The Moho in Australia and New Zealand

M. Salmon ⁎, B.L.N. Kennett, T. Stern, A.R.A. Aitken

Abstract

Australia and New Zealand share in part a history in the Gondwana supercontinent. Australia has a long and complex tectonic history with the last major accretion in the early Paleozoic, whereas New Zealand is still undergoing major plate boundary processes. The Australian continent is relatively well covered with both active and passive seismic techniques. Multiple sources of information are therefore available for building a model of Moho depth. Results from on-shore and off-shore refraction experiments are supplemented by receiver functions from a large number of portable stations and the recently augmented set of permanent stations. Moho picks from more than 10,500 km of full-crustal reflection profiles provide valuable additional constraints. The composite data set provides good sampling of much of Australia, though coverage remains low in some remote desert areas. The various datasets provide multiple estimates of the depth to Moho in many regions, and the consistency between the different techniques is high. Some of the thinnest crust lies beneath the Archean craton in the Pilbara, and in the neighbourhood of the Simpson desert. Thick crust is encountered beneath parts of the Proterozoic in Central Australia, and beneath the Paleozoic Lachlan fold belt in southeastern Australia. There are a number of zones of sharp contrast in depth to Moho, notably in the southern part of Central Australia.

Despite most of the continental material around New Zealand being submerged, Moho data for this region is mainly onshore concentrating on the Australia–Pacific plate boundary. Two major wide-angle reflection transects provide the bulk of the active source data with just a few traditional reflection profiles offshore. The plate boundary provides an abundance of local earthquakes for tomographic imaging and this data is supplemented with receiver functions from both portable and permanent networks. Onshore the combined coverage is as dense as that of Australia, although it could be argued that a higher spatial resolution is required to capture the nature of the Moho of tectonically active New Zealand. Three regions of thickened crust can be identified, one beneath the Southern Alps, another beneath Fiordland, and below the Wanganui Basin between the North and South Island. Thin crust is identified west of the volcanic arc, with extensive underplating below the back-arc region.

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1. Introduction

The Moho marks the physical base of the crust, and in many cases displays the largest wavespeed and density contrast of any lithospheric interface. Once the effects of surface topography are taken into account, the variations in the depth to Moho provide a rough estimate of the lithospheric body forces and associated loading at a particular location. This study provides a contrast between the variation in the Moho in seemingly stable Australia and that of New Zealand, which is subjected to active plate boundary forces.

Australia, much of New Zealand, and Eastern Antarctica were in close proximity in Gondwanaland and carry with them a common heritage after the breakup of the supercontinent. Whereas Australia has an ancient western core including some of the oldest rocks on Earth with subsequent eastern accretion in the early Paleozoic, New Zealand rocks are rather young and have been profoundly affected by modern plate boundary processes.

In both Australia and New Zealand a combination of active and passive seismic studies provide good control on the general behaviour of the Moho. Some desert areas in Australia are poorly sampled, and much of the submerged continental material around New Zealand also has limited seismological control on crustal thickness.

2. The Moho in Australia

Australia has a long and complex tectonic history. The Australian continental crust was accreted in three major episodes, each contributing about one third of the continental area from the Archean cratons in the west to Phanerozoic provinces in the east. A set of Archean components were assembled into three major cratons in the Proterozoic: West Australia, the North Australian Craton, and the South Australian Craton formed by ~1830 Ma, and this cratonic assemblage was joined to the Rodinian supercontinent by 1300–1100 Ma (Cawood and Korsch, 2008). The supercontinent broke up about 800 Ma. Subsequently, the fold belt structures of the Phanerozoic Tasman Orogen in the eastern third of Australia were accreted onto the eastern margin of the Precambrian cratons in the late Paleozoic in a series of stages (e.g., Direen and Crawford, 2003). In the Mesozoic, the continental margin of the subducting Pacific Plate lay on the eastern edge of the Australian land mass. Subsequently a chain of hot-spot related volcanism has developed through eastern Australia from around 30 Ma to the present. The eastern margin of Australia has been influenced by sea-floor spreading in the Tasman Sea from 80 Ma, and back-arc spreading in the Coral Sea. The Lord Howe Rise was pulled away from Australia during Tasman Sea spreading to form a submerged continental ridge between Australia and New Zealand. Extensive Mesozoic and younger sedimentary rocks and thick regolith cover about 80% of the land area of Australia, so that outcrop is limited.

