

# Mantle wedge anisotropy in the Hikurangi subduction zone, central North Island, New Zealand

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[1] The anisotropic characteristics of the Hikurangi subduction zone in central North Island, New Zealand are studied using shear-wave splitting measurements from 55 local earthquakes recorded on a 200 km profile of 19 stations. The eastern fore-arc shows trench-parallel fast directions and a low average delay time of 0.2 s. The source of anisotropy is confined to the upper 60 km and is likely to be deformation induced within the overriding Australian plate. Central western North Island shows N-S trending fast anisotropy which may signify the presence of a viscous blanket of mantle material being entrained by the absolute motion of the Australian plate. Between these regions a dramatic switch to extension-parallel fast directions and delay times of 0.35 s are seen across the back-arc in the Taupo Volcanic Zone (TVZ). These results suggest asthenospheric flow beneath the overriding plate with the olivine a-axes oriented in the extension direction down to a maximum depth of 100 km. **Citation:** Morley, A. M., G. W. Stuart, J.-M. Kendall, and M. Reyners (2006), Mantle wedge anisotropy in the Hikurangi subduction zone, central North Island, New Zealand, *Geophys. Res. Lett.*, 33, L05301, doi:10.1029/2005GL024569.

## 1. Introduction

[2] The mantle wedge above a subduction zone is the region where fluids from the subducted plate are mixed with convecting mantle to generate magmas [e.g., *Tatsumi*, 1989]. Observations of the physical controls on this process come from seismology. In particular, seismic anisotropy can be used to infer strain and flow patterns in the mantle [e.g., *Savage*, 1999]. In this study, we estimate seismic anisotropy using shear wave splitting observations from local subduction zone earthquakes along a profile of stations across the central North Island region and interpret it in terms of mantle wedge processes beneath the back-arc extension region of the Taupo Volcanic Zone (TVZ; Figure 1).

[3] North Island, New Zealand lies on the obliquely converging Hikurangi subduction zone between the overriding Australian and the subducting Pacific plate. The TVZ is the actively volcanic eastern section [*Wilson et al.*, 1995] of the Central Volcanic Region and marks the southern limit of back-arc extension in the Tonga-Kermadec subduction system.

[4] Seismic anisotropy in the mantle is usually interpreted as strain-induced lattice-preferred orientation of olivine where the a-axes align in the direction of mantle flow [*Ribe*, 1989]. SKS phases reveal sub-slab trench-parallel flow beneath North Island [e.g., *Brisbourne et al.*, 1999; *Marson-Pidgeon et al.*, 1999; *Hofmann*, 2002]. *Gledhill and Gubbins* [1996] suggest the slab may be in retrograde motion whereas *Marson-Pidgeon et al.* [1999] propose the slab acts as a passive-rigid barrier to mantle flow both above and below the slab. Most theories of mantle dynamics predict entrained mantle flow parallel to the relative or absolute plate motion of the subducted slab [e.g., *Silver and Chan*, 1991].

[5] Observations of shear-wave splitting in slab events beneath the North Island show a lot of variability. Trench-parallel polarisations have been explained by fluid-filled cracks aligned in response to strike-slip compression along the Hikurangi margin [*Gledhill and Stuart*, 1996]. *Audoine et al.* [2004] explain trench-perpendicular fast directions,  $\emptyset$ , across the TVZ as evidence for extension-parallel flow driving fluids away from the trench.

## 2. Data Analysis

[6] We examine recordings from a detailed NW-SE profile of 18 stations (Figure 1), spaced at 15–20 km intervals across the central North Island and part of a larger scale passive seismic experiment named CNIPSE [*Reyners and Stuart*, 2002]. In addition, recordings from the New Zealand National network station MOZ were also processed.

[7] The profile is oriented parallel to the dip of the subducting Pacific plate and has good crustal structure control from the NIGHT refraction and reflection experiments [e.g., *Harrison and White*, 2004; *Stratford and Stern*, 2004]. A total of 55 earthquakes with magnitude greater than 3.5 and depth range from 57 km to 293 km were selected for their high quality shear wave recordings. The epicentres lie in a 195 km wide swath centred about the station profile. All arriving shear-waves are within the shear-wave window [*Evans*, 1984] defined here as straight ray paths with an incidence angle less than 45°.

