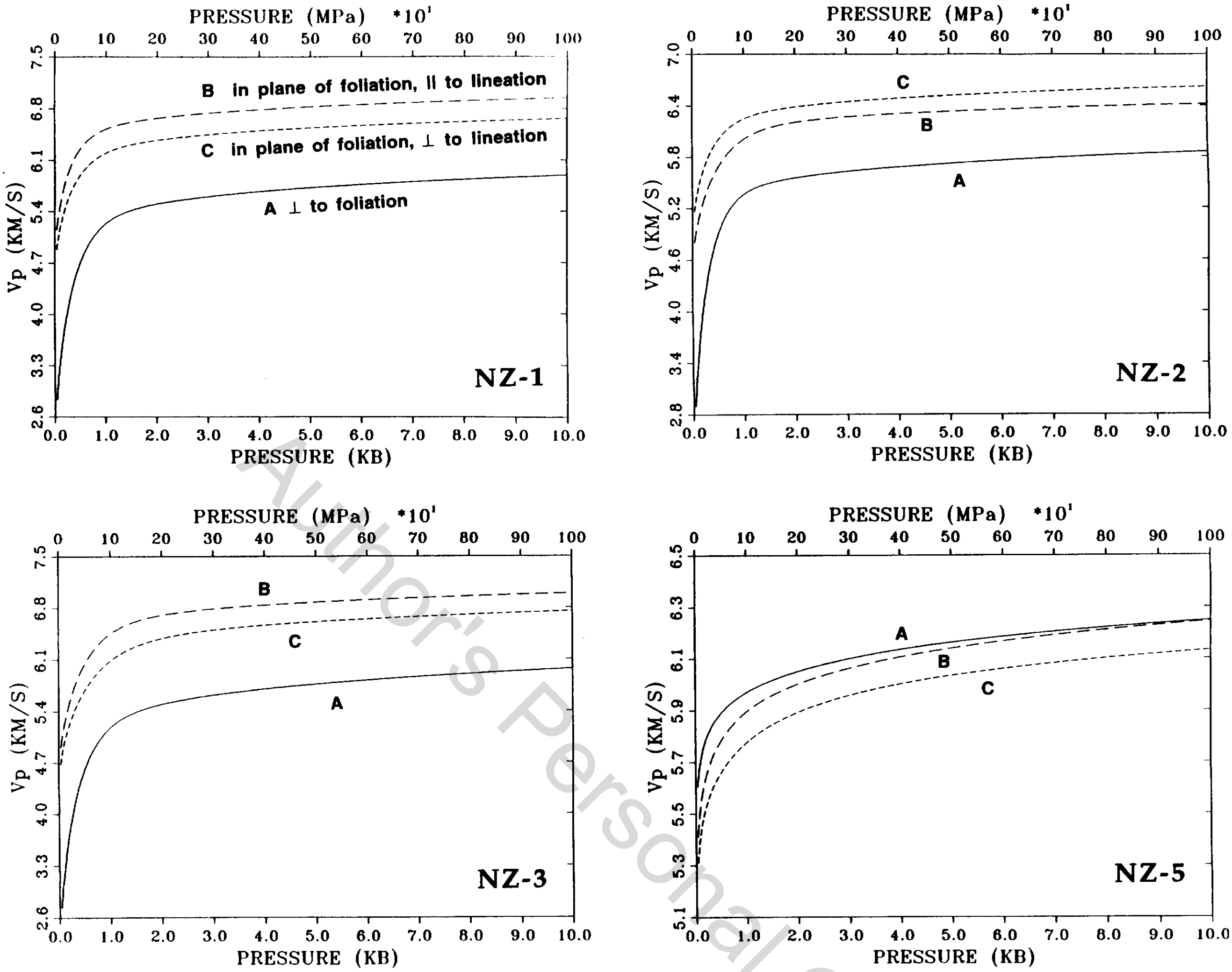

Fig. 2 Compressional velocity as a function of pressure for four field samples. Top two samples (NZ-1 and NZ-2) are from the Alpine Fault Zone, lower left (NZ-3) is from the Haast Schist, and the lower right (NZ-5) is from the Torlesse greywackes. Core A is perpendicular to the plane of foliation (solid line), core B is in the plane of foliation and parallel to lineation (dashed line), and core C is in the plane of foliation but perpendicular to the lineation (dotted line). Note the differences in magnitude of velocity between the three core directions for all samples. At pressures c. >1 kbar, cracks are closed and anisotropy originates from preferred mineral orientation (e.g., Christensen 1985). The velocity scale for NZ-5 has been significantly expanded; this sample of Torlesse greywacke is essentially homogeneous (see Fig. 3).

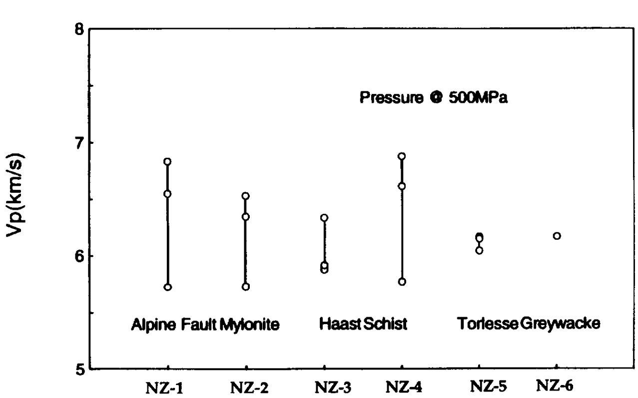

Fig. 3 Amount of velocity anisotropy. Velocity values are shown for all three core directions for each of the six samples at a pressure of 5 kbars (500 MPa). Anisotropy increases toward the Alpine Fault. Sample NZ-6 had only one core but appears in hand-sample to be low in anisotropy.