In Fig. 1 we show a simplified model of the tectonics of Australia, with an indication of the age of the major elements. The areas in light tone have extensive regolith cover with very little outcrop, but even in the areas indicated by darker tones and patterns outcrop can be patchy. The cratonic boundaries based on the work of Cawood and Korsch (2008), and the Tasman line based on the reinterpretation by Direen and Crawford (2003) are also included in Fig. 1. The original concept of the Tasman line was based on the easternmost outcrop of Precambrian material, but such outcrop is limited along much of the length. Many different interpretations have been invoked based on lineations derived from potential field measurements (gravity, magnetics) that are likely to arise from features in the upper part of the crust. The Tasman line has been related to the edge of the continent at the time of break-up of Rodinia, but in the mantle the main contrasts lie somewhat to the east (Fishwick et al., 2008; Kennett et al., 2004). Recent crustal reflection surveys in South Australia and Western Victoria support the location indicated in Fig. 1, that links to changes at the base of the crust.

The light gray dashed line in Fig. 1, shows the general outline of the eastern edge of thickened crust based on the Moho depth shown in Fig. 2. The zone of thickened crust has a general correspondence to the Tasman line, but displays a noticeable excursion into central Australia that might be linked to a zone of slightly thinner lithosphere on the eastern margin of the thick cratonic zone (Fishwick et al., 2008).

The first general outlines of Moho depth in Australia came from the work of Collins (1991) who presented a compilation of refraction results across the continent. The major features of the pattern of crustal thickness began to appear in Clitheroe et al. (2000) with the inclusion of information from 65 receiver function studies, mostly from portable broadband stations, in addition to the 51 estimates employed by Collins (1991). Collins et al. (2003) added Moho depth information from off-shore refraction work to extend the Moho depth patterns out to the oceanic domains. Some further data from marine sources was included in the study by Concharov et al. (2007). The most recent study is that by Kennett et al. (2011), which considerably enlarged the available data sets by utilising more recent receiver function studies and also Moho depth constraints from the extensive full-crustal reflection profiling across Australia.

2.1. Data sources

A number of major refraction experiments were carried out from the 1960s into the 1980s and provide an important control on seismic wavespeeds across the continent. Most subsequent activity has been offshore aimed at understanding the nature of the crust around the continent, though there have been some off-shore-on-shore experiments in Western Australia. Reflection studies of the whole crust have grown from short experimental spreads in the 1960s that provide spot sensing of the Moho (Dooley and Moss, 1988) to large-scale transects with more than 12,000 km of full-crustal reflection profiles. Finlayson (2010) provides a historical overview and extensive bibliography of the full range of active seismic experiments up to 2006.

A nearly 2000 km long reflection transect with 20 second recording was built up across southern Queensland in the 1980s using explosive sources and was accompanied by wide-angle reflection work (Finlayson, 1993). Explosive sources continued to be used until 1997, when they were replaced with arrays of powerful vibrator sources. Recently there has been a major national investment in seismic reflection work funded through investment from Geoscience Australia, state and territory geological surveys and, since 2007, the AuScope infrastructure initiative. Over 7500 km of full crustal reflection profiles have been acquired with recording to 20 s or more since 2004. This very large effort has provided new insights into crustal structure, architecture and evolution in a number of parts of the continent. The dense sampling provided by the reflection transects has been of considerable value in mapping the character and geometry of the Moho across the continent.

The configuration of earthquake belts around the margins of Australia provides a wealth of events at suitable distances to be used as probes into the seismic structure of the lithosphere. Until recently there have only been a few permanent high-fidelity seismic stations on the Australian continent. As a result much information comes from extensive deployments of portable broadband stations for periods of a few months to a couple of years at each site. This approach to lithospheric studies was pioneered with the SNAP experiment (van der Hilst et al., 1994) where a group of stations were progressively moved across the continent in a sequence of deployments.

