Upper Plate Heterogeneity Along the Southern Hikurangi Margin, New Zealand

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Abstract Controlled and natural source seismic data are used to build a 3-D P wave model for southern North Island, New Zealand, where the Pacific Plate subducts beneath the Australian Plate at a rate of ~41 mm/year. Our analysis reveals an abrupt along-strike transition in overthrusting plate structure within Cook Strait. Contrasts in properties (Vp, Vp/Vs, and Qs) likely reflects the degree of deformation in the Australian Plate, where the Alpine-Wairau and Awatere Faults mark the northern boundary of a terrane that has undergone >50° of clockwise vertical-axis rotation since the early Miocene. Heterogeneity of the crustal transition is likely associated with changes in frictional and elastic properties that may impact elastic stress accumulation and inhibit southward propagation of megathrust earthquakes. Low connectivity of faults in Cook Strait is consistent with the heterogeneity we observe and may promote complex earthquake triggering by lateral stress loading during earthquakes or slow slip events.

Plain Language Summary Subduction zones produce the largest earthquakes and tsunami on Earth and knowledge of structures and physical rock properties at subducting margins will inform how and where strain is accumulated, as well as how stress is relieved. Combined information from earthquakes, seismic data, gravity observations, and geological mapping constrain a new 3-D subduction zone image at the southern Hikurangi margin, central New Zealand, where the Pacific Plate dives beneath the Australian Plate. The image reveals an abrupt inherited along-strike transition in the upper Australian Plate structure through Cook Strait. The region is notable because the 2016 magnitude 7.8 Kaikoura earthquake ruptured more than a dozen faults in northern South Island, south of Cook Strait, and triggered large afterslip on the subduction interface. However, the Kaikoura earthquake afterslip did not extend across the Cook Strait transition, into the southern North Island, where the subduction interface is currently strongly coupled or locked. Our work offers new insights suggesting that structure and frictional properties of the overthrusting upper plate might also limit the lateral extent of rupture in future earthquakes on the southern Hikurangi subduction zone.

1. Introduction

Information about the physical properties and slip behavior of subduction thrust faults can be derived from analysis of the geological structure of the overthrusting plate, because geodetic and paleoearthquake studies show that most of the elastic strain released in earthquakes or slow slip events has accumulated in the upper plate (Collot et al., 2004). Elastic properties influence how and where strain is accumulated, as well as how stress is relieved, with numerical models of earthquake rupture dynamics and slow slip events revealing strong dependencies on elastic properties of the overthrusting plate (Sallarès & Ranero, 2019; Williams & Wallace, 2018). The frictional behavior of megathrusts has been shown to change in response to lateral changes in forearc lithology. A clear example comes from northeast Japan, where along-strike juxtaposition of volcanic and plutonic rocks with accretionary complexes either side of the Median Tectonic Line was a key control on the area and magnitude of coseismic slip during the 2011 Mw 9.0 Tohoku-Oki earthquake (Bassett et al., 2016).
Here, we present a study of the southern Hikurangi subducting margin, New Zealand (Figure 1), where contemporary continuous Global Positional System (cGPS), and repeat observations of campaign geodetic data that span up to 140 years, indicate that the subduction interface is currently strongly coupled or locked (Figure 1) to depths of 25–30 km over a 90- to 110-km-wide zone perpendicular to the strike of the margin (Wallace et al., 2012). Although there is no historic record of great megathrust earthquakes (Mw >8.0) at the Hikurangi margin (Webb & Anderson, 1998), the crustal strain accumulation measured by cGPS techniques suggests that the southern part of the Hikurangi plate interface fault will eventually undergo slip as Mw 8.0 or greater earthquakes (Wallace et al., 2014). Paleoseismic interpretations reveal up to 10 subduction earthquakes may have occurred in the past 7,000 years, with the last at 520–470 years BP at the southern Hikurangi margin (Clark et al., 2019).

Earthquake tomography studies in southern Hikurangi reveal spatial variations in material properties of the overthrusting plate that may influence plate coupling and rupture behavior during large earthquakes. The upper plate in the region of strong plate coupling beneath Wellington coincides with fast Vp (Bassett et al., 2014), low Vp/Vs (Eberhart-Phillips & Reyners, 2012; Reyners & Eberhart-Phillips, 2009), and high electrical resistivity (Heise et al., 2013). Reyners and Eberhart-Phillips (2009) suggest that geological terranes may be controlling plate coupling, and Bassett et al. (2014) interpret the presence of a geological terrane boundary within Cook Strait from residual travel time anomalies. Controlled-source reflection, refraction, and earthquake tomography along a two-dimensional transect across the southern North Island (Henrys et al., 2013) revealed a broad low-Vp zone up to 10 km thick above the subduction interface at depths of 16–30 km, probably associated with underplated sediments. Each of these studies lacks the spatial resolution to explore these relationships in detail throughout the region. We use joint controlled-source and local earthquake tomography, combined with an analysis of residual gravity anomalies to constrain the 3-D geological architecture of the southern Hikurangi margin.

