

# Distributed deformation in the lower crust and upper mantle beneath a continental strike-slip fault zone: Marlborough fault system, South Island, New Zealand

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## ABSTRACT

Converted phases from teleseisms recorded by a seismic array spanning the northern half of the Marlborough fault system, South Island, New Zealand, show a continuous unbroken Moho underlying a seismically anisotropic lower crust beneath the two northernmost faults of the fault system. These observations suggest that distributed deformation, not slip on a narrow vertical fault, accommodates displacement in the lower crust below the 120–480 km of right-lateral slip across the Wairau fault, one splay of the Marlborough fault system, and the northward continuation of the Alpine fault. Beneath the Wairau fault, the Moho dips 25°–30° southeast from a depth of ~26 km northwest of the fault to a depth of ~34 km southeast of the fault. Farther to the southeast, Ps conversions from the Moho continue under the Awatere fault ( $34 \pm 10$  km of slip) with a constant amplitude and depth of ~34 km. Across the two faults, converted energy from 16–20 km depth varies with back-azimuth in a manner suggesting the presence of anisotropy in the lower crust. These observations imply that one of the tenets of plate tectonics, that faults defining plate boundaries pass through both crust and upper mantle, does not apply to New Zealand, or to continents in general.

**Keywords:** strike-slip faults, rheology, tectonics, lower crust, seismic anisotropy, ductile deformation.

## INTRODUCTION

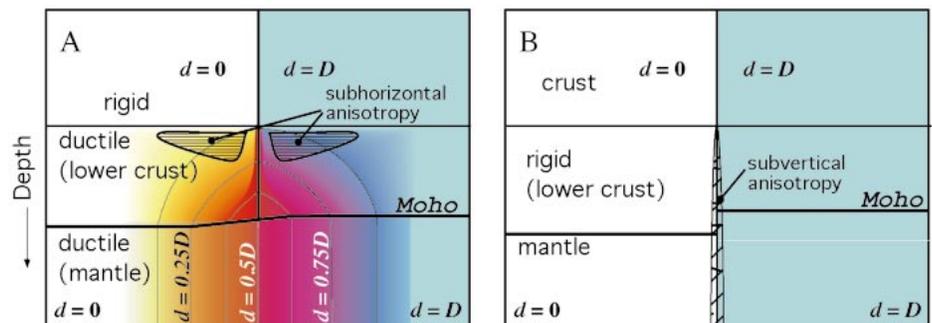
Shortly after the recognition of plate tectonics, its limitations within continental settings became apparent. Deformation between oceanic plates is limited to narrow zones along plate boundaries, but deformation on continents extends across regions hundreds to thousands of kilometers wide. Some suggest that in continents a weak crust merely blurs movements across discrete zones akin to plate boundaries in the mantle (e.g., Tapponnier et al., 1982). Alternatively, if continuous pervasive deformation occurred in the continental mantle, the middle to lower crust would strain differently to link the brittle upper crust with the continuously deforming uppermost mantle. Thus, one basic difference between these views concerns the degree to which faults with large offsets at the surface continue into the mantle as faults or fault zones, or as broader regions of distributed deformation.

These views of lower crustal and upper mantle deformation require different Moho topography and deformation-induced fabrics in the crust beneath strike-slip faults with large offsets (Fig. 1). If the lower crust and mantle

lithosphere behaved as essentially rigid blocks, the Moho beneath faults with large displacements ( $\geq 100$  km) should have a discrete step where two blocks of differing crustal thickness are juxtaposed. Relative motion between adjacent crustal blocks would be accommodated along the block boundaries with