A very useful component of the passive seismic work comes from the use of receiver function studies that exploit the conversions and reverberations that follow the onset of the seismic signal. These receiver functions provide important information on crustal and uppermost mantle structure, particularly on the depth and nature of discontinuities that generate converted waves. The receiver function studies provide an important supplement to the limited sampling available from refraction
experiments and provide a fuller continental coverage. Initial work in eastern Australia by Shibutani et al. (1996) was extended by Clitheroe et al. (2000) to cover most of the continent, using portable broad-band stations and the limited number of high-quality permanent stations at the time. A set of receiver function studies have been made of the West Australian cratons as detailed coverage has become available through portable broad-band deployments (see Reading et al., 2007, 2012). More than 150 additional receiver function results were used by Kennett et al. (2011) to augment the set employed by Collins et al. (2003).

The suite of full-crustal reflection profiles provide a wealth of information on crustal character, architecture and thickness. Kennett et al. (2011) undertook a systematic analysis of all the profiles, reviewing the station geometry and preparing a consistent set of displays for each profile. Moho picks have been made for over 10 000 km of line at 20 or 40 km intervals. These picks were taken at the base of the zone of prominent reflections, with a depth conversion based on the assumption of a r.m.s. velocity of 6 km/s at the base of the crust. Unfortunately little control is normally available on the appropriate wave-speed profile, but cross-calibrations can be made with the results of other methods including refraction work in southern Queensland and receiver functions in Western Australia. Despite the simple approximation used for depth conversion of the reflection Moho picks, the crustal thickness estimates are in good agreement with those obtained from other methods.

The various seismic datasets provide multiple estimates of the depth to Moho in many regions and the consistency between the different techniques is high. In a number of instances, differences in the estimates for Moho depth can be associated with the aspects of the structure highlighted by the particular methods. Thus, for example, receiver functions may see a discontinuity at the top of a reflection package whilst the reflection Moho pick would be made at the base.

2.2. Moho depth

Kennett et al. (2011) have brought together the full range of seismological information and presented a new Moho depth distribution that provides strong controls across the continent. For consistency with earlier results they employed a definition for the base of the crust such that the Moho is taken as the boundary where the velocities on the lower side are greater than 7.8 km/s for P waves and 4.4 km/s for shear waves. Where the transition from crust to mantle occurs through a velocity gradient the base of the transition is chosen. This model has been updated to include results from full-crustal reflection profiling in Western Australia in 2012, across the Albany–Fraser belt, which provides detailed information in an area where previously there was little constraint. The new results have led to a re-examination of earlier information. It appears that a prominent lower crustal reflector may have been previously interpreted as the Moho. With a re-assignment of Moho depths at just a couple of sites, we get a very coherent picture with a band of locally thicker crust wrapping around the southern edge of the Yilgarn craton.

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This new comprehensive model (Fig. 2) provides a much denser sampler of most of the continent than before, though coverage remains low in the remote areas of the Simpson and Great Sandy deserts. In Fig. 2 we show the individual data points with the colour code associated with their specific data value, superimposed on the interpolated surface of Moho depth. There is evidence in a number of parts of Australia, e.g., Central Australia (Goleby et al., 1989) for localised jumps in the Moho of 10 km or more. Consequently it is not obvious that a smooth Moho surface should be sought. In addition it is necessary to take into account the mild discrepancies between different styles of depth estimates for Moho depth.

The Moho surface in Fig. 2 has been constructed using the interpolation tools from the GMT package (Wessel and Smith, 1998) with a conservative approach targeted at 0.5 degree resolution across the continent. Within each 0.5 × 0.5 degree cell the weighted mean Moho depth from all relevant Moho depth estimates is extracted; the weighting of the individual data points is based on the data reliability (Kennett et al., 2011). The weighted means for each cell are then interpolated using an adjustable tension continuous curvature gridding algorithm (Smith and Wessel, 1990). The tension factor is set to 0.45 to allow for steep Moho topography. The resulting surface is displayed allowing the influence of each cell to extend no further than 250 km. Even with this generous choice of data point influence there are still regions in the deserts of Western Australia without control on the Moho depth. The error associated with the representative surface can be expected to be comparable to that estimated by Clitheroe et al. (2000), i.e., no more than 2 km where there is good data control and perhaps reaching 5 km in the least well-sampled areas, which are smaller than before. As noted by Kennett et al. (2011), the controls on the Moho are sufficient that the pattern of Moho depth is not sensitive to the particular interpolation scheme employed.