2. Data and Methods

We use three-dimensional (3-D) joint controlled and natural source seismic tomography to image the crust and subducting slab over a 320 × 300-km region of the southern Hikurangi margin (Figure 1). The controlled-source seismic data set includes data from the SAHKE project, which was carried out in two field seasons between 2009 and 2011 (supporting information and Henrys et al., 2013).

Marine multichannel seismic shots recorded on land stations were resampled to a minimum inline shot spacing of 1 km, leading to a final selection of 3,993 shots and 77,408 P wave travel times. To simply parameterize a gridded model for the crustal velocity structure, we stripped the water layer and repositioned source locations to the seabed, applying bathymetry corrections to the travel times, assuming near-vertical propagation at seawater velocities. Local earthquake data were compiled from the ~5-month period of the SAHKE passive deployment (Evanzia et al., 2017) and previous studies (Eberhart-Phillips & Bannister, 2010; Eberhart-Phillips & Reyners, 2012). The final catalogue comprised 3,683 earthquake events in total, including 98,499 P phases and 31,661 S phases. Arrival times of local earthquakes and shots were used in a simultaneous inversion for hypocenters and 3-D P wave and Vp/Vs structure (Eberhart-Phillips & Reyners, 2012; Thurber & Eberhart-Phillips, 1999; Um & Thurber, 1987). The initial Vp and Vp/Vs grids were built using the NZ-wide 3-D velocity model (Eberhart-Phillips et al., 2017a), which is based on fitting a national earthquake catalogue. The controlled-source shots
expand ray coverage and resolution offshore, particularly at shallow (<30 km) depths. Horizontal grid spacing varies between 20 × 20 and 5 × 10 km. Vertical grid spacing increases from 1 km at the top of the model to 20 km at the base. Multiple inversions were carried out on staggered grids to reduce bias introduced by our choice of domain discretization. The final model was calculated as the mean of the output models of four staggered inversions. Details of checkerboard tests and comparison with initial NZ-wide velocity model are described in the supporting information.

3. Results

Margin-normal and margin-parallel slices through the final 3-D model are shown in Figure 2. In the margin-normal direction (Figures 2b, 2c, and S4a–S4f), the forearc can be divided into three domains. The crust in the eastern coast of North Island and the offshore forearc are characterized by laterally homogeneous wave speeds that are everywhere <6 km/s and are predominantly <5 km/s. West of model-km 130, seismic wave speeds increase abruptly, with Vp in the upper and middle crust regionally exceeding 5 km/s, and locally exceeding 6 km/s within uplifted limbs of thrust faults (Figures 2b and 2c). The transition is expressed as a sharp east-to-west reduction in Vp/Vs ratio from 1.75 to 1.60, as seen previously by Eberhart-Phillips and Reyners (2012), and is spatially correlated to an active thrust fault imaged on seismic reflection data that splays off the subduction interface (Henrys et al., 2013). At the surface, this fault bounds the western edge of the Aorangi Range (Begg & Johnston, 2000). East of Kāpiti Island (model-km 65 on Profile A-A’, Figure 2), Wanganui Basin contains 3.5-km thickness of low-velocity sediments and lateral variations in crustal structure at model-km 0 and 25 are likely associated with the Kāpiti-Manawatu (Lamarche et al., 2005) and Taranaki faults (Stagpoole & Nicol, 2008). Crust underlying Wanganui Basin is ~30 km thick and has Vp of 6.0–6.5 km/s. The Moho dips 4–5° southeast and intersects the subduction interface at 30- to 35-km depth.

The subducting Hikurangi Plateau crust is imaged below the plate interface as Vp 6.5–7.0 km/s above an extensive high Vp mantle (8.0–8.8 km/s) with a steep velocity gradient immediately below the subduction interface. Intriguingly, the highest concentration of subducting plate seismicity occurs directly below the region of low Vp/Vs ratio in the overlying Australian Plate (Figure 2c).