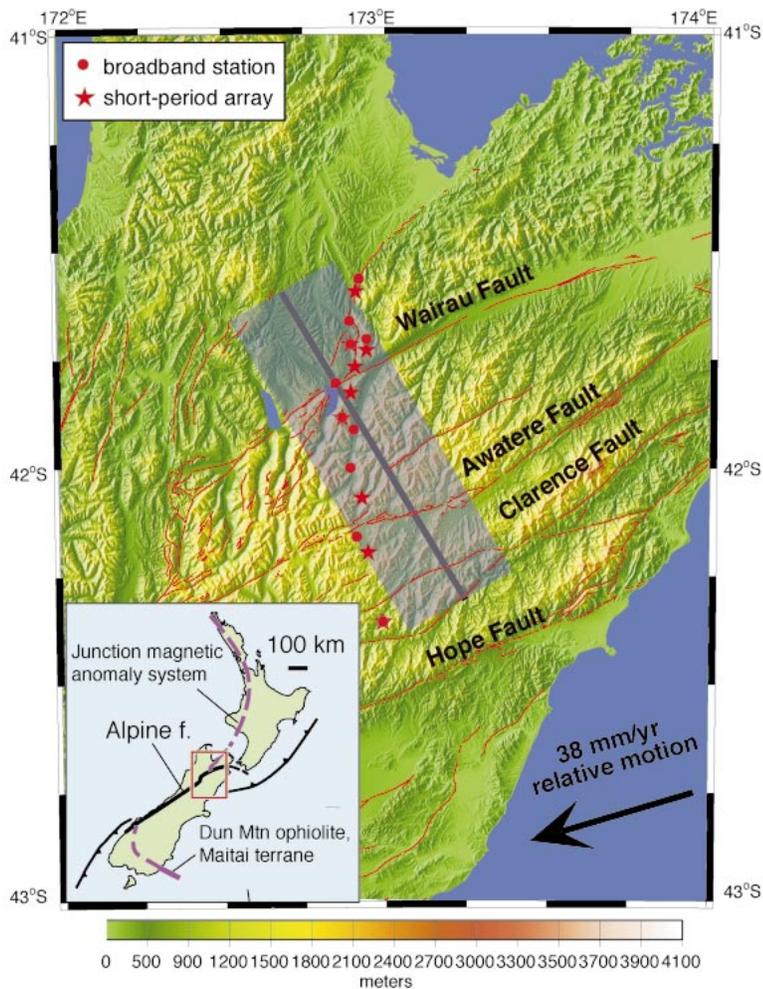
vertical strike-slip faults extending into the lower crust and upper mantle as thin shear zones (Fig. 1B). Conversely, if deformation in the lower crust and upper mantle was distributed over a broad region, the depth of Moho should vary smoothly without a step beneath the fault, and middle and lower crustal strain would vary spatially. Distributed, pervasive shear will tend to align rock fabrics roughly parallel to the displacement contours (Fig. 1A), thus producing subhorizontal foliations beneath the faulted upper crust and lineations roughly paralleling the slip direction. Such foliated rock is likely to be seismically anisotropic (Godfrey et al., 2000).

The presence of such features remains in dispute. Some studies have interpreted variations in crustal thickness across faults to show that they penetrate the Moho (Henstock and Levander, 2000; Weber et al., 2004; Zhu, 2000). Unfortunately, these studies are limited by ambiguities between seismic wavespeed and interface depth, limited lateral resolution of wide-angle interpretations, and difficulties in identifying the base of the crust on processed seismic images. Some studies constrain the minimum depth extent of faults to be that



**Figure 1. Two competing models that describe strain accommodation in continental strike-slip fault zones. Spatial variation in displacement ( $d$ ) across each strike-slip fault system is demonstrated by color variation and contour lines with total strike-slip displacement equal to  $D$ . A: Distributed deformation in lower crust and mantle. B: Deformation concentrated on fault that cuts across lower crust and mantle. Model A would require continuous unbroken Moho throughout region and possibly presence of midcrustal horizontal shear zone to accommodate vertical variations in strain. We expect highly anisotropic subhorizontal foliation to develop perpendicular to maximum strain gradient. With significant amount of offset, model B might predict Moho step ( $\sim 5$  km wide) beneath narrow vertical shear zone as two pieces of crust with differing thickness become juxtaposed. In this model, all strain is concentrated along vertical shear zone, leaving rest of lower crust relatively unstrained.**