The structural orientation of the anisotropic terranes will produce additional travel-time complexities. Field observations indicate that the foliations within the Alpine Fault and Haast Schist Terrane are near-vertical at the Alpine Fault and that in general the dip decreases away from the fault (Grindley 1963; Adams & Gabites 1985). Certain models also suggest that the Alpine Fault soles into a subhorizontal position under the Canterbury Plains and is thus subparallel to the Haast Terrane (Wellman 1979; Koons 1989, 1990; Norris et al. 1990). This lateral variability in the principal orientations of the terranes will affect seismic waves which are propagating in a uniform direction. For example, a seismic refraction shot located on the east side of the South Island (e.g., Reyners & Cowan 1993; Smith et al. 1995, this issue) will propagate through the subhorizontal portions of the Haast Terrane only to encounter an upturned portion of this terrane at the near-vertical Alpine Fault. As described above, if the overall foliations of the terranes are

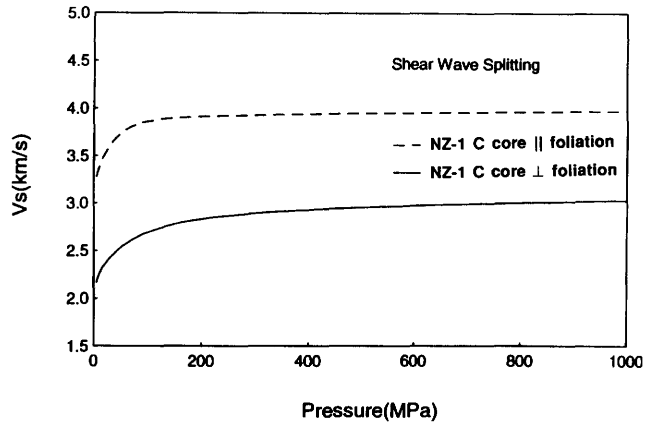

Fig. 4 Shear-wave velocities indicating the potential for shear-wave splitting. Using the C-direction core for NZ-1 (Franz Josef borehole), a shear wave was propagated whose motion was parallel to the mylonite foliation (dashed line). A second shear wave was propagated whose motion was perpendicular to the mylonite foliation (solid line). The direction of propagation (C-direction) was in the plane of the foliation but normal to the mylonite lineation. The two shear-wave velocities are nearly 1 km/s different at elevated pressures.

oriented parallel to their geometrical trends, then the refraction waves will travel horizontally through the B or C directions in the subhorizontal Haast Terrane, but while still travelling horizontally will encounter the A direction at the fault zone, lengthening its travel time. An additional effect must be taken into account here with the location of the seismograph station: a horizontal refraction ray-path becomes near-vertical in the uppermost crust near the seismograph station. This ray-path orientation must be superimposed onto the subsurface structures in order to determine which velocity anisotropy direction is sampled during which part of the ray-path. Similar travel-path/travel-time complexities may need to be corrected for the proper analysis of South Island local or micro-earthquakes, which are distributed in a three-dimensional pattern relative to the seismograph network (Anderson et al. 1993; Reyners & Cowan, 1993).

The anisotropy exhibited in the Southern Alpine samples is not due to cracks but results from metamorphic foliation fabrics and associated mica orientation. The observed anisotropy is typical of many greenschist and amphibolite facies terranes (Christensen 1965; Brocher et al. 1991; Szymanski & Christensen 1993). For this reason, the more intense the metamorphism, the stronger the foliation fabric and hence the anisotropy; this accounts for the increasing percentage of anisotropy toward the Alpine Fault.

A standard approach in the analysis of passive or active source seismic data is to interpret gross rock types from the derived seismic velocities. These velocity-to-rock type conversions have been enhanced by petrophysical calibrations as summarised by Christensen & Fountain (1975), Fountain & Christensen (1989), and Holbrook et al. (1992). These interpretations are usually conducted knowing that specific rock types have a velocity distribution and that exact rock identifications are not possible. Velocity anisotropy exaggerates the range of velocities which can be assigned to a rock type. For the Haast Schist samples in this study, the velocities at depth, when all directions are taken into account, range from 5.8 to 7.0 km/s; this range covers the full distribution of velocities of most types of crustal rocks. The faster velocities of the Haast Schist could be erroneously inferred to be caused by mafic rocks such as gabbros or amphibolites.

CONCLUSION

Compressional and shear-wave velocity anisotropy are pronounced in the Alpine Fault Zone and Haast Schist Terrane. Rocks within these terranes which have strong metamorphic foliation fabrics exhibit high degrees of anisotropy; rock types such as the Torlesse greywackes with little developed foliations are not highly anisotropic. The Alpine Fault mylonites and Haast Schist have up to 17% anisotropy at elevated pressures representing the middle crust. This degree of anisotropy will affect passive and active source seismic-wave propagation and must be considered during the analysis of such data. Since there are only six measurements, we emphasise that these results, showing anisotropy up to 17%, suggest the need for more anisotropy studies in conjunction with seismic refraction/reflection experiments.

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