In the margin-parallel direction, we identify an abrupt transition in crustal structure that occurs offshore the southern tip of North Island within Cook Strait (model-km ~110). In the P wave velocity structure (Figures 2e, S4g–S4i, and S5a), this transition is marked by a 10-km step in the depth of the 5-km/s isovelocity contour. To the north, Vp is regionally >5 km/s and exceeds 6 km/s in the lower crust and in isolated (possibly faulted or uplifted) blocks in the middle crust. To the south, isovelocities dip northeast and <3.5 km of low-velocity (Vp < 4 km/s) sediments have accumulated in the Wairau and Wairarapa Basins of Cook Strait. Vp increases with a shallow and homogeneous gradient through the middle crust and lower crust, and wave speed variations at the depth of the subduction interface are of a similar magnitude to those imaged in the upper crust.

The along-strike transition in crustal structure is particularly well expressed by the Vp/Vs ratio (Figures 2f and S5b). Southern North Island forearc has Vp/Vs < 1.70, in contrast to the region south of the transition, where Vp/Vs is >1.75. The transition is also well expressed in the seismic quality factor Q (Figures 2g and S5c), which is the inverse of seismic attenuation, with Qs dropping by a factor of 2–4 from north-to-south across this boundary (Eberhart-Phillips et al., 2014).

We note that the apparent location of the transition in crustal structure occurs ~15 km farther southwest in images of Vp/Vs and Q, than is inferred from the P wave velocity structure. This may reflect differences in the spatial resolution of Vp and Vp/Vs images and/or the sensitivity of these parameters to different physical properties (Eberhart-Phillips et al., 2014). The location of the P wave transition is correlated with an ~80-mGal reduction in residual free-air gravity anomaly, consistent with an expected positive correlation between density and Vp. Increased Vp/Vs, by contrast, may reflect increased fluid pressure or clay content, and low Qs may be related to increased fluid pressure, increased fracturing, and grain size reduction. Considering all three inversion images and model resolution (Figures S2 and S4), we conservatively estimate the crustal transition zone along this cross section to lie between Y = −100 and Y = −120 km.

Both background seismicity and aftershocks following the 2016 Mw 7.8 Kaikoura earthquake show relationships with the along-strike transition in crustal structure (Figures 2e and 2f). Analogous to observations...
Figure 2. Southern Hikurangi composite cross sections perpendicular (A-A’) and along strike (B-B’) to the margin (Figure 3a). (a, d) Slip rate deficit distribution at the plate interface (Wallace et al., 2012) and residual gravity anomaly. (b, e) Cross section of the 3-D Vp, (c, f) Vp/Vs models, and (g) Qs (Eberhart-Phillips et al., 2017b). The velocity models are masked where the Derivative Weight Sum (Toomey & Foulger, 1989) is less than 10. Subduction interface (black line) from Williams et al. (2013), based on earthquake locations and crustal structure studies, and the Australian Plate Moho (dashed black line in panels b and c) is from Henrys et al. (2013). The crustal transition zone along B-B’ lies between Y = −100 and −120 km, shown by the hatched pattern (d), and is close to where the Wairau and Awatere Faults are mapped offshore (Figures 3a and 3b). Superimposed are earthquake hypocenters (+ symbols; b, c, e, and f) described in the text and Kaikōura earthquake aftershocks (Lanza et al. (2019), white filled circles; e–g). Dashed white lines are interpreted upper crustal faults (Henrys et al., 2013).
made in the dip-parallel direction (Figure 2c), seismicity within the crust of the subducting Hikurangi Plateau is highest where the overlying plate has low Vp/Vs ratio. The northeast-to-southwest increase in Vp/Vs ratio in the Australian forearc (Figure 2f) is accompanied by a reduction in seismicity in the subducting slab and an increase in seismicity in the overlying plate. Aftershocks following the 2016 Kaikoura earthquake were in the overlying plate and located almost exclusively south of the transition in crustal structure in a region characterized by low Vp, high Vp/Vs and low Qs (Figures 2e and 2f and Lanza et al., 2019).

4. Physical Interpretation

Onshore geology, offshore fault mapping, and tectonic reconstructions of the Neogene evolution of New Zealand provide a framework for interpreting the observed transition in crustal structure. In Figure 3a, we show a horizontal slice through the P wave velocity model taken at 8-km depth. We also show a map of residual free-air gravity anomalies (Bassett & Watts, 2015a) that supports our inference of an abrupt transition in crustal structure within Cook Strait (Figure 3b).