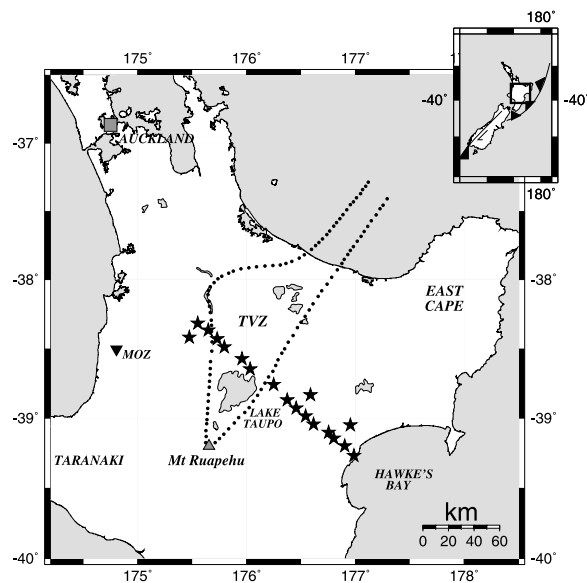
[8] We filtered recordings with a 2 pole Butterworth bandpass filter (0.5 Hz–3.0 Hz). A total of 489 station-event pairs satisfied the location, magnitude and shear wave window constraints. Band limited wavetrains, null measurements, poor radiation patterns and noisy signals prevented further analysis on 160 of these traces.

[9] The S-waves from the remaining 329 station-event pairs were analysed for splitting using the *Silver and Chan* [1991] technique. Using a grid-search, the method calculates the covariance matrix for the two horizontal seismogram components over all possible values of  $\emptyset$  and delay times,  $\delta t$ . The optimum splitting parameters are those which

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**Figure 1.** Station locations with the TVZ outlined by a broken line. Stars are CNIPSE stations and the triangle is New Zealand National network station MOZ.

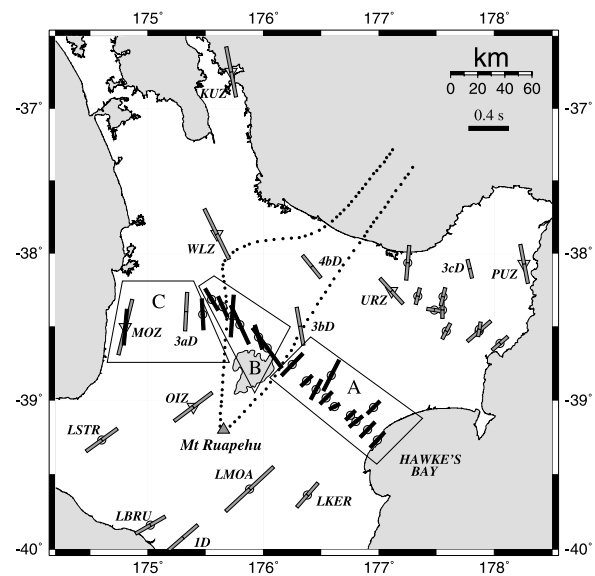
minimise the smaller eigenvalue of the two-dimensional polarisation matrix of linearised horizontal particle motion. We use a cluster analysis technique [Teanby *et al.*, 2004] to remove any subjectivity on choice of window length.

[10] The associated error for each station splitting parameter is  $\pm 1\sigma$  yielding typical error values for  $\Theta$  and  $\delta t$  of  $\pm 16^\circ$  and  $\pm 0.2$  s respectively. We identified two doublets (earthquakes with near-identical locations) 123 days apart which were used to assess the processing error. Differences in estimated fast direction and source polarisation were less than  $5^\circ$  and uncertainties in delay time were less than 0.02 s.