2.2.1. Gravity inversion

Aitken (2010) has developed an inversion scheme for Moho depth (MoGGIE), exploiting the gravity field across Australia in combination with seismic constraints. Such an inversion has the potential to generate models of Moho geometry where seismic data are sparse or are poorly distributed. Aitken (2010) generated a map of Moho depth building on the Collins et al. (2003) compilation; the constrained inversion of the gravity field results in the introduction of shorter wavelength features in Moho depth. Indeed there is a strong correspondence between the model presented by Aitken (2010) and the Moho depth patterns from the new seismic compilation of Kennett et al. (2011). Common features that are not in the Collins et al. (2003) results include the extension of the zone of thickened crust from the north into South Australia with an oblique termination abutting a further zone of thickening in the Gawler Craton, and also the extension of moderately thick crust into the Capricorn Orogen. Aitken (2010) points out that there is a strong directionality to features in the gravity field, particularly the sequence of strong gravity lows and highs in central Australia with a dominantly east–west orientation. With sparse seismic observations it can be difficult to capture such character in the interpolated maps of Moho depth. Kennett et al. (2011) therefore included a number of control points from Aitken’s work with low weighting, and these are indicated by double circles in Fig. 2.

Aitken et al. (this issue) has undertaken an update of his 2010 gravity inversion using the new Moho data compilation, the Moho surface and information on data consistency from Kennett et al.
He has made inversions using with a range of different density and geometry constraints. Eleven successful density and crustal thickness models were used to calculate the mean Moho surface and its standard deviation. The initial model based on Fig. 2 is largely validated, and dramatic changes are few. As expected the changes from the surface shown in Fig. 2 are focused within the less well constrained parts of the model, namely offshore regions and within central-western Australia. From the ensemble of the gravity inversions an estimate can be made of the standard deviation in the modelled Moho surface (Fig. 3), the variability in these gravity-based models is generally low offshore, but highly changeable onshore. The largest apparent Moho variability is observed in central-western Australia, where the crust is thick, and high-density. This region is probably not well described by the initial model of crustal densities derived from the Kennett et al. (2011) results. Although areas of high variability exist in the gravity models, variability is much lower throughout eastern and western Australia, even where seismic coverage is relatively sparse, indicating that only minor changes to the initial model were required to satisfy the gravity field in these regions. The standard deviation image from the gravity inversions (Fig. 3) is very useful in indicating where additional seismic data constraints are desirable, either due to current sparse sampling or where the density structure is somewhat anomalous and additional gravity information would also be useful. We note that the standard deviation of the gravity estimates is large in the Albany–Fraser belt, where the new seismic results indicate crust around 40 km thick (Fig. 2) compared with closer to 30 km in the Kennett et al. (2011) model.

2.2.2. Patterns of Moho depth

The new results allow considerable refinement of the patterns of Moho depth across the continent. The oldest portions of the West Australian craton, the Pilbara craton and the northern Yilgarn craton, have Moho depths in the range from 30 to 35 km. The crust thickens slightly beneath the Neoarchean Hamersley block at the southern edge of the Pilbara, which has extensive banded iron formations, but the main change lies in the Capicorn Orogen where the Moho depth exceeds 40 km. Control in the Capicorn region is strong from a combination of refraction experiments, receiver functions and recent reflection transects. The thickest crust with a rather indistinct base is found in the Glenburgh terrane at the western edge of the Capicorn Orogen. In the Yilgarn craton itself, Reading et al. (2007) have noted a progression in crustal structure with greater Moho depth associated with younger parts of the craton in the west. This trend can be seen very clearly in Fig. 2. The progression with crustal age in the Archean of Western Australia is quite similar to that recently proposed by Thompson et al. (2010) for the region around Hudson Bay in Canada. There is little control on the very narrow strip of the Pinjarra Orogen along the western coastline of Australia, just a few receiver functions sit in this zone to the west of the Pilbara. Moho depth appears to be about 30–35 km, with thick sedimentary piles in places. The gravity field results exploited by Aitken (2010), Aitken et al. (this issue) suggest that Moho depth greater than 40 km extends across the entire Kimberley block, extending the zone of thickened crust seen in the seismic results.

