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Sub-crustal earthquakes within the Australia–Pacific plate boundary zone beneath the Southern Alps, New Zealand

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ABSTRACT

Sub-crustal earthquakes have been observed sporadically for ∼40 years in the central South Island of New Zealand. We report on 20 events recorded between December 2008 and February 2012 near the Alpine Fault in the continental collision zone between the Australian and Pacific plates. A subset of 18 events at depths of 47–74 km occurs south of Mt. Cook and together with recently reported tremor locations indicates along-strike variations in deformation behaviour along the plate boundary. The sub-crustal earthquakes south of Mt. Cook increase in depth, frequency and size southwards towards the Puysegur subduction zone. Focal mechanisms could be determined for 14 earthquakes and exhibit predominantly strike-slip and reverse faulting solutions. Stress inversion analysis of the focal mechanisms yields a stress field favouring oblique-reverse faulting. We interpret the geographic and vertical distributions of these sub-crustal events in relation to a previously proposed tectonic model of a remnant passive margin that formed south of New Zealand in the Eocene and was overridden when dextral strike-slip motion initiated on the Alpine Fault. We infer that sub-crustal earthquakes occur along the leading edge of this structure, which is attached to the continental Australian crust.

1. Introduction

1.1. Tectonic framework

Continental collision between the Australian and Pacific plates in the central South Island of New Zealand has uplifted the Southern Alps, a young (∼5 Ma), actively deforming orogen. The Southern Alps are bounded on the western side by the Alpine Fault, a transpressive structure that has accommodated ⩾460 km of dextral motion (Sutherland, 1999). Shortening of the crust by 40–110 km since 11 Ma (Walcott, 1998; Cande and Stock, 2004) has caused crustal thickening that increases southwards in the central South Island. The crustal structure beneath the Southern Alps has been investigated in previous active-source seismic studies (South Island Geophysical Transect (SIGHT); Davey et al., 1998; Okaya et al., 2007; Stern et al., 2007) and tomography (Southern Alps Passive Seismic Experiment (SAPSE); Eberhart-Phillips and Bannister, 2002; Kohler and Eberhart-Phillips, 2002). Two-dimensional velocity models along transects parallel and perpendicular to the orogen reveal that 18–25 km-thick crust that had previously been thinned by rifting starting in the late Cretaceous (King, 2000; Cox and Sutherland, 2007) was subsequently thickened beneath the Southern Alps (Scherwath et al., 2003; Van Avendonk et al., 2004).

The present-day Moho has been identified at a depth of ∼27 km in the offshore seismic profile west of the Alpine Fault (T3 in Fig. 1; Melhuish et al., 2005), and at maximum depths of 37 km and 44 km beneath the northern and southern SIGHT transects, respectively, perpendicular to the Alpine Fault (Van Avendonk et al., 2004; Scherwath et al., 2003). The crustal deformation zone is asymmetric and concentrated on the Pacific side of the plate boundary: A sharp step in the Moho occurs beneath the Alpine Fault in the west, the deepest Moho structure is offset 10–20 km to the east from the highest topography of the Alps, and the eastern flank shows a gradual depth decrease (Davey et al., 1998). Earthquake refraction analysis by Bourguignon et al. (2007) revealed Moho depths of 48 ± 4 km in the Wanaka area (Fig. 1).

Three-dimensional models of the Moho structure from receiver function and active-source seismic observations (Spasojević and Clayton, 2008; Salmon et al., in press), gravity data and tomography (Woodward, 1979; Eberhart-Phillips and Bannister, 2002) all suggest that the crustal root beneath the Southern Alps deepens and widens to the south. Beneath T3 SIGHT transect, the crustal root is almost twice as thick as required to isostatically balance the Southern Alps, and is offset southeastward of the area

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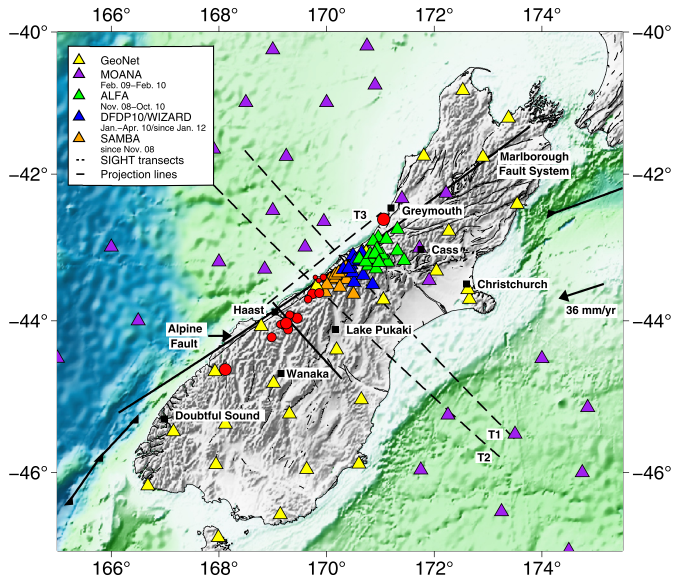

