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Quantitative tectonic reconstructions of Zealandia based on crustal thickness estimates

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[1] Zealandia is a key piece in the plate reconstruction of Gondwana. The positions of its submarine plateaus are major constraints on the best fit and breakup involving New Zealand, Australia, Antarctica, and associated microplates. As the submarine plateaus surrounding New Zealand consist of extended and highly extended continental crust, classic plate tectonic reconstructions assuming rigid plates and narrow plate boundaries fail to reconstruct these areas correctly. However, if the early breakup history shall be reconstructed, it is crucial to consider crustal stretching in a plate-tectonic reconstruction. We present a reconstruction of the basins around New Zealand (Great South Basin, Bounty Trough, and New Caledonia Basin) based on crustal balancing, an approach that takes into account the rifting and thinning processes affecting continental crust. In a first step, we computed a crustal thickness map of Zealandia using seismic, seismological, and gravity data. The crustal thickness map shows the submarine plateaus to have a uniform crustal thickness of 20–24 km and the basins to have a thickness of 12–16 km. We assumed that a reconstruction of Zealandia should close the basins and lead to a most uniform crustal thickness. We used the standard deviation of the reconstructed crustal thickness as a measure of uniformity. The reconstruction of the Campbell Plateau area shows that the amount of extension in the Bounty Trough and the Great South Basin is far smaller than previously thought. Our results indicate that the extension of the Bounty Trough and Great South Basin occurred simultaneously.

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1. Introduction

[2] In order to gain insight into a region's early plate kinematic history, and into the likely errors of a plate tectonic reconstruction showing such a history, a reconstruction has to take crustal extension explicitly into account. Classic plate-kinematic reconstructions cannot be expected to give precise results in areas of crustal extensions where magnetic seafloor spreading anomalies and fracture zones of oceanic crust are not observed, as these are the major constraints for calculating rotation parameters and the timing of plate motions. Areas where these data might be missing include oceanic crust overprinted by large volume magmatic extrusions, and thinned continental crust where extension did not reach the stage of seafloor spreading. In this paper, we present a novel complement to plate tectonic reconstructions by applying a crustal balancing method which takes into account continental rifting and extension at plate and micro-plate boundaries. This method reduces the errors caused by inappropriate identification and characterization of the continent-ocean boundary. The extension or compression of continental crust is difficult to simulate without invoking crustal thickness, meaning here and throughout the entire paper the thickness of the crystalline crust. On a grid showing crustal thickness, the crust can be divided vertically so that a certain percentage of the crustal thickness in a plate boundary region can be assigned to one plate and the remaining part to its conjugate. An important prerequisite is knowledge of the present crustal thickness of the deformed and undeformed parts of the plates.

[3] It has been shown that the basins and troughs around New Zealand are partly or entirely underlain by highly extended continental crust [*Laird*, 1993; *Scherwath et al.*, 2003; *Van Avendonk et al.*, 2004; *Lafoy et al.*, 2005a; *Grobys et al.*, 2007; J. W. Grobys et al., Extensional and magmatic nature of the Campbell Plateau and Great South Basin from deep crustal studies, submitted to *Tectonophysics*, 2007 (hereinafter referred to as Grobys et al., submitted manuscript, 2007)]. With its large extended continental plateaus and basins (Figure 1), Zealandia is a good example of the results of extensional processes and a good area for testing their consequences and demands for making plate-kinematic reconstructions.

[4] A plate-kinematic reconstruction of Zealandia and Marie Byrd Land of West Antarctica can give important insights on how a compressional plate boundary turns into an extensional one and how seafloor spreading starts [*Bradshaw*, 1989; *Luyendyk*, 1995]. Understanding these processes in general and for this region in particular will help improving reconstructions of the global plate circuit, which consists of two large, almost decoupled, subcircuits (Pacific and Gondwana [*Cande and Stock*, 2004a]), mainly by constraining the regional tectonic setting at the time Zealandia started to separate from Antarctica.

2. Tectonic Introduction

[5] The West Gondwana continental margin between the Ross Sea and Marie Byrd Land sectors underwent a transition from a convergent to a passive margin regime. The Phoenix Plate, and, after cessation of spreading in the Osbourn Trough, the Pacific Plate subducted beneath Chatham Rise, which originally lay north of eastern Marie Byrd Land, until the Hikurangi Plateau collided with it in Cretaceous times. Shortly after the cessation of seafloor spreading at Osbourn Trough, Chatham Rise started separating from West Antarctica, opening Bounty Trough and Great South Basin [*Mortimer et al.*, 2006]. Extension followed subduction and collision very closely, with estimates of their respective timings often overlapping. According to *Worthington et al.* [2006], spreading at Osbourn Trough and subduction beneath East Gondwana ceased at circa 86 Ma, while Chatham Rise is interpreted to have separated from Thurston Island and Marie Byrd Land at circa 90 Ma [*Larter et al.*, 2002; *Eagles et al.*, 2004], as the Bounty Trough and Great South Basin opened [*Eagles et al.*, 2004]. Bounty Trough is interpreted to have undergone a first back-arc extensional phase during the subduction of the Phoenix Plate followed by tectonic inversion when the Hikurangi Plateau collided with Chatham Rise [*Grobys et al.*, 2007], which in turn was followed by a second extensional phase in late Cretaceous times [*Eagles et al.*, 2004]. The youngest syn-rift sediments in the Great South Basin are of Cretaceous age [*Cook et al.*, 1999; Grobys et al., submitted manuscript, 2007] dating the end of extension to 86.5 Ma. The oldest seafloor spreading southeast of the Chatham Islands is marked by anomaly 34y (83 Ma) [*Davy*, 2006]. Campbell Plateau, further west, started to separate from West Antarctica during chron 33r (83.0–79.1 Ma) [*Larter et al.*, 2002]. While *Mukasa and Dalziel* [2000] suggested a segmentation of Campbell Plateau into an eastern and a western part, it is widely accepted that the plateau can be considered a single unit in a plate-kinematic sense [e.g., *Wandres and Bradshaw*, 2005].