Reflection profiling across the Officer basin from the eastern edge of the Yilgarn craton to the Musgrave block in 2011 revealed a zone of thick crust near 26°S, 126° E that was not expected from previous sparse receiver function sampling. The receiver function results near the ends of the line are consistent with the reflection line but give no hint of a crustal thickening by more than 10 km in between. The thickening may be due to mantle underplating in the fusion zone between the Western and Northern Australia cratons. The 2012 reflection profiling across the Albany–Fraser belt indicates localised thickening of the crust at the edge of the Yilgarn craton.

There is generally good control on the major features in the crust through Central Australia from a combination of reflection profiles and receiver function studies, with some major early refraction experiments.

Fig. 3. Estimate of standard deviation of Moho estimates for Australia from ensemble inversion of gravity data with seismic constraints from Kennett et al. (2011). The white patches show the 0.5 × 0.5° cells where the seismic constraints are operative.
The thickest crust in Australia occurs in this region, but is somewhat fragmented. On the reflection transects distinct sharp jumps in the Moho of up to 20 km are associated with the major east–west gravity anomalies (e.g., Goleby et al., 1989; Korsch et al., 2011).

In the north of the Central Australian zone, the crust appears to thin in the Pine Creek Inlier to less than 35 km thick but we have no direct control in the structure in Arnhem Land to the east. In the Proterozoic MacArthur basin, a little further south, refraction and reflection work indicates very thick crust. The Tennant Creek block also has crust thickness up to 50 km, but the base of the crust shows an extended gradient from crust into mantle (Bowman and Kennett, 1991). Much of the Arunta block also has rather thick crust (more than 50 km) with a gradational base and a weak reflection Moho (e.g., Korsch et al., 2011).

A prominent feature of the southern part of Central Australia is the strong gradient in Moho depth close to 135°E that juxtaposes 30 km crust against much thicker material (45 km or more). The area with the thinnest crust is broadly coincident with a topographic low containing the Lake Eyre basin that lies below sea level.

Although the Gawler Craton in the south has Archean material, some as old as the Pilbara, the Moho depth is greater than for the older parts of the West Australian cratons at more than 40 km, with good control from reflection profiling. The Curnamona craton also appears as a distinct entity with thicker crust than its surroundings. The eastern side of the Gawler Craton was reworked in the Delamarian Orogen.

The Mt Isa block has rather thick crust (greater than 40 km) with quite sharp edges to the south and the northeast. There is a strong gradient zone at the base of the crust and the Moho is only moderately distinct in reflection. On the reflection profile to the Georgetown Inlier, as the crust thins rapidly to around 35 km the reflection Moho becomes very clear. The structures in this area suggest a zone that has been rifted and then recompressed to give the present day configuration. Under the Georgetown Inlier distinct domains of consistent seismic character can be recognised and the transition between domains can be marked by Moho steps of up to 8 km.

Control on the Paleozoic structures is mostly from refraction and receiver function studies, but extensive reflection and refraction work in the 1980’s provides good control along a 1200 km transect from the Eromanga basin to the coast. In the southern part of the Lachlan Orogen, the presence of thick crust with a basal crustal gradient is well established from refraction experiments. There is only modest seismic control on the New England Orogen, but this zone appears to have thinner crust (around 35 km thick) than the Lachlan Fold belt.

The patterns of Moho depth across the Australian continent do not display any clear dependence on surface or basement age, though Mesozoic–Cenozoic cover limits the available sampling. However, there is a tendency for thicker crust in the Proterozoic orogens, such as the Capricorn of Western Australia and the Arunta of Central Australia. Strong local contrasts in Moho thickness can be recognised in a number of places from the extensive reflection profiles, but cannot be readily represented in a continent-wide Moho surface as in Fig. 2. We have noted above the features associated with strong east–west gravity anomalies in the centre of the continent, the Arunta example is presented in Goleby et al. (1989), and an equally prominent change is seen in the Musgrave block on the 2008 reflection profiling (Korsch and Koschin, 2010). At the southern margin of the Capricorn orogen it appears that the Moho from the Proterozoic domain is pushed under the Yilgarn craton. A similar pattern is seen at the Yilgarn/Musgrave contact. We note also localised thickening at the Yilgarn craton margin in the ~1420 Ma Albany–Fraser orogeny. In northeastern Australia there is a rapid transition from the very thick Mt. Isa Block (~1900 Ma) into thinner crust to the east that then thickens again into the Georgetown Inlier (of similar age to Mt. Isa).