### 3. Results

[11] Splitting results are spatially divided into three groups: A, B and C (Figure 2). In group A, NE-SW trench-parallel fast directions extend across eastern North Island from Hawke's Bay to the eastern margin of the TVZ with average  $\Theta$  and  $\delta t$  of  $44^\circ \pm 15^\circ$  and  $0.20$  s  $\pm 0.10$  s. In group B we see a maximum  $80^\circ$  swing in fast polarisation direction to trench-perpendicular across the eastern boundary of the TVZ and a 0.22 s increase in delay time. Stations in the TVZ (group B) have an average  $\Theta$  and  $\delta t$  of  $158^\circ \pm 21^\circ$  and  $0.35$  s  $\pm 0.21$  s respectively. Group C shows N-S trending fast directions with delay times greater than those seen in group A and approximately equal to those across the TVZ. Average  $\Theta$  and  $\delta t$  for central western North Island are  $1^\circ \pm 15^\circ$  and  $0.35$  s  $\pm 0.12$  s.

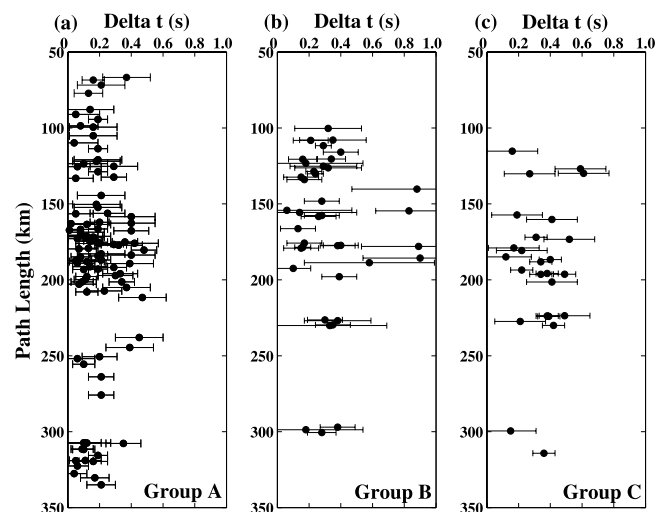
[12] All three groups demonstrate little change in  $\Theta$  and  $\delta t$  with increasing path length. Figure 3 shows fast-slow delay times plotted as a function of ray path length for each of the three groups. Increasing depths show no apparent delay time variation implying that the various sources of anisotropy seen in this study are confined to depths no greater than the shallowest event recorded in the group. In group A the shallowest recorded event is 60 km deep which is used to calculate a minimum anisotropy of 1.6%. In group B the shallowest event is 100 km deep which yields a minimum



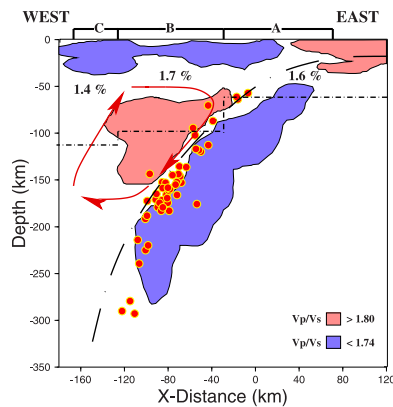
**Figure 2.** Results from this study are black and from previous local earthquake studies [Audoine *et al.*, 2000, 2004; Head, 2001] are grey. Fast-observations are divided into groups A, B and C, each sharing similar trending splitting results.

of 1.7% degree anisotropy and in group C the shallowest event is 115 km deep and yields a minimum of 1.4% anisotropy.

[13] We relate the results to a  $V_p/V_s$  tomographic cross section from the local earthquake study by Reyners *et al.* [2006]. The cross section is located along  $Y = -30$  km on the Reyners *et al.* [2006] velocity grid and coincides with our station profile (Figure 4).  $V_p/V_s$  provides our model with constraints for the origin of the seismic anisotropy by differentiating between regions of the mantle wedge dominated by melt (high  $V_p/V_s$ ) and regions of concentrated hydrous minerals (low  $V_p/V_s$ ) [Watanabe, 1993]. Figure 4 suggests ray paths recording trench-parallel fast directions in group A propagate through the slab and the crust beneath



**Figure 3.** Fast-slow delay time profiles for each group of splitting results.



**Figure 4.** All 55 earthquakes are projected onto *Reyners et al.* [2006]  $Y = -30$  km  $V_p/V_s$  tomographic cross section (coincident with our station profile). The degree and depth of mantle wedge anisotropy is shown. Arrows indicate small-scale mantle wedge convection.  $V_p/V_s > 1.80 \rightarrow$  partial melt;  $V_p/V_s < 1.74 \rightarrow$  higher concentrations of water [Reyners et al., 2006]. Dashed line marks top of slab.

the uplifted accretionary wedge. Extension-parallel fast directions observed in group B are produced from paths which traverse the core of the mantle wedge and ray paths in group C sample deeper sections of the mantle wedge and the western crustal structure (Figure 4).