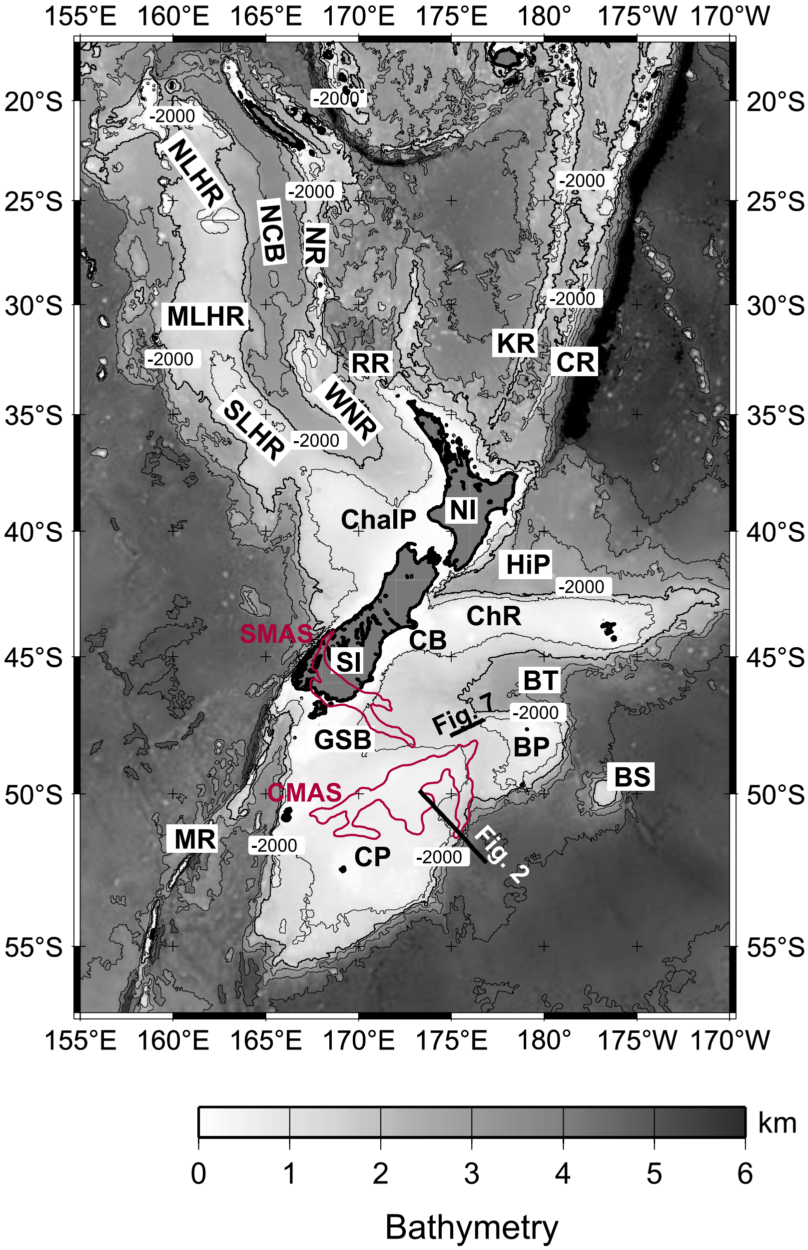

Figure 1. Bathymetric overview map [*Smith and Sandwell*, 1997] of Zealandia. Contour interval is 1000 m. Bold lines show the position of the profiles shown in Figures 2 and 7. Abbreviations are as follows: NI, North Island of New Zealand; SI, South Island of New Zealand; CB, Canterbury Basin; ChR, Chatham Rise; HiP, Hikurangi Plateau; BT, Bounty Trough; BP, Bounty Platform; BS, Bollons Seamounts; CP, Campbell Plateau; MR, Macquarie Ridge; GSB, Great South Basin; ChalP, Challenger Plateau; SLHR, Southern Lord Howe Rise; MLHR, Middle Lord Howe Rise; NLHR, Northern Lord Howe Rise; NCB, New Caledonia Basin; NR, Norfolk Ridge; WNR, West Norfolk Ridge; RR, Reinga Ridge; KR, Kermadec Ridge; CR, Colville Ridge.

[6] The opening history of the New Caledonia Basin is by far less well known than those of the Bounty Trough and Great South Basin. While the Lord Howe Rise is considered to consist of thinned and intruded continental crust [*Shor et al.*, 1971; *Woodward and Hunt*, 1971], the New Caledonia Basin has been interpreted to consist partly of thinned continental crust and partly oceanic crust. Evidence for extended continental crust is stronger in the northern and southern parts than in the central part [*Uruski and Wood*, 1991; *Auzende et al.*, 2000; *Wood and Woodward*, 2002; *Vially et al.*, 2003]. *Lafoy et al.* [2005a] assumed oceanic crust in the Central New Caledonia Basin on the basis of

Table 1. Database of Information Used to Constrain the Crustal Thickness

Name	Methods	References
Bounty Trough	seismic refraction, sediment thickness, gravity	*Davy* [1993]; *Grobys et al.* [2007]
Campbell Plateau	gravity, sediment thickness	*Davey* [1977]; this work
Challenger Plateau	gravity	*Wood and Woodward* [2002]
Chatham Rise	seismology, gravity	*Reyners and Cowan* [1993]; *Davy and Wood* [1994]
Great South Basin	seismic refraction, sediment thickness, gravity	*Davey* [1977]; *Cook et al.* [1999]; this work; Grobys et al. (submitted manuscript, 2007)
Lord Howe Rise and New Caledonia Basin	gravity, sediment thickness, seismic refraction	*Davey* [1977]; *Jongsma and Mutter* [1978]; *Herzer et al.* [1997]; *Van de Beuque et al.* [1998]; *Lafoy et al.* [2005a]; *Lafoy et al.* [2005b]
North Island	gravity	*Beanland and Haines* [1998]
South Island and Canterbury Basin	seismic refraction, seismology	*Godfrey et al.* [2001]; *Kohler and Eberhart-Phillips* [2002]; *Mortimer et al.* [2002]; *Scherwath et al.* [2003]; *Van Avendonk et al.* [2004]

broad and diffuse magnetic anomalies. It is interpreted that a first basin-forming phase occurred in the New Caledonia Basin region between 95 and 65 Ma [*Lafoy et al.*, 2005a]. A second phase of extension, possibly associated with seafloor spreading, occurred in the New Caledonia Basin at 62–56 Ma [*Gaina et al.*, 1998b; *Lafoy et al.*, 2005a].