The range and diversity of such Moho features in regions not subject to orogenesis since at least 500 Ma, implies considerable longevity of Moho topography. Indeed, in the Australia environment the features may well have survived from their time of formation.

3. The Moho in New Zealand

New Zealand formed as part of the same accreted margin as the Tasman Orogen. The Western Province, Challenger Plateau and Campbell Plateau can be correlated with the New England and Lachlan Fold Belts (e.g., Cooper and Tulloch, 1992; Veevers et al., 1994). The Eastern Province, which makes up the majority of the area above sea level, and the Chatham Rise can be correlated to New Caledonia (Mortimer et al., 1998). Mid Cretaceous rifting saw the submerged New Zealand continental fragment separate from Australia and Antarctica (Sutherland, 1999).

The modern plate boundary began to form at around 45 Ma (King, 2000). In Fig. 4 we show the current boundary configuration, which consists of two opposing subduction systems separated by a strike slip fault system accommodating oblique convergence. In the Tonga-Kermadec subduction system the Pacific plate subducts beneath the Australian plate. This system continues southward into the Hikurangi subduction zone, where the Hikurangi Plateau subducts beneath North Island, New Zealand. Subduction in this region has been developing since ~30 Ma. Subduction north of New Zealand has formed a typical back-arc spreading centre, which has propagated into the continental crust forming the Central Volcanic Region. At the southern end of the Hikurangi margin the Australian plate is being warped downward forming the Wanganui Basin (Stern et al., 1992). Subduction ceases at the base of the North Island and transitions into a series of strike slip faults, which merge into the Alpine fault. This major fault has accommodated 460 km of right lateral slip (Clark and Wellman, 1959) and 60–100 km of convergence (Canale and Stock, 2004; Walcott, 1998) since the Cenozoic, causing the uplift of the Southern Alps along the spine of the South Island. The Alpine fault terminates in the south at the Puysegur subduction zone, where the Australian plate subducts beneath the Pacific plate. This is a younger subduction zone (~10 Ma) than the one to the north and links to the south into the Macquarie ridge.

Unlike Australia the current tectonic deformation of New Zealand plays a more important role in the depth of the Moho than the origin and age of the rocks. One feature of the New Zealand continent is that only ~10% of the continental area sits above sea level.

In this paper we present a map of the Moho across New Zealand and its surroundings based on direct seismic observations. Previous works have tended to concentrate on specific tectonic questions, and have looked narrowly at specific areas. Crustal thickness of continental New Zealand as a whole has been mapped using gravity data supplemented by seismic data (Groby et al., 2008) and from an interpretation of seismic tomography (Wood and Stagpoole, 2007).

3.1. Data sources

Crustal scale refraction and reflection profiles of New Zealand commenced around the North Island in the mid 1980s with the offshore reflection line across the South Taranaki and South Wanganui Basins (Davey, 1987) and an onshore refraction survey from the tip of the North Island to the Central Volcanic Region (Stern et al., 1987). Unlike work in Australia the controlled source data uses only explosives and ship-borne airguns. The narrow geometry of New Zealand has enabled offshore shooting into land-based stations providing wide-angle reflection and refraction data along the same line, which gives sections good depth and velocity control.

There have been three major controlled source transects aimed at imaging plate boundary structure, one in the South Island and two in the North Island. The South Island transect was shot using the offshore-onshore technique and consisted of two 600 km lines across the middle of the South Island and a 200 km line along the east coast (Okaya et al., 2002). The first North Island transect runs 250 km from

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the east coast to the west coast bisecting the Central Volcanic region (Henrys et al., 2003; Stratford and Stern, 2006). This transect also includes a 120 km leg that runs perpendicular to the main line through the Central Volcanic Region. The results of this experiment produced a number of questions about the Central Volcanic Region, and this section was reshot with more detail in 2005 (Stern and Benson, 2011). The second transect across the North Island used the same offshore-onshore method as the South Island transects across the southern Hikurangi margin. This data was acquired in 2010 and interpretations are not yet available. Additional offshore-onshore seismic surveys have also been conducted northeast of the Central Volcanic Region (Bassett et al., 2010), on the Campbell Plateau (Grobys et al., 2009) and the Bounty Trough has been imaged using a similar technique, but using ocean bottom seismometers in place of the onshore seismometers (Grobys et al., 2007). Traditional ship-borne reflection data is available south of New Zealand (Melhuish et al., 1999), here depth to Moho is estimated using sonobuoy refraction data down to 10 km and a crustal velocity of 6.5 km/s below this.