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**Figure 2. Shaded topographic map of northern end of South Island of New Zealand showing faults of Marlborough fault zone. Inset shows tectonic setting of New Zealand. Stars locate high-density arrays of short-period seismometers, and dots show single broadband stations used to fill gaps between arrays. Assuming that structure varies perpendicular to strike of Wairau fault, receiver function amplitudes within shaded area were projected onto heavy line. Displacement of Junction magnetic anomaly (purple line, inset) indicates total offset across Alpine fault, most of which was absorbed in Marlborough by Wairau fault.**

of seismic reflectors that terminate beneath the surface traces of strike-slip faults (Hole et al., 2000; McBride, 1994; Weber et al., 2004). The pervasive shear model (Fig. 1A), however, does not require the adjacent crustal sections to be the same, but only that they not be blocks separated by through-going faults. Other studies have attempted to directly image fault planes to map their depth extent (Hole et al., 2001, 1996; Parsons and Hart, 1999). Although intriguing, these results are not entirely convincing because nearly horizontal raypaths are difficult to calculate with conventional ray tracing techniques, and shot-receiver offsets are rarely sufficient to sample many of these rays.

#### MARLBOROUGH FAULT SYSTEM

One of the most well developed and active continental strike-slip systems on Earth ex-

tends along the spine of the South Island of New Zealand. Currently, slip on the Alpine fault along with subduction at the Hikurangi Trench to its northeast and the Puseygun Trench to its southwest accommodate most of the Pacific-Australia relative plate motion (Fig. 2). Roughly 460 km of right-lateral slip on the Alpine fault accounts for more than half of the  $850 \pm 100$  km of relative plate motion since ca. 45 Ma across the central South Island (Sutherland, 1999). The Marlborough fault system, situated at the northern end of the South Island, represents the diffuse transition from localized transpression along the Alpine fault to oblique subduction at the Hikurangi Trench over a distance of nearly 200 km (Fig. 2). Transcurrent motion along the four major Marlborough faults accommodates virtually all plate motion (Bourne et al., 1998; Little and Jones, 1998). One defect

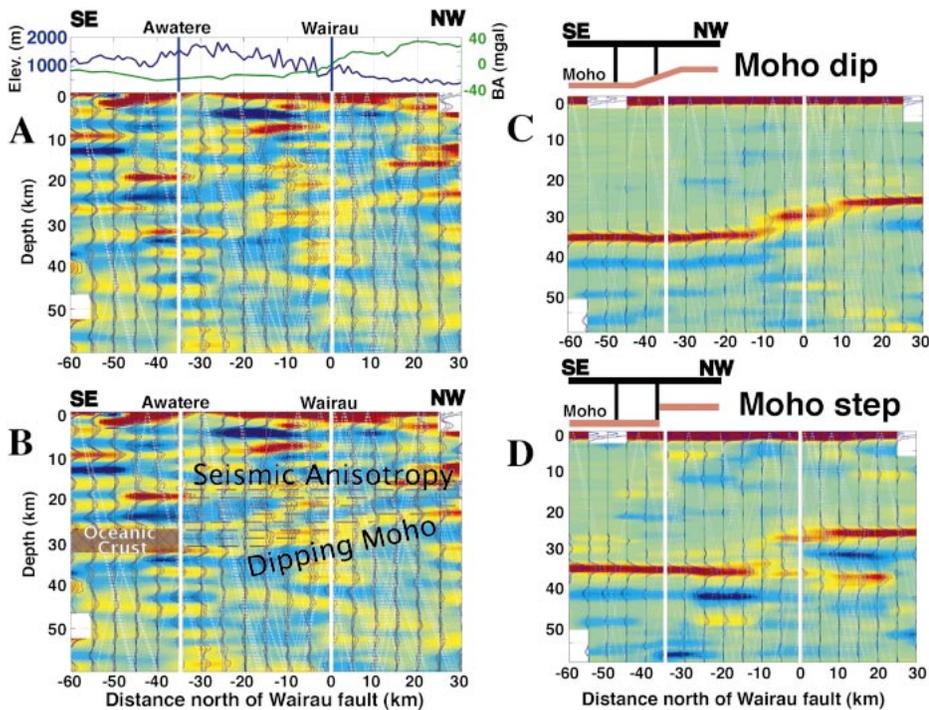
makes the Marlborough region imperfect as a laboratory for continental deformation: the downgoing slab of Pacific lithosphere beneath it is just below the Moho beneath the Hope fault, and dips to  $\sim 70$  km beneath the Wairau fault.