[7] Zealandia underwent a major reorganization phase in the period from circa 45 Ma onward [*Sutherland*, 1995; *Cande and Stock*, 2004b]. After the cessation of spreading along the Tasman Ridge at circa 52 Ma [*Gaina et al.*, 1998b], spreading began in the Emerald Basin south of New Zealand [*Kamp*, 1986; *Sutherland*, 1995]. As the instantaneous pole of relative motion between Australia and the Pacific plate moved gradually southward, the spreading direction became more and more oblique [*Sutherland*, 1995]. At circa 22–21 Ma, key elements of the present plate boundary through New Zealand had developed [*King*, 2000]. A further major change in the pole of relative motion between Australia and the Pacific plate occurred at circa 6–5 Ma, when it moved northwestward, causing the initiation of today's transpressional plate boundary.

[8] An extensional event prior to New Zealand's separation from Marie Byrd Land has been reported for the period circa 140–100 Ma. Evidence for this event comes from metamorphic core complexes in the South Island [*Spell et al.*, 2000; *Forster and Lister*, 2003] and from the upper Jurassic–Cretaceous stratigraphy of the Taranaki Basin [*Uruski*, 2003]. The younger (125–100 Ma) extensional events in New Zealand coincide with the development of a core complex in Marie Byrd Land [*Luyendyk et al.*, 1996], and the older events (140–125 Ma) have been linked extensional events in a precursor of the West Antarctic Rift System [*DiVinere et al.*, 1995; *Müller et al.*, 2000]. An accurate reconstruction of the New Zealand – Antarctic sector of Gondwanaland [e.g., *Wandres and Bradshaw*, 2005] allows an estimate of the timing of crustal extension of the submarine plateaus at the margins of Zealandia and Antarctica.

3. Crustal Thickness Grid

[9] Crustal thickness grids help define and characterize tectonic units within a region. In this study, we use the crustal thickness grid as the basis to compute rotation parameters, by assuming a constant crustal thickness applied in a region prior to its extension.

[10] We combined published and new 2-D and 3-D models of crustal thickness to generate a gridded regional crustal thickness map (Table 1). Three-dimensional models of crustal thickness already exist for the Nord and South Islands of New Zealand, and the Challenger Plateau (Figure 1). We modeled 29 new minimum-structure 2-D gravity

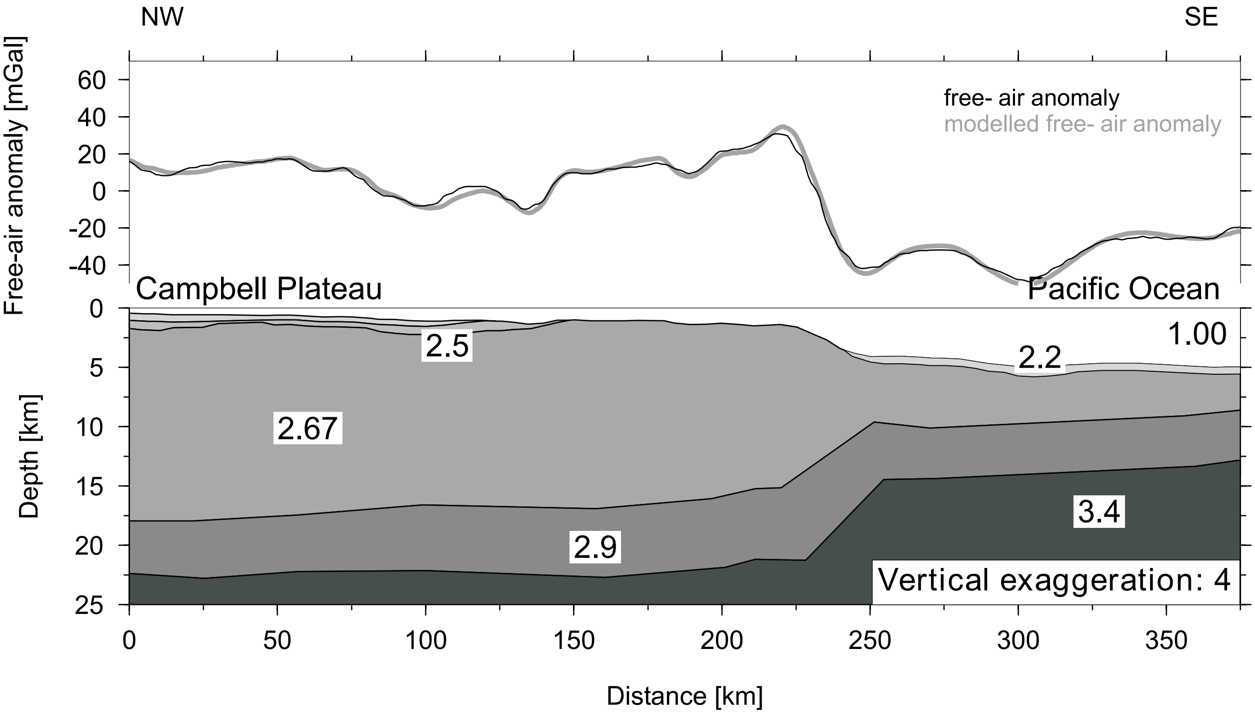

Figure 2. Minimum structure gravity model, with bodies striking orthogonal to the plane of the section and extending uniformly from each end of the section. Position of this section is shown in Figure 1. Observed gravity data are taken from *Smith and Sandwell* [1997]. Black numbers are densities in g/cm^3.

profiles (e.g., Figure 2) together with the various previously published gravity, seismic refraction and seismological models. We extracted free-air gravity values from a global satellite-derived data set [*Smith and Sandwell*, 1997], and bathymetric information was derived from either the seismic profiles or from satellite altimetry [*Sandwell and Smith*, 1997]. A number of ship soundings contributed to the bathymetry grid in the Zealandia area, reducing the risk of using a circular method. Wherever possible, sedimentary layers were constrained for the gravity profiles using multichannel seismic data. Sediment thickness data were not available for some areas of the Lord Howe Rise and New Caledonia Basin. Here, we estimated sediment thicknesses on the basis of geological and bathymetric information. Given the minimum structure criterion for the gravity models, we used the same densities in each one.

[11] The crustal thickness models had to be adjusted for the differences in crustal thickness yielded using different techniques. To do this, we used the interfaces in seismic refraction models of the Great South Basin, Bounty Trough, Canterbury Basin and New Caledonia Basin as a reference (Figure 3). Seismic refraction lines connected by gravity profiles showed a consistent crustal thickness. Only the crustal thickness of the South Island, which is based on seismological data [*Kohler and Eberhart-Phillips*, 2002] had to be reduced by 8 km in order to fit the refraction data. Compared with a crustal thickness map of the North and South Islands of New Zealand by *Wood and Stagpoole* [2007], this grid differs only by a maximum 2–3 km thickness in the Southern Alps. After depth corrections, line and grid data were interpolated at 5 km intervals and gridded with a spacing of 3 × 3 min, using a continuous curvature gridding algorithm [*Smith and Wessel*, 1990]. The resulting grid extends from 57°S to 17°S and from 157°E to 175°W (see auxiliary material[1] Table S1).