## 4. Source of Anisotropy

### 4.1. Eastern North Island

[14] In water-rich, high-stress regions a fabric transition to type-B olivine [Jung and Karato, 2001] in the mantle wedge can generate fast polarisation directions perpendicular to the flow direction. Our results suggest the source of the anisotropy is less than 60 km deep and stress magnitudes in the experiments of Jung and Karato [2001] are higher than those seen in the mantle wedge [Audoin et al., 2004; Nakajima and Hasegawa, 2004].

[15] Along-strike dip variations in the slab can cause trench-parallel flow [Hall et al., 2000] in the fore-arc mantle wedge, although mantle flow is unlikely to explain such a rapid change in fast direction at the edge of the TVZ. We prefer a model where the anisotropy originates in the crust due to the fast directions following trends in regional deformation [Beavan and Haines, 2001]. A likely fore-arc mechanism is crack induced anisotropy [Gledhill and Stuart, 1996] from major strike slip faults and crustal flexure of the overriding Australian plate. If all anisotropy in this region is confined to 30 km crust [Harrison and White, 2004] then 3% anisotropy is obtained.

[16] Ray paths to group A travel through and along the subducted slab (Figure 4). Figure 3a shows no increase in fast-slow delay time with hypocentral depth indicating no apparent slab anisotropy in central North Island. In the Wellington region Matcham et al. [2000] report 4.4% trench-parallel ( $30^\circ$ ) fast anisotropy within the Pacific slab which is likely due to fossil anisotropy from the formation of oceanic lithosphere [Marson-Pidgeon et al., 1999; Audoin et al., 2004] or NE-SW normal faults in the subducted crust [Du et al., 2004]. Brisbane et al. [1999] discuss the presence of a horizontal olivine symmetry axis

in the subducted slab in southern North Island but an axis plunging parallel to the plate interface in central North Island. This lateral variation may reflect a change in intraplate stress southward toward South Island, where the plates are locked.

### 4.2. Taupo Volcanic Zone

[17] We propose that extension-parallel fast anisotropy exists in the upper mantle beneath the TVZ and remains consistent with two of the most common hypotheses of olivine orientation [McKenzie, 1979], that olivine minerals will orient with maximum extension direction and that they orient parallel to flow [Ribe, 1992]. Buttle and Olson [1998] show that the down-dip component of motion made by the subducted slab induces flow in the mantle wedge that is characterized by shear layers along the top and bottom surfaces of the downgoing slab and along the bottom of the overriding plate (Figure 4). The APM (Absolute Plate Motion) of the subducted Pacific plate initiates small-scale mantle wedge convection [Reyners et al., 2006], and induces asthenospheric mantle flow beneath the overriding plate which creates an a-type olivine fabric aligned normal to the trench. Secondary convection and flow-induced strain is used to explain similar observations in north eastern Japan [Nakajima and Hasegawa, 2004].

[18] Traversing the TVZ, SKS phases show trench-parallel fast anisotropy with delay times as high as 3.2 s [Hofmann, 2002; Audoin et al., 2004]. This suggests that there is a significant amount of anisotropy below the slab that is dominant over the contribution to the splitting from above the slab.

### 4.3. Western North Island

[19] The trench-perpendicular flow reported beneath the TVZ is not laterally extensive across the length of the subduction zone (Figure 4) because the preferred mineral alignment beneath the overriding plate decreases with an increase in slab dip angle [Buttle and Olson, 1998]. The angle of dip under western North Island is little more than  $60^\circ$  which Buttle and Olson [1998] suggest will fail to induce any such preferred alignment and flow.

[20] The Kreemer et al. [2003] model predicts the APM of the Australian plate at MOZ as  $\sim 37.9$  mm/yr toward  $5.4^\circ$ . This could signify the presence of a viscous blanket of mantle material which is entrained by the true motion of the Australian plate and gives rise to a N-S preferred orientation of olivine a-axes below the western margin.