A simple seismic wave-speed structure and negligible crustal shortening make Marlborough an ideal location to test competing models of crustal strain accommodation beneath strike-slip faults. Graywacke of the Torlesse Supergroup underlies nearly two-thirds of the Marlborough region and nearly the entire region southeast of the Wairau fault. Inferences from seismic tomography indicate that this unit extends into at least the middle crust (Eberhart-Phillips and Reyners, 1997). This laterally uniform wave-speed structure minimizes bias in mapping crustal thickness variations south of the Wairau fault. The orientations of the Marlborough faults, parallel to Pacific-Australia plate motion (Cande and Stock, 2004), suggest that shortening perpendicular to them has been small.

#### DATA COLLECTION AND ANALYSIS

Between December 2000 and May 2002, we operated a network of five seismic arrays, each consisting of eight to nine short-period three-component seismometers (2 Hz free period: Mark Products L22), and, when available, one broadband sensor (Guralp CMG3-ESP) (Fig. 2). To minimize artifacts from near-surface scattering, we formed beams of ground velocity for each component and each teleseismic event by time shifting seismograms by the predicted P-wave delay relative to the predicted P arrival time at a reference location within the high-density array, and then stacking them. We deconvolved stacked vertical component seismograms from stacked radial and transverse components seismograms to produce radial and transverse receiver functions (Ligorria and Ammon, 1999), which ideally represent arrivals of Ps, S waves converted from the direct P wave (Langston, 1977; Phinney, 1964). The amplitude of the converted arrival depends on the impedance contrast across an interface and the incidence angle of the incoming wave to the interface.

To study the lateral variations in subsurface features and further mitigate contamination from topographic and near-surface scattering, we stacked the receiver functions into common conversion point bins after depth migration (Dueker and Sheehan, 1998) and incidence angle-dependent amplitude normalization. We averaged receiver function amplitudes within a volume extending 40 km along the strike of the Wairau fault, 5 km normal to strike, and 250 m in depth (Fig. 2). Bootstrap resamplings ( $n = 100$ ) of amplitudes within each bin yielded a mean and an uncertainty (Fig. 3; Efron and Tibshirani, 1986) not dominated by



**Figure 3.** Real and synthetic common conversion point images of lithosphere beneath Marlborough fault system. **A:** Uninterpreted stacked image using real data (with topography and Bouguer gravity anomaly profiles included above plot). **B:** Same as A, but with geological interpretation superimposed. **C:** Synthetic stacked images created from model with Moho dip. **D:** Same as C, but model contains Moho step. White lines indicate projections of Wairau and Awatere faults on cross sections. Model with unbroken but dipping Moho (C) better matches A, including high-amplitude region observed within dipping section of Moho.

a few aberrant receiver functions. Bins were then averaged over 15 km along the section line.

### MOHO TOPOGRAPHY

We interpret the strong converted phase at ~24 km depth northwest of the Wairau fault on the common conversion point stacked image as the Moho (Fig. 3). It dips  $\geq 25^\circ$  beneath the Wairau fault, and becomes flat again 15 km southeast of the fault at ~34 km. A second converted phase southeast of the Wairau fault defines an interface at ~26 km; this converted phase is stronger than that from the Moho in the southern part of the image. Most likely, the arrival from ~26 km marks the top of oceanic crust thought to underlie much of the South Island (e.g., Reyners and Cowan, 1993). In some regions the impedance contrast between the overlying Torlesse Supergroup and the presumed oceanic crust is greater than that at the Moho.