[12] We estimate that the lateral error involved in digitizing published crustal thickness data from paper journals should not be larger than ~10 km. The sparse data coverage in the Lord Howe Rise area and at the margins of the plateaus is a second source of errors. Therefore we were not able to map the Macquarie, Colville, and Kermadec ridge systems, as their small size would have required denser coverage. In general, the accuracy of the crustal thickness map decreases from the centre of

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[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/gc/2007gc001691.

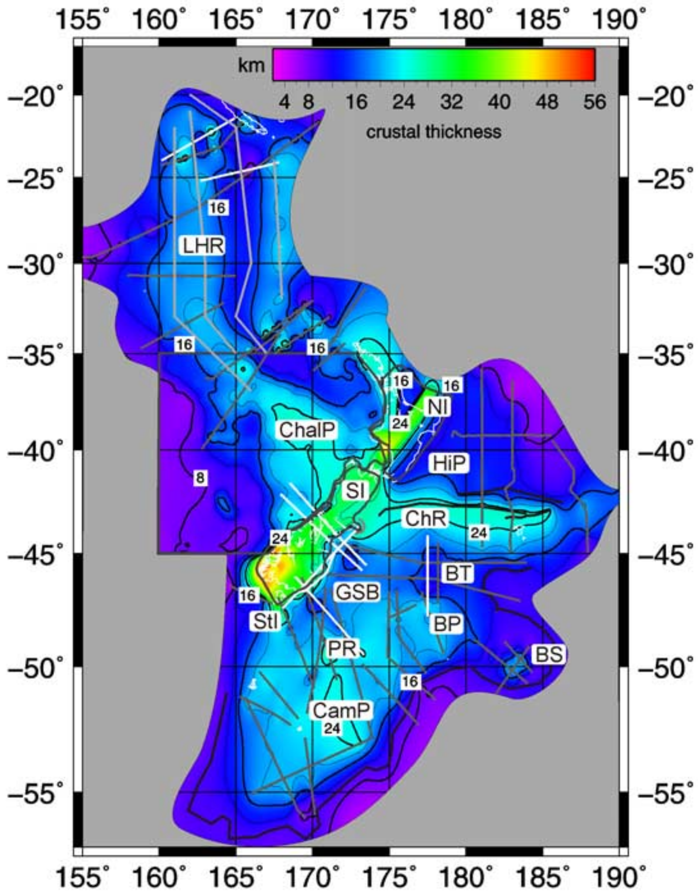

Figure 3. The crustal thickness map of Zealandia shows the main features of the microcontinent. Unconstrained areas are masked. White lines are seismic refraction profiles, dark grey lines are gravity models based on seismic reflection profiles, and light grey lines are gravity models based on satellite bathymetry information only. Abbreviations are as follows: NI, North Island of New Zealand; SI, South Island of New Zealand; BP, Bounty Platform; BS, Bollons Seamounts; BT, Bounty Trough; CamP, Campbell Plateau; ChalP, Challenger Plateau; ChR, Chatham Rise; GSB, Great South Basin; HiP, Hikurangi Plateau; LHR, Lord Howe Rise; PR, Pukaki Rise; StI, Stewart Island.

a plateau toward its margins (Figure 3). Crustal thickness for the deep sea was extrapolated from a few known areas (e.g., seafloor around Bollons Seamount [*Davy*, 2006]).

[13] The crust southeast of New Zealand, Campbell Plateau, Bounty Platform, Chatham Rise and Bollons Seamount has a uniform thickness of 20–24 km (Figure 3). The crustal thickness increases to ~26 km at Pukaki Rise, on the central Campbell Plateau. Pukaki Rise cannot be mapped entirely due to insufficient data coverage. However, patches of increased thickness are arranged along a line tentatively suggesting the location of Pukaki Rise. The map shows the crustal thickness decreasing from the Inner Bounty Trough (~18 km) toward the Outer Bounty Trough (~10 km). Two small areas with decreased thicknesses (~14 km) are shown in the Canterbury and the Great South basins (Figure 3).

[14] The map resolution in the Challenger Plateau region is much higher, as this area was taken from the grid of *Wood and Woodward* [2002], where denser profile data were available. The three ridge systems east of the New Caledonia Basin tend to be merged in the map, because the ridges are covered by a few lines only and some of the lines do not extend across all three ridges (Figure 3). The crustal thickness west of the New Caledonia Basin decreases northward from the Challenger Plateau (~24 km). The thinnest crust is at the midpoint of Lord Howe Rise between 33°S and 27°S (~18 km). Further north, the thickness increases again to ~22 km. The part of New Caledonia Basin adjacent to the Middle Lord Howe Rise (33°S–

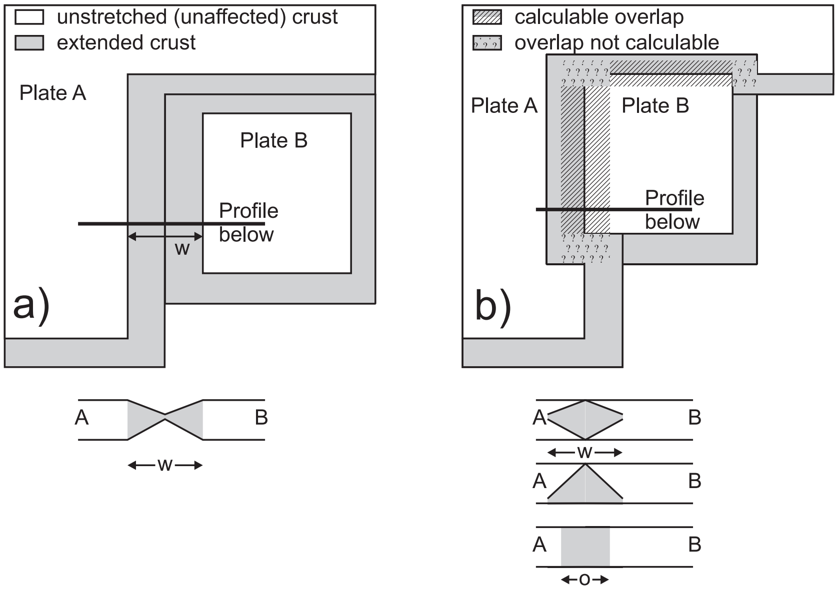

Figure 4. This simplified reconstruction of three plates shows the problems of overlapping plates if the continent ocean boundary is used as a best fit criterion in regions of thinned crust. Plate c is rotated relative to plate a. (a) Initial position of the plates. The basin with thinned crust (grey color) has width w. White areas are regions with crust unaffected by crustal thinning. The bottom sketch is a cross section through the basin. (b) Final situation with the fit of the COB as best fit criterion. The shaded areas indicate regions of overlap according to the equation in the text. The areas with question marks indicate regions where it is difficult to calculate the overlap. The bottom sketches illustrate how the overlap is estimated.

