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Three-dimensional imaging of impact of a large igneous province with a subduction zone

Martin Reyners [a,*], Donna Eberhart-Phillips [a,b], Phaedra Upton [a], David Gubbins [c]

[a] GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
[b] Department of Earth and Planetary Sciences, University of California Davis, Davis, CA 95616, USA
[c] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom

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ABSTRACT

How the thickened crust of a large igneous province on an incoming oceanic plate is accommodated at a subduction zone remains an open question. New Zealand is one of the few places to study this, as at ca. 105 Ma the ca. 35 km-thick Hikurangi Plateau impacted the Gondwana subduction zone in what is now the South Island. Here we report on results from a forty-station portable seismograph array in the southern South Island, designed to delineate the leading edge of the subducted plateau. Three-dimensional images of Vp and Vp/Vs reveal the southwestern part of the plateau was a relatively narrow salient, and the first part to be subducted. The plateau then rotated clockwise about this salient until the southern edge of the plateau was parallel to subduction strike and subduction ceased at ca. 100 Ma. Our results suggest that the global-scale plate reorganization event at 105–100 Ma was due to a cessation of subduction caused by the Hikurangi Plateau choking the Gondwana subduction zone, rather than the subduction of mid ocean ridges as previously proposed. The choking of Gondwana subduction by the plateau also led to a concentration of slab pull in the adjacent subducted oceanic crust, explaining the episode of basin opening and intraplate magmatism there that occurred at the same time. Our study underlines the havoc caused by impact of a large igneous province with a subduction zone.

1. Introduction

The Hikurangi Plateau was originally part of Ontong Java – the largest large igneous province on Earth. Ontong Java Plateau formed ca. 122 Ma ago (Neal et al., 1997). Seismic reflection and refraction measurements indicate that the plateau has a crustal structure resembling that of normal Pacific oceanic crust, but each layer is abnormally thickened by up to a factor of five (Furumoto et al., 1976; Hussong et al., 1979), with total thickness 35–42 km. Also, unusually high Vp of 8.4–8.6 km/s, appropriate for eclogite (Saunders et al., 1996), have been detected at the base of the northwest and southwest portions of the plateau (Furumoto et al., 1976). Shortly after formation of the plateau (at ca. 120 Ma), the Hikurangi and Manihiki plateaux rifted from it, and subsequently the Hikurangi Plateau rifted from the Manihiki Plateau at the Osbourn Trough and drifted south. The Hikurangi Plateau then impacted the Gondwana convergent margin, and plateau crust can be traced 50–100 km southward beneath the Chatham Rise (Fig. 1) on seismic reflection profiles (Davy et al., 2008).

There has been some debate as to the timing of this impact, and the accompanying cessation of spreading at the Osbourn Trough. This is largely due to the fact that the region surrounding the trough formed during the Cretaceous Normal Superchron (Chron 34, 121–83 Ma). Early work by Billen and Stock (2000) inferred magnetic anomalies near the trough (possibly anomalies 33 and 32), which led them to suggest that spreading continued after 83 Ma. Schellart et al. (2006) relied on this work for their tectonic reconstruction for the SW Pacific, taking Osbourn Trough spreading as ceasing at ca. 82 Ma. But more recent work by Downey et al. (2007), including abyssal-hill fabric, indicates that spreading at the Osbourn Trough ceased prior to 87 Ma or 93 Ma, depending on whether the Manihiki and Hikurangi Plateaux rifted at 115 Ma or 121 Ma. Mortimer et al. (2006) present isotopic data which constrain this rifting event to prior to 115 Ma, suggesting a cessation of spreading prior to 93 Ma.