Fig. 1. Sub-crustal earthquakes (red dots) recorded since November 2008 and station networks operational in 2008–2012 as specified in the legend. Black dashed lines are SIGHT transects T1–T3 (Scherwath et al., 2003; Van Avendonk et al., 2004; Melhuish et al., 2005), and solid lines mark the profiles shown in Figs. 5 and 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of highest topographic elevation (Davey et al., 1998; Stern et al., 2002; Scherwath et al., 2003, 2006). The excess thickness of the crust implies a deficit of mass reflected by the negative isostatic gravity anomaly (maximum amplitude of 30 mgal), but a positive density anomaly in the mantle is needed to account for the downward pull of the Moho and to suppress topography (Stern et al., 2000, 2002; Bourguignon, 2009). The negative isostatic gravity anomaly is elongated and overlies the centre of over-thickening of the crust. The decrease of teleseismic P-wave travel-time residuals along transects across the South Island has been used to model a sub-vertical, symmetric high-velocity mantle anomaly (Stern et al., 2000). A P-wave velocity anomaly of 7% relative to the reference value of 8.1 km/s was inferred for a body of 80 km width and 100 km vertical extent centred at 120 km depth. Three-dimensional modelling by Scherwath et al. (2006) resolved the shape in more detail. Tomographic studies with limited resolution in the mantle suggest a minimum increase of 2–4% in P-wave velocity at depths of >60 km (Kohler and Eberhart-Phillips, 2002).

1.2. Previous detection and analysis of sub-crustal earthquakes

Sporadic sub-crustal earthquakes in the central South Island were recorded by the Lake Pukaki network between 1975 and 1983 (Calhaem et al., 1977; Haines, 1979; Reyners, 1987). This dense nine-station network was installed during impounding of Lake Pukaki for hydroelectric power generation and recorded 48 events occurring at depths of >15 km; of these, 15 occurred deeper than 33 km. Event depths extended to 73 km but well-located earthquakes were confined to depths <50 km. Reyners (1987) obtained composite focal mechanism solutions which indicated predominantly strike-slip faulting.

Kohler and Eberhart-Phillips (2003) analysed sub-crustal earthquakes with well-constrained depths exceeding 30 km and magnitudes of $M_L \leqslant 4.0$ recorded by the New Zealand National Station Network between 1990 and 2000. In combination with the events recorded by the Pukaki network, their results showed that sub-crustal earthquakes are more frequent at the southern end of the Southern Alps than at the northern end. The shallowest of the events described by Kohler and Eberhart-Phillips (2003) and previous workers occurred within or below the crustal root, while the deepest extended down to 75 km with one event at 97 km. In general, the sub-crustal earthquakes are of small to moderate magnitudes ($M_L \leqslant 4.0$), except for the 8 May 1943 Lake Hawea earthquake, for which Reyners (2005) inferred a magnitude of M_W 5.9 and a depth of ∼50 km.

Reyners and Robertson (2004) suggested that intra-continental subduction of the Hikurangi plateau continues beneath the central South Island and becomes aseismic due to a change in the dehydration conditions. Based on the increase in earthquake depths from east to west beneath the Southern Alps, Reyners (1987) suggested that events near and below the Moho in this region occur on a 19°-dipping plane associated with westward subduction of the Pacific mantle lithosphere beneath the Southern Alps. Reyners et al. (2011) suggested that this subduction continues south to the Puysegur subduction zone. An alternative interpretation was proposed by Molnar et al. (1999) and Stern et al. (2000), who argued in favour of continuous mantle thickening beneath the central South Island rather than subduction along a discrete plane, on the basis of P-wave delays recorded on an array of 160 temporary seismographs. Those data suggest that thickening of the mantle lid beneath central South Island occurs in a zone extending vertically beneath the crustal root. Continuous thickening was favoured by Kohler and Eberhart-Phillips (2003), who demonstrated that the sub-crustal earthquakes occur in regions of high P-wave velocity or along the boundaries of such regions. Kohler and Eberhart-Phillips (2003) concluded that these events are controlled by high shear-strain gradients associated with depressed geotherms and viscous deformation of mantle lithosphere. Using finite element modelling, Pysklywec et al. (2002) suggested that both features—plate-like underthrusting/subduction and homogeneous thickening—are manifestations of the same process in different regimes: a subduction-like slab forms in the upper rigid part of the mantle while a mantle drop forms underneath in the lower weaker mantle.

2. Data and methodology

We analyse 20 sub-crustal earthquakes occurring at depths of 47–96 km beneath the Southern Alps using data collected by a large number of seismometers deployed in five separate networks. All 20 events were detected with the Southern Alps Microearthquake Borehole Array (SAMBA), which started recording in November 2008 (Boese et al., 2012), and stood out due to impulsive phase arrivals at several SAMBA stations. Re-examination of the events using additional data from other temporary seismic networks operating in the central South Island and offshore (Section 2.1) has yielded well-constrained hypocentres (Section 2.2), magnitudes of M_L 1.0–3.5 (Section 2.3), and focal mechanism solutions for 14 events (Section 2.4). These results are compared to and interpreted in conjunction with previously reported sub-crustal events at depths of 30–50 km in the Pacific plate and 40–100 km in the boundary zone beneath the Alpine Fault.

2.1. Seismic networks

In 2009, a large number of temporary and semi-temporary seismic stations were in operation throughout the South Island and offshore, in addition to the permanent national seismic network (GeoNet; Fig. 1). At the time, the GeoNet network comprised 26 broadband stations in the South Island with inter-station distances of ∼100 km (Petersen et al., 2011). The Marine Observations of Anisotropy Near Aotearoa (MOANA) network comprised 30 broadband OBS stations and four onland broadband stations (Collins et al., 2010; Yang et al., 2012), and started recording in February