27°S) was suggested by *Lafoy et al.* [2005a] to consist of oceanic crust. However, in our map, the New Caledonia Basin has a uniform crustal thickness of ~14 km, except between 35°S and 37°S, where it decreases to ~11 km. The step from the New Caledonia Basin to the Norfolk, West Norfolk and Reinga ridges appears to be mapped well, while the eastern margins of the Norfolk and Reinga ridges are not imaged. For this reason, we masked this region in Figure 3. Where they are well imaged, the three ridges have a range of crustal thickness of ~18–24 km. The West Norfolk and Reinga ridges have the higher thicknesses of ~20–24 km, while the Norfolk Ridge has a maximum thickness of ~21 km and is thinnest (~18 km) opposite the (thin) Middle Lord Howe Rise.

4. Method of Fitting Plate-Kinematic Boundaries

[15] Common plate-kinematic reconstructions are based on the assumption (1) that continental and oceanic plates and plate segments are rigid and (2) that they are and were always separated by well-defined first-order discontinuity boundaries. It has been shown, e.g., for the East Greenland Volcanic Margin [*Voss and Jokat*, 2007] that the transition zone between continental crust unaffected by rifting and pure oceanic crust can be as wide as 180 km. Similarly, *Grobys et al.* [2007] showed that the ~350 km wide Bounty Trough in New Zealand, which did not reach the seafloor spreading stage, is in large parts underlain by highly extended continental crust.

[16] If, for a plate-kinematic reconstruction, the plate boundaries are considered the outer boundaries of the unaffected continental crust, a “tight fit” reconstruction leads to an overlap whose width can be calculated as $o = w * (\beta - 1)/\beta$, where w is the total width of the continent-ocean transitions and β is the stretching factor (Figure 4). For the Bounty Trough, where $\beta = 2.7$ and w = 350 km, the overlap caused by a reconstruction of rigid plates would be ~220 km. The overlap in such a reconstruction could be removed if the outer boundary of the plates were 0.5 * o larger than the outer boundary of the unaffected continental crust. This would require the knowledge of β-factors, which can be gleaned from the stretched and unstretched crustal thicknesses. These considerations are harder to make at corners and strong bends along plate boundaries because of

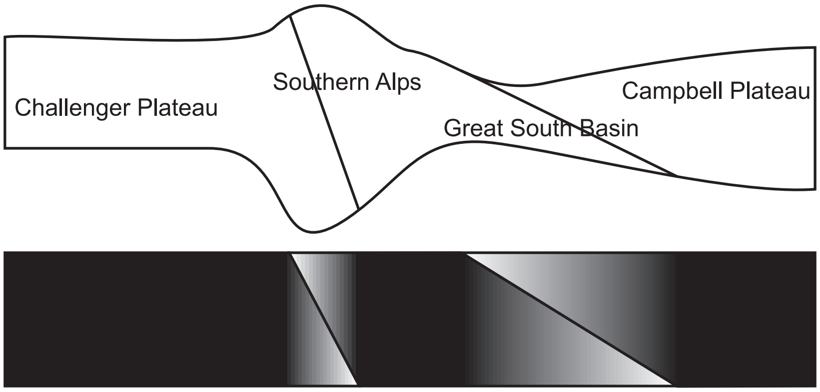

Figure 5. This simplified schematic cross section from the Challenger Plateau to the Campbell Plateau illustrates the idea of vertically dividing the crust in two overlapping plates. The Alpine Fault, which is a transpressional plate boundary, is modeled as a steeply dipping thrust fault. In the extensional zone of the Great South Basin the crust is separated over a wide area, resulting in a wide overlap. The bottom sketch illustrates the factors of the masks to be multiplied with the crustal thickness grid. White color represents a factor of 0; black represents a factor of 1. The sum of all masks in overlapping areas is always 1.

the possibility of oblique extension, and the results are therefore more error-prone.

[17] In order to gain insight into a region's early plate kinematic history, and into the likely errors of a plate tectonic reconstruction showing such a history, a reconstruction has to take continental crustal stretching explicitly into account. For this, we rotate the crustal thickness grid using finite plate rotation parameters. To account for the overlapping plates assuming a crustal extension model, we picked overlapping masks for each of the plates to be rotated (Figure 5). The mask outlines were derived on the basis of the crustal thickness grid (Figure 6a) and the bathymetry (Figure 1). The grid nodes of the mask are assigned a value of 1 in the area of the unstretched continental crust, a value between 1 and 0 in the continent-ocean transition zone (COTZ) or extended crust of a basin and a value of 0 outside the COT of a plate (Figure 6b) leading to a zero crustal thickness, in such a way that sum of all the masked nodes at each position in the grid is 1. In extensional areas such as the Great South Basin, the overlapping areas are wide (i.e., the hypothetical detachment fault has a gentle slope) and at transform plate margins the separation between the plates has a steep slope (Figure 5). The masks (Figure 6b) were multiplied with the crustal thickness grid (Figure 6a) to obtain a representation of a plate with a reduced crustal thickness (Figure 6c).

[18] For each extensional basin studied, the reduced crustal thickness plate from one side of the basin was rotated back to the other side of the basin. The best fit rotation was found by varying the pole coordinates and the rotation angle systematically within set intervals (Figure 6d). After each rotation interval, the crustal thicknesses of each grid cell of all overlapping plates were summed to obtain a new crustal thickness grid (Figure 6e). The new grid represents the crustal thickness of the area before the plate movement. Rotations producing an overlap in a former basin will result in reconstructions with crustal thicknesses that are too large. Rotations that produce an underlap will lead to crustal thicknesses that are too small. A rotation that closes a basin obliquely (local overlap and local underlap) would result in a region of mixed inappropriate crustal thicknesses.