The transition in crustal structure identified in the strike-parallel seismic cross section (hatched, Figure 2d) is located in close proximity to where the Awatere and associated faults are mapped offshore (Pondard & Barnes, 2010). Across this fault zone, our seismic velocity model shows an abrupt 10-km increase in depth to the 5-km/s isovelocity surface (Figure 2e). This expression is consistent with previous studies showing the onshore Awatere Fault to be marked by an abrupt NW-SE reduction in seismic velocity and a sharp >8-km increase in depth to the 6-km/s isovelocity surface (Ellis et al., 2017). Based on geophysical similarity and continuity, we associate the crustal transition with the Awatere Fault zone, and we interpret the easterly extension of the zone to follow an arcuate geometry that broadly coincides with Cook Strait Canyon to its intersection with the Boo Boo Fault (Pondard & Barnes, 2010) (Figures 3a and 3b).

The steepest residual free-air gravity anomaly gradient (Figure 3b) coincides with the southern extent of seismic wave speeds >6 km/s at 8-km depth (Figure 3a) and in the west is coincident with the offshore extension of the Wairau Fault (Pondard & Barnes, 2010). This fault was the original link between the Alpine Fault and the Hikurangi margin during the Miocene and accumulated 140 km of right-lateral displacement, offsetting Mesozoic basement terranes and the Eskhead Mélange (Figure 3c) (Mortimer, 2004). The absence of large displacement (>50 km) strike-slip structures in North Island requires this fault to lie offshore. We interpret the westerly extension of the Alpine-Wairau Fault as following an arcuate geometry parallel to that of the Awatere Fault (Holdgate & Grapes, 2015; Walcott, 1978).
The position of the Awatere and Wairau Faults beyond their intersection with the Boo Boo Fault cannot be determined from our 3-D seismic velocity model. The arcuate form of the residual free-air gravity anomaly, however, suggests that these faults extend farther west and are progressively rotated to a geometry almost perpendicular to the local strike of the Hikurangi trough (Figure 3). The fault geometry we interpret is consistent with paleomagnetic and structural data indicating extensive (>50°) clockwise vertical axis rotations since the Middle Miocene in northern Marlborough (Little & Roberts, 1997; Rowan & Roberts, 2008). The physical mechanism accommodating vertical axis rotations is proposed to be a migrating hinge model, analogous to a flexed telephone book (Little & Roberts, 1997). This mechanism is consistent with the wide distribution of brittle fracture in Torlesse rocks in northeast South Island and distributed cataclastic flow may accommodate aseismic deformation within rotation zones (Little & Roberts, 1997). The northern boundary of the rotating northern Marlborough domain is fixed by the clockwise rotated ancestral trace of the Alpine-Wairau Fault (Little & Roberts, 1997).

5. Discussion

5.1. Relationships With Megathrust Slip Behavior

Within Cook Strait, the slip-rate deficit on the Hikurangi subduction interface drops from >25 mm/year beneath southern North Island, to <15 mm/year within northern Marlborough (Figures 1 and 2d) (Wallace et al., 2012). A large component of this reduction reflects the increasing obliquity of relative plate motion, resulting in a higher proportion of plate displacement (~80%) being accommodated by strike-slip faults in the overthrusting plate (Wallace et al., 2012). Elastic block models of GPS velocities that incorporate slip rate constraints for active faults imply a reduction in strength of interseismic coupling on the Hikurangi megathrust within Cook Strait (Figure 4a). However, the low strain rates, increasing distance from terrestrial cGPS networks, and uncertainties on slip rates of crustal faults make accurate assessments of geodetic coupling of the subduction interface beneath Cook Strait a challenge.

The most compelling evidence of an along-strike transition in the frictional behaviour of the subduction interface was provided by the 2016 Mw 7.8 Kaikōura earthquake (Figures 2e–2g and 4b). This earthquake ruptured more than a dozen faults in northern South Island (Hamling et al., 2017; Holden et al., 2017), and triggered widespread slow slip on most of the Hikurangi subduction zone with large (up to 50 cm) after-slip on the subduction interface directly beneath the rupture zone (Wallace et al., 2017; Wallace et al., 2018). In contrast to transient deformation along the east coast of North Island, changes in the sense and rate of motion at cGPS sites in northern South Island persisted for over a year, resulting in up to 20 cm of...
northeast displacement and a broad uplift-subsidence pair recorded in both cGPS and interferometric synthetic aperture radar data (Wallace et al., 2018). This broad deformation pattern is inconsistent with slip on crustal faults and suggests broad aseismic deformation on a deeper low-angle structure such as the subduction interface beneath northern South Island.