The band of converted energy that we interpret as the Moho dipping south beneath the Wairau fault includes gaps and variations in amplitude that might obscure a step in the Moho. To test this, we calculated synthetic seismograms by solving the wave equation numerically for a wide range of incident P waves and then formed synthetic common conversion point images with the observed

station-event geometry. The results (Figs. 3C, 3D) show that an 8 km step in the Moho should be resolved by our data set, and the synthetic image (Fig. 3D) clearly differs from our observed image. In contrast, a smoothly dipping Moho produces an image with small gaps and offsets that are caused by processing of the inhomogeneous distribution of rays (Fig. 3C). We cannot rule out the presence of several 1 to 2 km steps distributed across the 30-km-wide zone due to the imaging limitations of the ~1 Hz teleseismic waveforms, but for this study such deformation can be considered continuous.

### LOWER CRUSTAL ANISOTROPY

The presence of a Moho that is unbroken despite the large variation in crustal thickness across the Wairau fault indicates that the lower crust has undergone distributed, pervasive shear. Strain localized along surface faults becomes distributed over broader regions within the middle to lower crust (Bourne et al., 1998; Fig. 1), and should create widespread deformation fabrics (mylonitization) (Godfrey et al., 2000).

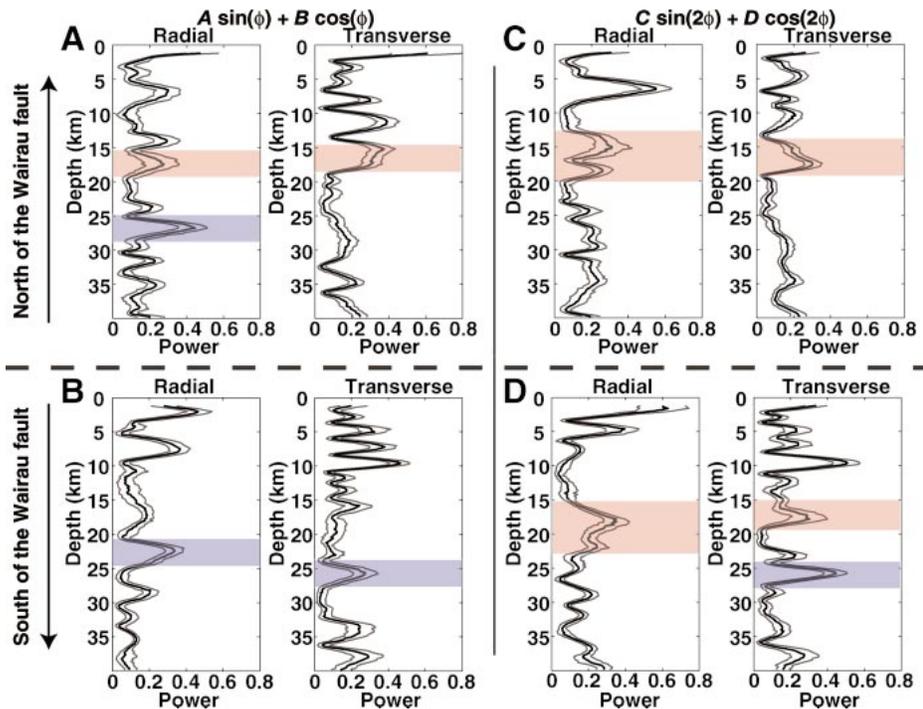
To constrain variations in the magnitude and depth of anisotropy on either side of the Wairau fault, we segregate receiver functions into those from rays north of the fault at a depth of 30 km from those to the south. An-

isotropy causes the amplitude of converted phases to vary with back-azimuth ( $\phi$ ) as  $A\sin(\phi) + B\cos(\phi) + C\sin(2\phi) + D\cos(2\phi)$ ; the  $2\phi$  terms result from a horizontal axis of symmetry of anisotropy, but any effect among plunging axes of symmetry, dip of an interface, or scattering can create  $1\phi$  variations in amplitude (Levin and Park, 1998). Using a least-squares inversion, we solve for best-fit values of  $A$ ,  $B$ ,  $C$ , and  $D$  on both radial and transverse receiver functions within a 2 km depth window centered every 200 m in depth (Fig. 4). To avoid biases introduced by errant receiver function amplitude values, we used a bootstrap resampling with replacement procedure during the inversion process.