New Zealand is seismically active, which has provided local earthquake sources for seismic tomography. Since the GEONET project began in 2001 onshore coverage of permanent national network seismic recorders has greatly increased to nearly 50 stations, additionally there are many smaller networks and temporary arrays. Tomographic images do not explicitly define the Moho, but it can be identified where resolution is sufficient and the Moho has a strong velocity gradient (e.g., Eberhart-Phillips and Bannister, 2010).

Receiver functions from broadband and short-period instruments also provide information on lithospheric structure. Receiver functions

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**Fig. 4.** Plate boundary configuration of New Zealand and major geological units. Key to marked features: BT — Bounty Trough, CaP — Campbell Plateau, ChP — Challenger Plateau, CR — Chatham Rise, CVR — Central Volcanic Region, EP — Eastern Province, HP — Hikurangi Plateau, HSZ — Hikurangi Subduction Zone, LHR — Lord Howe Rise, PSZ — Puysegur Subduction Zone, WB — Wanganui Basin, WP — Western Province.
are available for much of New Zealand, but there is varying success in identifying the Moho with this method. The Moho beneath New Zealand varies rapidly in both depth and nature, and the presence of a subducting slab beneath much of the North Island makes interpretation of receiver functions difficult. Despite this we have included over 30 constraints from receiver functions from both permanent stations (Horspool et al., 2006; Spasoveč and Clayton, 2008) and targeted campaigns (e.g., Bannister et al., 2007 and Salmon et al., 2011).

The various datasets provide multiple estimates of depth to Moho in just a few regions although some datasets have more than one interpretation for the Moho. This is mainly due to the varying definitions for the Moho used by different groups. For example the Moho beneath the Central Volcanic Region has been estimated at 15 km, 25 km and 30 km using almost the same data (Harrison and White, 2004; Stern and Benson, 2011; Stratford and Stern, 2004). The differences here are due to a heavily intruded and underplated crust, whether the underplate will eventually evolve into mantle or crust, and different assumptions about mantle seismic velocities.

3.2. Moho depth

We have brought together the available seismological information, and present a Moho depth distribution for the New Zealand continental area. Definition of the Moho was harder in the case of New Zealand; mantle velocities vary considerably below New Zealand as a result of subduction (Haines, 1979; Seward et al., 2009), some areas of crust are heavily underplated and plate interfaces provide ambiguity between the overriding and subducting plates.

Below the South Island the Moho is taken as the boundary where the velocities on the lower side reach 7.8 km/s. This area of New Zealand has a limited amount of subducted material below it making it more analogous to Australia. There is little sheer wave data for the region. For the northwestern North Island the Moho bounding P-wave velocity is taken as 7.4 km/s and for shear we use 4.2 km/s. Subduction processes here have brought hot fluid rich material into the mantle resulting in lower mantle velocities. Lower shear wave velocities might also be expected below the Central Volcanic Region, but there is little shear wave data in this region. Where present we have taken the Moho to be at the base of any underplating.

Fig. 5 shows the model of the seismological Moho beneath New Zealand. This model has been created in a similar fashion to the Australian Moho, but because there are fewer multiple estimates from independent data within each 0.5 x 0.5 grid cell all data have been given equal weighting. Where there is no other data, Crust2.0 (Bassin et al., 2000) has been used as a background model for interpolation. The resulting surface is displayed allowing the influence of each cell to extend no further than 250 km as for the Australian model. Regions where there is a plate interface have been hatched, and Moho estimates in these areas have been excluded since it is not clear which interface will be highlighted. Superimposed on the model are the individual data points used in its construction. Onshore New Zealand is well covered by data for the 0.5 degree resolution, particularly across the South Island. The shortage of traditional deep seismic reflection profiles means that any sharp jumps in the Moho are likely to be smeared. Error in the Moho surface is hard to define with the lack of multiple data sets, but typical errors in wide angle reflection estimates are of the order of ±1 km.

The Moho map reflects the origin and the tectonics of New Zealand. Offshore continental plateaus have a crustal thickness of ~25 km which reflects the stretching that has occurred with the opening of the Tasman Sea, and explains why these areas are submerging. The northwestern North Island also has a crustal thickness of 25 km, yet this area has been domed upward above sea level due to a buoyant mantle (Pulford and Stern, 2004).