The distribution of afterslip on the Hikurangi subduction interface after the 2016 Kaikōura earthquake is shown in Figure 4b. The pattern primarily shows a large area of crust beneath the Awatere Fault moving northeast relative to the underlying oceanic plate and southern North Island. No afterslip occurred north of the ancestral trace of the Alpine-Wairau Fault, except at depths where the subduction interface is within the mantle wedge and no longer in contact with crust of the forearc. Large amplitude (>30 cm) afterslip and most aftershocks occur south of the rotated Awatere Fault (Figure 4b), suggesting that the geological architecture of the overthrusting plate is impacting slip behaviour on the underlying subduction interface. The regional anticorrelation between interseismic coupling and slow slip (afterslip or triggered) following the Kaikōura earthquake supports inferences of reduced interseismic coupling within Cook Strait.

There is a variety of physical mechanisms that may explain the caustive links to what we propose. It has been suggested that hanging wall terranes (Figure 3c), juxtaposed by the Alpine-Wairau Fault, may influence frictional properties of the megathrust through their different permeabilities and hence fluid pressures near the plate interface (Reyners & Eberhart-Phillips, 2009). This idea is consistent with the along-strike contrast in Vp/Vs ratio in western Cook Strait but cannot be extended east of the Eskhead Mélange (Pahau-Rakaia boundary), where lithological contrast across the Alpine-Wairau Fault terminates (Figure 3c).

A modified interpretation that overcomes spatial limitations imposed by terrane boundaries is that contrasts in seismic structure may reflect the degree of deformation of the Australian Plate. The Alpine-Wairau Fault marks the northern boundary of the northern Marlborough Domain, which has undergone >50° of clockwise vertical axis rotation since the early Miocene (Little & Roberts, 1997). We suggest that brittle fracture caused by deformation results in increased porosity of the hanging wall and hence variable Vp, Vp/Vs, and Qs. Regions of low Vp/Vs in the hanging wall are north of the region of high crustal deformation and overlie regions of increased seismicity in the crust of the Hikurangi Plateau (Figure 2f). High rates of seismicity in the subducting crust may be promoted by high pore fluid pressures due to a permeability barrier at the plate interface preventing water from moving upwards. Above the interface, the permeability barrier and the lower porosity leads to less liquid and therefore lower Vp/Vs and strong interseismic locking (high slip deficit, Figures 2a and 2c). In map view, this effect is manifest as a deepening of strong coupling in the region of low Vp/Vs where the interseismic megathrust may act as a fluid barrier (Figure 4a). We anticipate that coseismic rupture would promote postseismic fluid flow as seen in Vp/Vs study of the Mw 8.0 Antofagasta, Chile, earthquake (Husen & Kissling, 2001) and stress rotations following slow slip along the Hikurangi margin (Warren-Smith et al., 2019).

5.2. Implications for Margin Segmentation and Earthquake Rupture Boundaries

Our tomography combined with geological mapping suggests that the contrast in subduction interface slip behavior between southern North Island and Cook Strait can be related to inherited crustal structures in the overthrusting Australian plate. Establishing this link may have implications for hazard associated with the subduction interface and crustal faults of the forearc.

It is possible that the contrast in fault slip behavior at depth may be sharper than expressed by the geodetic coupling model (Figures 1 and 4a). Sharp contrasts in fault strength act to focus frictional resistance to creep (Hillers & Wesnousky, 2008), and this model has been proposed to explain the anomalously large slip amplitude of the 2011 Tohoku-Oki earthquake (Bassett et al., 2016). The local implication is that if frictional resistance against creep within Cook Strait is lower, then this may increase the rate of strain accumulation on the subduction interface beneath southern North Island.

A second consideration is the impact of the transition in crustal structure on the area of megathrust fault rupture. Numerical models show that dynamic earthquake rupture fronts decelerate as they penetrate into unloaded velocity strengthening regions (Tinti et al., 2005). Cook Strait has long been viewed as a zone of fault termination (Carter et al., 1988; Pondard & Barnes, 2010). Both the Alpine-Wairau and Awatere Fault traces interpreted in this study coincide with stepovers or zones of fault termination (Figure 3b). Thus, the potential for throughgoing rupture between crustal faults of the North Island Dextral Fault Belt.
and their South Island counterparts of the Marlborough Fault Zone may be reduced by the lack of structural continuity. The Alpine-Wairau Fault might limit southward propagation of megathrust earthquakes, either because of structural complexity inhibiting rupture propagation or because of the Marlborough domain being unloaded.

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References