Impact of the Hikurangi Plateau coincided with a sudden change in tectonic regime from subduction to extension in New Zealand (Bradshaw, 1989; Laird and Bradshaw, 2004). Primary evidence is a major Albian unconformity, with the youngest 'basement' strata locally containing Albian fossils, with the youngest

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* Corresponding author.
E-mail addresses: m.reyners@gns.cri.nz (M. Reyners), eberhartphillips@ucdavis.edu (D. Eberhart-Phillips), p.upton@gns.cri.nz (P. Upton), gubbins@earth.leeds.ac.uk (D. Gubbins).

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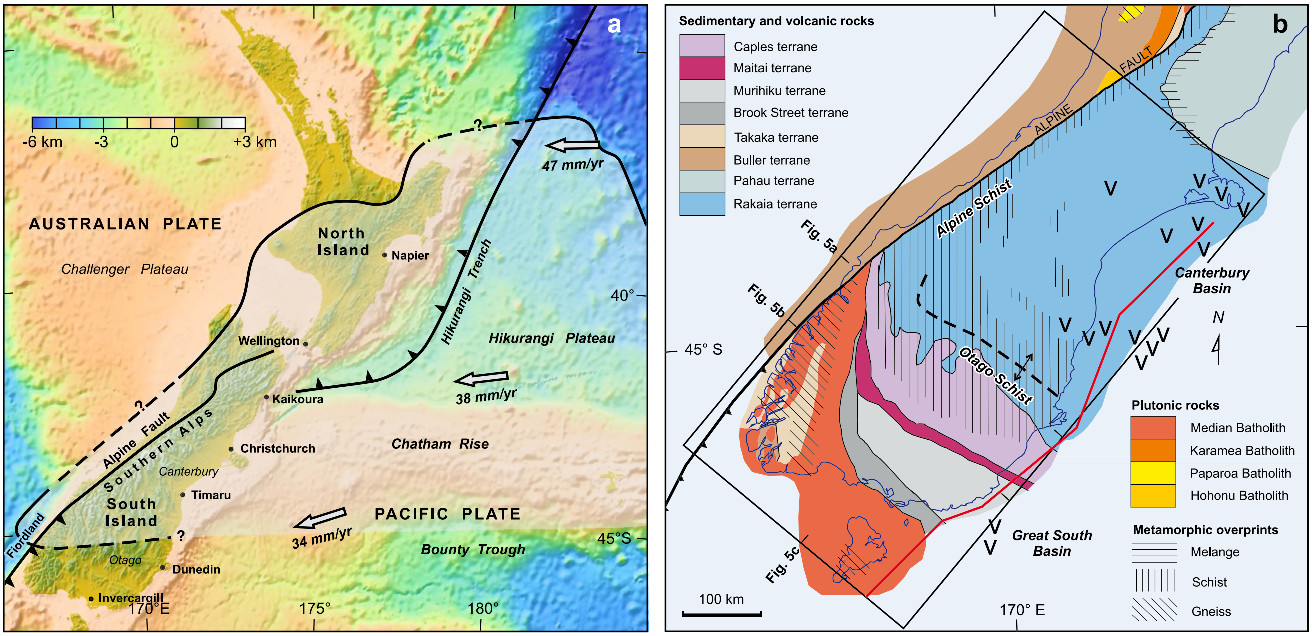

Fig. 1. Tectonic and geologic setting. The tectonic map of New Zealand (**a**) shows the Hikurangi and Fiordland subduction zones, with barbs on the plate boundary indicating subduction direction. Arrows show the current velocity of the Pacific plate relative to the Australian plate (DeMets et al., 2010). The light shading shows the extent of the Hikurangi Plateau, with its subducted western edge unrolled to the surface (Reyners et al., 2011). This edge is shown dashed where less certain. Geological terranes in the southern South Island (Mortimer, 2004) are shown in (**b**). The box shows the study region, with the locations of the depth sections in Fig. 5 indicated. The dashed line shows the Otago Schist antiform, the red line off the east coast shows the SESI seismic reflection profile, and V symbols denote the location of <110 Ma intraplate volcanism (Mortimer et al., 2002). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