This analysis confirms the dipping Moho and suggests pervasive anisotropy in the middle crust, though we cannot constrain well the orientations of fast and slow propagation. The increase of the  $1\phi$  power with limited increase in  $2\phi$  power occurs at the depth of the dipping Moho (Fig. 4), consistent with our inference that the Moho dips to the southeast. A flat Moho with discrete offsets should not produce significant variations of amplitude with back-azimuth. We suggest that the increase in  $2\phi$  power near the Moho reflects differences in strain and mineralogy between the crust and mantle. A large increase in  $2\phi$  power (marked by a red swath) between 15 and 20 km depth on both sides of the Wairau fault indicates the presence of seismic anisotropy at midcrustal depths (Fig. 4). There is a slight difference in the depth of strongest  $2\phi$  power across the Wairau fault, perhaps reflecting a variation in the depth of the brittle-ductile transition due to rheological variations across the fault.

### DISCUSSIONS AND CONCLUSIONS

Both the unbroken Moho and the pervasive anisotropy below ~15 km depth support the notion that surface faulting becomes a broad diffuse zone of deformation at depth in the crust (Fig. 1A) over a region at least as wide as the area densely sampled by this experiment (~60 km). The absence of a single discrete offset in the Moho argues strongly against a discrete shear zone in either the lower crust or upper mantle. We consider the juxtaposition of two sections of dipping Moho originally hundreds of kilometers apart so that they match to be improbable, regardless of whether the Wairau fault dips vertically or undergoes a contorted shape at depth. Similarly, the development of strong anisotropy at 15 km depth is unlikely to predate strike-slip faulting. The depths of anisotropy on both sides of the fault are similar (Fig. 4), but the pre-Cenozoic geologic histories differ considerably, with ophiolites accreted to a continental margin to the north and a thick sequence of turbidites to the south. Below ~15 km, crack-induced anisotropy is unlikely; most workers



**Figure 4.** Plots showing magnitude as function of depth of  $1\phi$  and  $2\phi$  back-azimuth variations for radial and transverse components from receiver functions to north (A and C) and south (B and D) of Wairau fault. Thinner lines represent  $2\sigma$  error bounds estimated through bootstrap resampling. Note increased  $2\phi$  power (marked by red swath on sections C and D) between 15 and 20 km depth on both sides of Wairau fault, indicating presence of seismic anisotropy beneath midcrustal interface. Increase of  $1\phi$  power and in some cases  $2\phi$  power on A, B, and D, marked by blue swath at depth of dipping Moho segments, supports our inference that Moho dips to southeast.

assign anisotropy to a preferred orientation of mineral grains (Godfrey et al., 2000). Although the relationship between crustal strain and seismic fast and slow axes remains controversial, the presence and cause of seismic anisotropy are not.

Seismic anisotropy of the lower crust in a zone  $> \sim 60$  km wide centered on the Wairau fault suggests that deformation in the mantle should occur over a comparable width. Previous studies of upper mantle anisotropy beneath Marlborough using both teleseismic SKS (Klosko et al., 1999) and deep New Zealand subduction-zone earthquakes (Audoiné et al., 2000) find that pervasive shear in the upper mantle accommodates the relative motion between the Pacific and Australian plates over a zone  $> 100$  km wide. Integrating these and our results suggests that deformation occurs by slip on discrete faults in the upper 15 km of the crust but is distributed as strain over a progressively broader region below, and therefore that rigid plates are a poor idealization of continental tectonics at continental boundaries.

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