5. Assumptions and Restrictions

[19] Various crustal extension models have been employed to explain the processes of basin formation. *Wernicke and Burchfiel* [1982] suggested a lithosphere-scale detachment system as an extensional model, the simple-shear model. The pure-shear model, proposed by *McKenzie* [1978], predicts a symmetric rift architecture and crustal thinning when applied to a homogeneous lithosphere. In their model, extension is distributed through the lithosphere uniformly with depth. Although the pure-shear model seems to be the preferred model of extension, or in some cases a combination of both models, e.g., for the Labrador Sea margin [*Louden and Chian*, 1999], the crust is

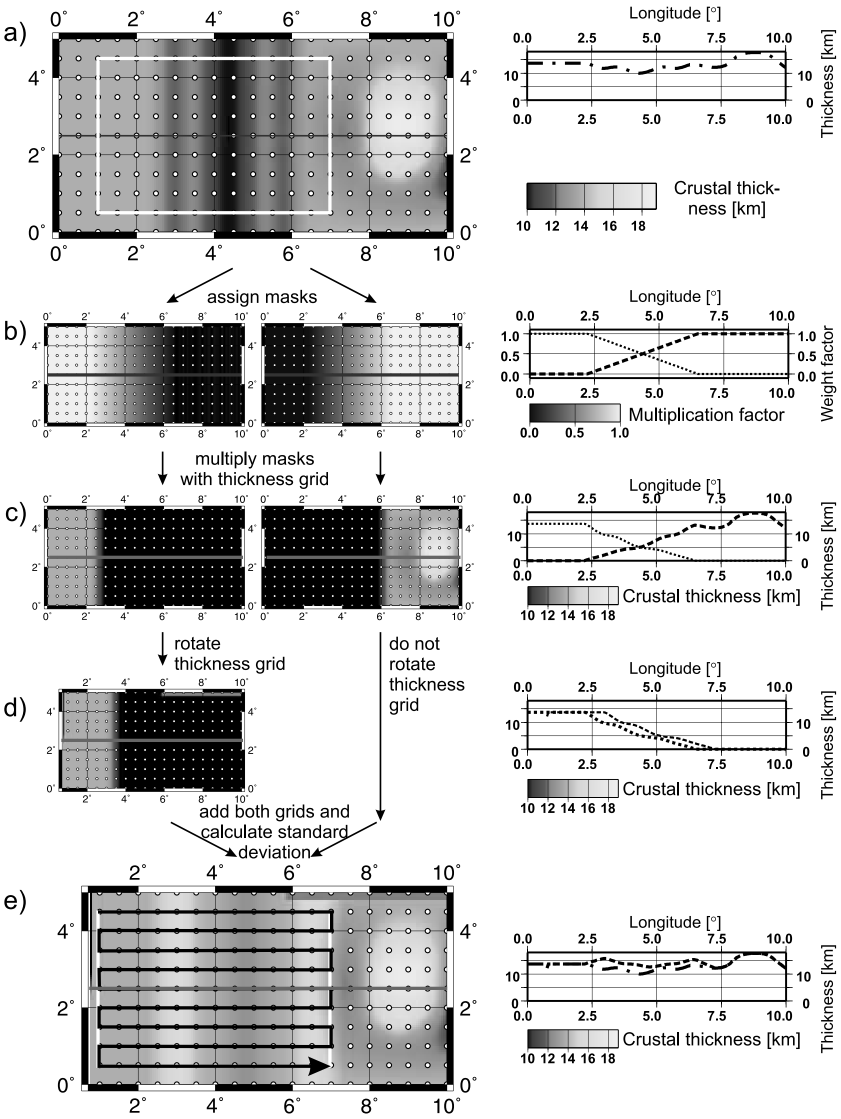

Figure 6. The processing flow illustrates the way in which the standard deviation of a single finite rotation is computed. (a) A crustal thickness grid is multiplied with (b) a mask. The masks are assigned on the basis of crustal thickness and bathymetric information and have values of between 0 and 1. The multiplication leads to (c) a separation into two grids representing different plates. (d) One of the grids is rotated and vertically summed with the second, unrotated grid. (e) The standard deviation of the resulting crustal thickness grid is calculated over all grid nodes within a significant window (grey box). Left sides are the grids; right sides are profiles of the grids along the grey lines. White dots with black circles represent the grid nodes.

split up vertically for our reconstruction as the simple-shear model suggest (Figure 5). This simplification in the reconstruction process has to be done because a reconstruction on the basis of a pure-shear model would need to employ a finite element modeling technique, as it would have to consider particle motion. A method based on an assumption of simple-shear should also reconstruct effects of pure-shear in the central areas of extension, but not in the bordering areas of crustal extension, as only the distribution of crustal thickness (or the crustal volume) is of relevance for the reconstruction, but not the motion of each particular piece of the crust. In the bordering areas of extension, the reconstruction could lead to a slight overthickening after the reconstruction. Both extensional reconstruction models, however, neglect intrusions. Intrusions add to the total crustal thickness, which means that in their presence a rotation angle calculated as described above might