associated zircons having been radiometrically dated at ca. 100 Ma. In general, the oldest strata overlying the unconformity contain fossils of similar Albian age, and the oldest radiometric dates also give similar dates of ca. 100 Ma, indicating a very rapid transition between the two tectonic regimes. The extension was substantial, with the Great South Basin off the southeast South Island (Fig. 1) accumulating more than 8 km of mid-Cretaceous and Tertiary sediments (Carter, 1988). Extension in the Great South Basin occurred simultaneously with extension in the Bounty Trough to the northeast (Grobys et al., 2008). Both these extensional features have essentially remained tectonically quiescent since the Cretaceous. Given the above geological information, we adopt the timing of Hikurangi Plateau impact with the Gondwana margin at 105–100 Ma, similar to Davy (2014). This timing is consistent with a recent determination of the age of the basaltic crust near the Osbourn Trough, which suggests spreading ceased at ca. 101 Ma (Zhang and Li, 2016).

Tectonic activity ramped up again in the western South Island with the inception of the Alpine Fault at ca. 23 Ma, and increasing convergence at the Pacific/Australian plate boundary led to westward subduction of the Hikurangi Plateau commencing at ca. 10 Ma (Reyners, 2013). So the plateau beneath the South Island has seen two episodes of subduction – the first episode during north–south convergence with Gondwana, and the current episode due to east–west convergence between the Pacific and Australian plates.

Relocation of New Zealand seismicity using a nationwide 3-D seismic velocity model (Eberhart-Phillips et al., 2010) has now allowed us to locate most of the subducted edges of the Hikurangi Plateau for the first time (Reyners et al., 2011; see Fig. 1). The plateau is identified by both the thickness of the dipping seismic zone (suggesting a ca. 35 km thick plateau) and the presence of a layer of high Vp (ca. 8.5 km/s) at its base. Both these features are similar to those of the parent Ontong Java Plateau. In the southwestern South Island, the southwestern corner of the plateau is well-defined by the collision of the plateau with the northern Fiordland subduction zone, where it bends the younger subducted Australian plate to vertical (Reyners et al., 2011). Also, detailed 3-D seismic tomography of the 2010 M_w 7.1 Darfield earthquake aftershock sequence beneath the Canterbury Plains west of Christchurch has clearly imaged the plateau dipping to the northwest, with the top of the plateau at ca. 10 km depth (Reyners et al., 2014). But south of Christchurch, a lack of well-recorded seismicity means we cannot accurately determine the southeastern edge of the plateau. We know the plateau must extend further south as permanent seismograph stations there record fast P-wave precursors. These are explained by propagation through a dipping layer of order 10 km thick, with Vp ca. 8.5 km/s (Love et al., 2015).

2. Local earthquake tomography in the southern South Island

We have thus supplemented the sparse GeoNet permanent seismograph network in the southeastern South Island with a forty-station broadband portable seismograph network. This portable network greatly increased our ability to accurately locate earthquakes in the southern South Island, not only within the network, but also in the surrounding region. The density of both seismograph stations and earthquakes has for the first time enabled detailed 3-D local earthquake tomography in the region. Here we describe a 3-D arrival time inversion for Vp and Vp/Vs. This inversion complements a previous inversion in the Fiordland subduction zone in the southwestern corner of the South Island (Eberhart-Phillips and Reyners, 2001).

The seismograph stations and earthquakes used in the inversion are shown in Fig. 2. The inversion grid is the same as that used in a New Zealand-wide study (Eberhart-Phillips et al., 2010), and is oriented along the strike of the Hikurangi subduction zone. Previous New Zealand-wide and Christchurch region studies were used as the initial model and form the 3-D model outside the study area (Eberhart-Phillips et al., 2010; Reyners et al., 2014). Data from 446 earthquakes and 15 shots recorded by the portable network were supplemented with 605 earthquakes from prior studies