## 5. Discussion and Conclusions

[21] We reveal a distinct series of extension-parallel fast directions extending across and immediately west of the TVZ. The results documented are some of the first well established indications of trench-normal flow in North Island, New Zealand. We confine the extension-parallel source to the upper 100 km suggesting at least 1.7% anisotropy. The down-dip component of motion made by the subducted Pacific slab in our corner flow model (Figure 4) induces trench-perpendicular mantle flow beneath the overriding Australian plate which aligns olivine a-axes perpendicular to the trench [Ribe, 1989; Buttle and Olson, 1998; Hall et al., 2000]. The eastern fore-arc shows trench-parallel fast directions and low delay times of 0.2 s.

The source of anisotropy here is likely confined to the crust and is crack induced from crustal flexure and strike-slip faulting. N-S trending fast anisotropy in central western North Island supports the existence of a viscous blanket of mantle material entrained by the APM of the Australian plate. The systematic across-arc variation in  $\Theta$  and  $\delta t$  is consistent with the mantle wedge anisotropy of north eastern Japan [Nakajima and Hasegawa, 2004].

[22] We report a transition from trench-normal fast anisotropy in the TVZ to trench-parallel anisotropy south of Mt Ruapehu [e.g., Audoiné et al., 2000]. This observation correlates with Reyners et al. [2006], who use tomography to interpret little return flow south of 39°S, but well-developed return flow beneath the central TVZ. Thicker than normal crust of the overlying plate south of Mt Ruapehu chokes off return flow causing the cool, high-viscosity nose between the plates to advance into the wedge [Kincaid and Sacks, 1997]. Without this return flow, fluxing of partial melt in the mantle is unlikely, explaining the lack of magmatism south of Mt Ruapehu. Here, the initiation of small-scale convection and trench-normal mantle flow is paralysed and instead, trench-parallel flow continues to dominate.