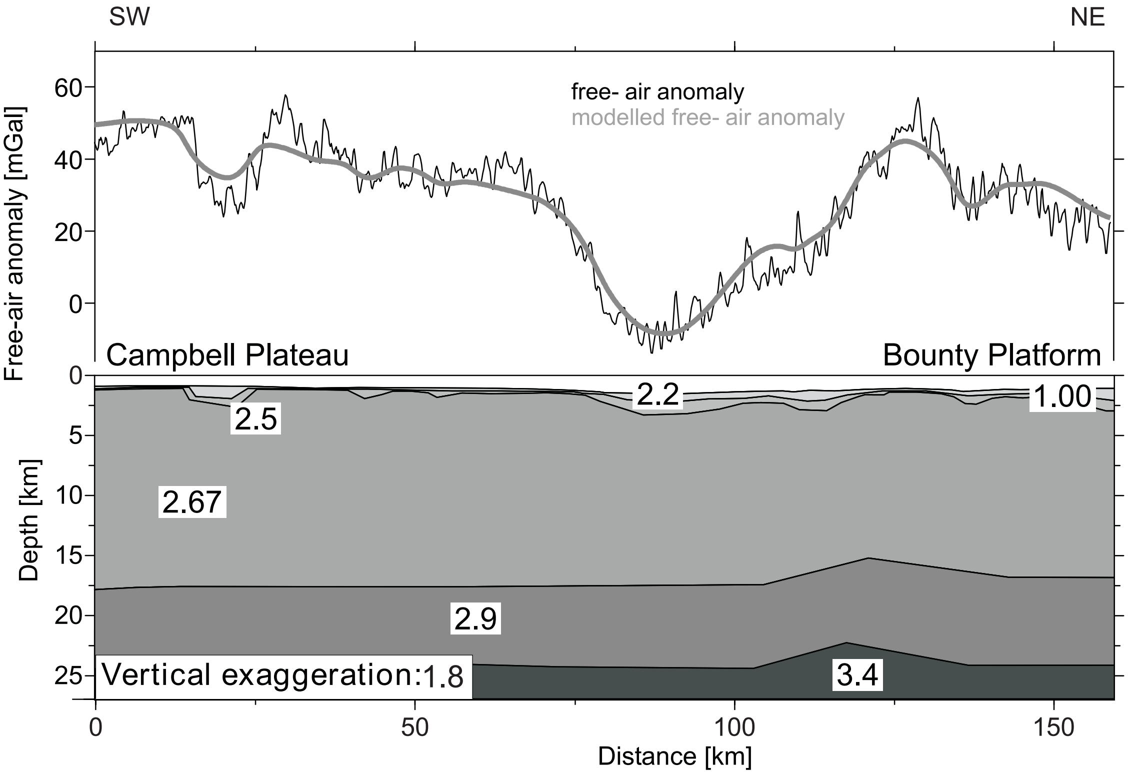

Figure 7. Minimum structure gravity model, with bodies striking orthogonal to the plane of the section and extending uniformly from each end of the section. Position of this line is shown in Figure 1. Gravity anomalies were obtained from a shipboard gravimeter. Black numbers are densities in g/cm^3.

be too small. In our case, this is likely in the Middle Bounty Trough, where intrusions are observed. In regions where many intrusions occur, e.g., the Kenya Rift [*Mechie et al.*, 1997], crustal thickness has to be corrected for the volume of intrusive rocks. An estimate of the extent of intrusion can be calculated on the basis of P wave velocity contrasts in seismic profiles [*Grobys et al.*, 2007]. Small intrusions should not lead to large errors because they do not greatly influence the standard deviation of the reconstructed crustal thickness.

[20] It is important to have a best fit criterion for a reconstruction technique. In our case, we use a criterion of least variability in crustal thickness in the reconstructed grid. Away from their margins, the present crustal thickness of the plateaus surrounding New Zealand is widely uniform. Grobys et al. (submitted manuscript, 2007) suggested that a general thinning of these plateaus occurred in a period prior to the extension of basins such as Bounty Trough, Great South Basin or New Caledonia Basin. For this reason, it seems reasonable to assume that the best fit reconstruction leads to a most uniform crustal thickness in the entire region. However, as this reconstruction technique calculates rotation parameters on a regional scale, the method requires only the assumption that the crustal thickness is uniform on both sides of a basin. To assess our best fit criterion, we calculated the standard deviation of the ‘‘unperturbed crustal thickness’’ within a window (Figures 6a and 6e) covering an area of crust far away from possible overlaps, existing or old basins, and their margins. We assumed that the best fit reconstruction was the one with the most uniform crustal thickness as expressed by the lowest standard deviation of unperturbed crustal thickness.

[21] Given some of its restrictions, our type of plate-fitting reconstruction should be most successful as a refinement to an existing conventional plate-kinematic reconstruction. The number of independent plates, the form and size of the masks and the dimensions and spacing of the grid itself can influence the result. We treated Campbell Plateau and Bounty Platform as a single plate, despite the presence of an intervening bathymetric depression of ~500 m depth. Gravity modeling (Figure 7) shows clearly that little extension has occurred across this depression, and suggests instead a shear zone origin. In support of this view,