There are three areas of thickened crust; one between the North and South Islands (Wanganui Basin), one along the spine of the South Island (Southern Alps), and in the southwest corner of the South Island inland of the Puysegur subduction (Fiordland). The Wanganui Basin is situated in the area where the plate boundary transitions from oblique subduction to multiple-strand strike-slip faulting. This region of thickened crust is characterised by a deep basin and downwarping of the topography. The crustal flexure and thickening of the crust is likely to be a combined effect of subduction pull, accommodation of convergence and the downpull from a probable mantle instability (Ewig, 2009). This downwarping is migrating southwards, drowning the mountain ranges at the northern end of the South Island (Stern et al., 2006). Fiordland shows a deep Moho at ≥40 km depth, although there is some uncertainty in the actual position of the Moho in this region due to the plate interface. Fiordland is also at the edge of the transition from subduction to oblique strike-slip, but here the topography has been elevated, and appears to be dynamically supported (Malservisi et al., 2003). The Moho beneath the Southern Alps reaches 42 km, which is an increase of 17 km compared to the depth of the Moho at the coastlines. Although the highest elevations in New Zealand occur in the central Southern Alps, the crustal root is nearly twice as large as is need to support the elevation (Stern et al., 2000). A teleseismic delay-time experiment shows that a high-wavespeed and therefore dense root exists beneath Alp that contributes a pull equivalent to sustaining about 50% of the inferred root.

The deepest Moho (48 km) in the South Island, as determined from active source work, is found in the Wanaka area about 100 km south of the central Southern Alps. Here the average topographic elevation is only about 800 m. From a combined gravity and seismic inversion, it appears that thickening of the lithospheric mantle due to convergence has produced a dense mantle root, which has warped the crust down to its present configuration (Bourguignon et al., 2007).

Thus Moho depth in much of New Zealand is not a simple Airy process linked to thickening of the crust to compensate for elevation, but instead a complex interaction between thickening of both the mantle lithosphere and the crust, and in areas of North Island also thinning of the mantle lithosphere.

4. Conclusions

We have used seismological data to construct Moho depth models for both Australia and New Zealand and in each case we see a wide range of Moho depths. Across Australia the pattern of Moho depth does not directly mirror the major tectonic blocks, though some of the zones of thickest crust are associated with the Proterozoic zones of interaction between the cratonic elements in the assembly of the core of Australia. In the east, thickened crust beneath the Paleozoic Lachlan Fold belt appears to be associated with crustal underplating. As more information becomes available, particularly from extensive full-crustal reflection profiling, there is increasing evidence for relatively rapid changes in Moho depth including localised jumps of several kilometres and possible duplication due to imbrication at the base of the crust. Many of the localised contrasts in Moho topography in Australia appear to be very old, and may well have survived from the orogenic processes that created them. In New Zealand the influences of modern plate tectonics give rapid changes in crustal thickness with strong wavespeed gradients that hinder techniques that rely on simple stratification, as e.g. some receiver function schemes. All features of the New Zealand Moho are likely to have been created quite recently.

Although there is limited control on Moho depth in Antarctica (see Baranov et al., this volume), there is a reasonable tie between the Moho depths when we move Australia and New Zealand back into the configuration before the breakup of Antarctica. The 35–40 km
thick crust beneath the Transantarctic mountains (Hansen et al., 2009; Lawrence et al., 2006) is similar to the southern part of the Lachlan fold belt in Australia; these structures both formed in the convergent margin along the eastern edge of Gondwana. Much of the cratonic parts of Eastern Antarctica have crustal thickness around 40 km, which is again similar to the Gawler craton in Australia. The thickest Antarctic crust in the subglacial Gamburtsev mountains reaches more than 50 km thick (Hansen et al., 2010), with rapid changes in Moho depth that are reminiscent of the complex east-west structures in central Australia arising from cycles of extension and compression (cf. Ferraccioli et al., 2011).

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Fig. 5. Moho depth for New Zealand and its surroundings. The location of Moho estimates and their type are indicated superimposed on the interpolated surface. Subduction zones are shown, along with hatching in regions where there is a plate interface.
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