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## References

- Audoiné, E., M. K. Savage, and K. Gledhill (2000), Seismic anisotropy from local earthquakes in the transition region from a subduction to a strike-slip plate boundary, New Zealand, *J. Geophys. Res.*, **105**, 8013–8033.
- Audoiné, E., M. K. Savage, and K. Gledhill (2004), Anisotropic structure under a back arc spreading region, the Taupo Volcanic Zone, New Zealand, *J. Geophys. Res.*, **109**, B11305, doi:10.1029/2003JB002932.
- Beavan, J., and J. Haines (2001), Contemporary horizontal velocity and strain rate fields of the Pacific-Australian plate boundary zone through New Zealand, *J. Geophys. Res.*, **106**, 741–770.
- Brisbourne, A., G. W. Stuart, and J.-M. Kendall (1999), Anisotropic structure of the Hikurangi subduction zone, New Zealand—integrated interpretation of surface-wave and body-wave observations, *Geophys. J. Int.*, **137**, 214–230.
- Buttles, J., and P. Olson (1998), A laboratory model of subduction zone anisotropy, *Earth Planet. Sci. Lett.*, **164**, 245–262.
- Du, W.-X., C. H. Thurber, M. Reyners, D. Eberhart-Phillips, and H. Zhang (2004), New constraints on seismicity in the Wellington region of New Zealand from relocated earthquake hypocentres, *Geophys. J. Int.*, **158**, 1088–1102.
- Evans, R. (1984), Effects of the free surface on shear wavetrains, *Geophys. J. R. Astron. Soc.*, **76**, 165–172.
- Gledhill, K. R., and D. Gubbins (1996), SKS splitting and the seismic anisotropy of the mantle beneath the Hikurangi subduction zone, New Zealand, *Phys. Earth Planet. Inter.*, **95**, 227–236.
- Gledhill, K. R., and G. W. Stuart (1996), Seismic anisotropy in the fore-arc region of the Hikurangi subduction zone, New Zealand, *Phys. Earth Planet. Inter.*, **95**, 211–225.
- Hall, C. E., K. M. Fischer, E. M. Parmentier, and D. K. Blackman (2000), The influence of plate motions on three-dimensional back arc mantle flow and shear waves, *J. Geophys. Res.*, **105**, 28,009–28,003.
- Harrison, A. J., and R. S. White (2004), Crustal structure of the Taupo Volcanic Zone, New Zealand: Stretching and igneous intrusion, *Geophys. Res. Lett.*, **31**, L13615, doi:10.1029/2004GL019885.
- Head, T. J. (2001), The nature of shallow anisotropy in the southern Raukumara Peninsula, New Zealand, determined by shear-wave splitting measurements from local earthquakes, honours thesis, 75 pp., Univ. of Leeds, Leeds, U.K.
- Hofmann, S. D. (2002), Seismic anisotropy in the crust and mantle: A study at the western edge of the central volcanic region, New Zealand, MSc thesis, 134 pp., Victoria Univ. of Wellington, Wellington, New Zealand.
- Jung, H., and S. Karato (2001), Water-induced fabric transition in olivine, *Science*, **293**, 1460–1463.
- Kincaid, C., and I. S. Sacks (1997), Thermal and dynamical evolution of the upper mantle in subduction zones, *J. Geophys. Res.*, **102**, 12,295–12,315.
- Kreemer, C., W. E. Holt, and A. J. Haines (2003), An integrated global model of present day plate motions and plate boundary deformation, *Geophys. J. Int.*, **154**, 8–43.
- Marson-Pidgeon, K., M. K. Savage, and K. Gledhill (1999), Seismic anisotropy beneath the lower half of the North Island, New Zealand, *J. Geophys. Res.*, **104**, 20,277–20,286.
- Matcham, I., M. K. Savage, and K. Gledhill (2000), Distribution of seismic anisotropy in the subduction zone beneath the Wellington region, New Zealand, *Geophys. J. Int.*, **140**, 1–10.
- McKenzie, D. (1979), Finite deformation during fluid flow, *Geophys. J. R. Astron. Soc.*, **58**, 689–715.
- Nakajima, J., and A. Hasegawa (2004), Shear-wave polarisation anisotropy and subduction-induced flow in the mantle wedge of northeastern Japan, *Earth Planet. Sci. Lett.*, **225**, 365–377.
- Reyners, M., and G. W. Stuart (2002), The central North Island passive seismic experiment, *Sci. Rep. 2002/11*, Inst. of Geol. and Nucl. Sci., Lower Hutt, New Zealand.
- Reyners, M., D. Eberhart-Phillips, G. W. Stuart, and Y. Nishimura (2006), Imaging subduction from the trench to 300 km depth beneath the central North Island, New Zealand, with Vp and Vp/Vs, *Geophys. J. Int.*, in press.
- Ribe, N. M. (1989), Seismic anisotropy and mantle flow, *J. Geophys. Res.*, **94**, 4213–4223.
- Ribe, N. M. (1992), On the relation between seismic anisotropy and finite strain, *J. Geophys. Res.*, **97**, 8737–8747.
- Savage, M. K. (1999), Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting?, *Rev. Geophys.*, **37**, 65–106.
- Silver, P. G., and W. W. Chan (1991), Shear wave splitting and subcontinental mantle deformation, *J. Geophys. Res.*, **96**, 16,429–16,454.
- Stratford, W., and T. Stern (2004), Strong seismic reflections and melt bodies in the mantle, North Island, New Zealand, *Geophys. Res. Lett.*, **31**, L06622, doi:10.1029/2003GL019232.
- Tatsumi, Y. (1989), Migration of fluid phases and genesis of basalt magmas in subduction zones, *J. Geophys. Res.*, **94**, 4697–4707.
- Teanby, N. A., J.-M. Kendall, and M. Van der Baan (2004), Automation of shear-wave splitting measurements using cluster analysis, *Bull. Seismol. Soc. Am.*, **94**, 453–463.
- Watanabe, T. (1993), Effects of water and melt on seismic velocities and their application to characterisation of seismic reflectors, *Geophys. Res. Lett.*, **20**, 2933–2936.
- Wilson, C. J. N., B. F. Houghton, M. O. McWilliams, M. A. Lanphere, S. D. Weaver, and R. M. Briggs (1995), Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: A review, *J. Volcanol. Geothermal Res.*, **68**, 1–28.

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