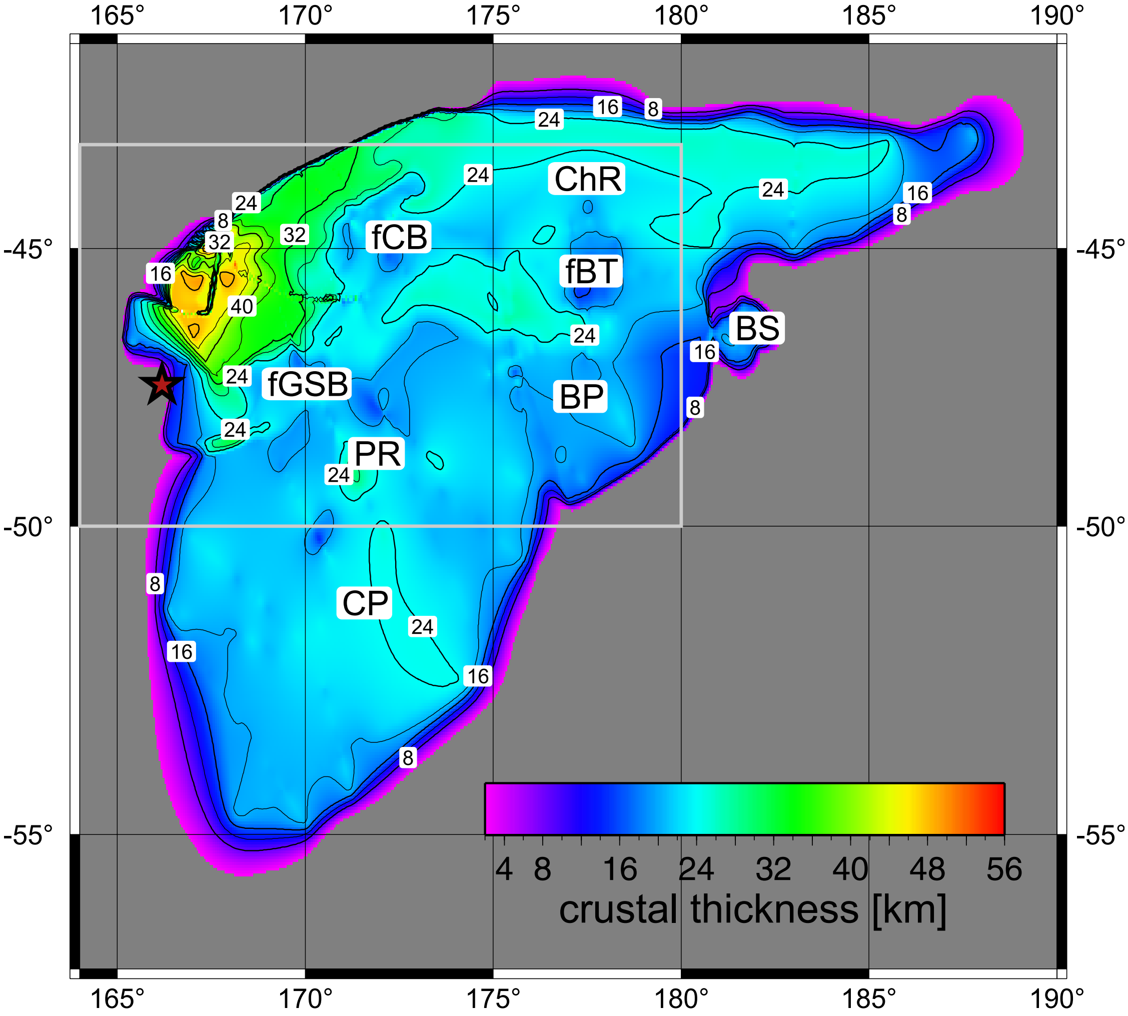

Figure 8. This crustal thickness map shows the result of the finite rotation. The light grey box indicates the region in which the standard deviations were calculated; the red star marks the rotation pole of Campbell Plateau relative to a fixed Chatham Rise. Contour interval is 4 km. Abbreviations are as follows: BP, Bounty Platform; BS, Bollons Seamounts; CP, Campbell Plateau; ChR, Chatham Rise; fGSB, former Great South Basin; fBT, former Bounty Trough; fCB, former Canterbury Basin.

the Campbell Plateau and Bounty Platform fit the shelf break of Marie Byrd Land very well in their present form [*Larter et al.*, 2002]. Existing reconstructions of the Zealandia – Antarctic sector of Gondwana did not suggest any great extension of the plateaus themselves (Campbell Plateau, Chatham Rise or Lord Howe Rise) during final breakup [*Larter et al.*, 2002; *Eagles et al.*, 2004], so we did not take into account the possibility of extension of the plateaus during the separation of Chatham Rise and Campbell Plateau from Marie Byrd Land between 95 and 85 Ma. Rather, we assume it is all prebreakup.

[22] We reconstructed the situation prior to the opening of Great South Basin and Bounty Trough at circa 90–86.5 Ma. Crystalline crust of the subaerial parts of Zealandia that were eroded and deposited as clastic sediments in the basins and troughs were excluded from the calculation of the crustal thickness grid as these volumes of eroded rock were relocated in times significantly later than the opening of the basins [*Wood and Stagpoole*, 2007]. For an ideal reconstruction with the method described by us, this volume of relocated rock should have been assigned to the regions of origin. However, this technique is in the highly reshaped microcontinent of Zealandia impossible. Although the sediments in the Great South Basin reach ~7 km at most, the errors resulting from this should be negligible, because the motion of the rotated plate is so small, that only the thinnest tip of the rotated plate could possibly reach the area of

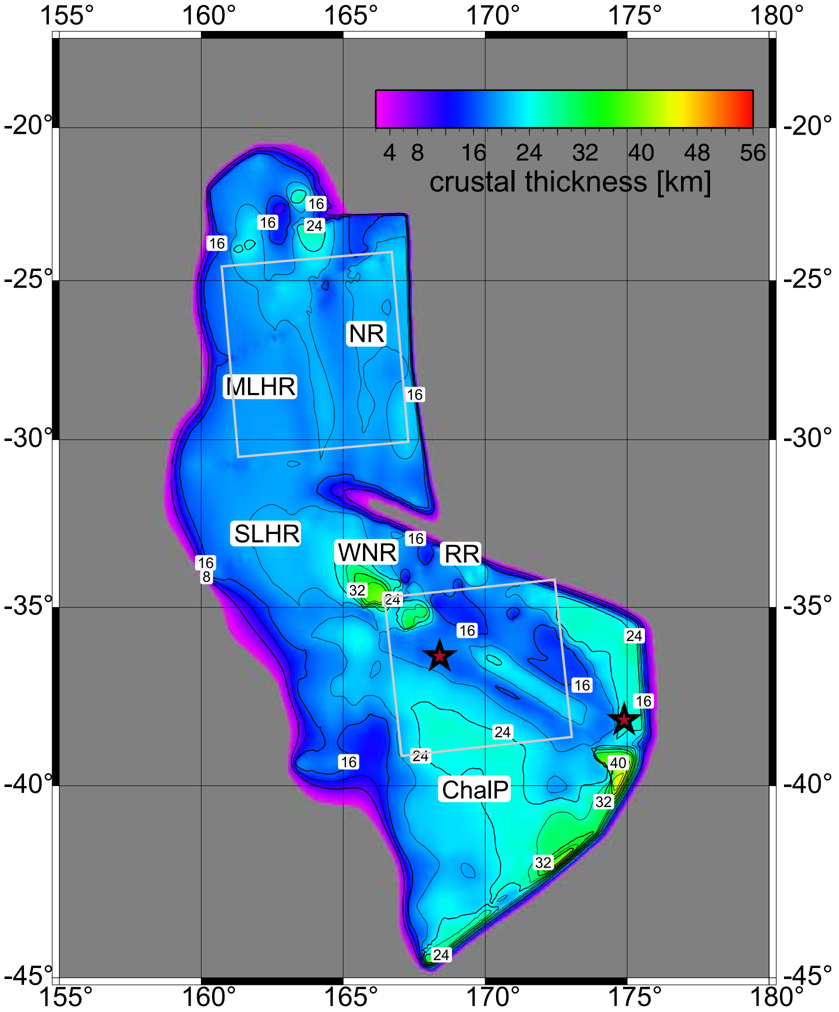

Figure 9. This crustal thickness map shows the result of the finite rotation with the final rotation poles. The light grey boxes indicate the regions in which the standard deviations were calculated; the red stars mark the rotation poles. Contour interval is 4 km. Abbreviations are as follows: ChalP, Challenger Plateau; SLHR, Southern Lord Howe Rise; MLHR, Middle Lord Howe Rise; NLHR, Northern Lord Howe Rise; NR, Norfolk Ridge; WNR, West Norfolk Ridge; RR, Reinga Ridge.

the origin of the sediments. If the motion would be larger, the crustal thickness would have been underestimated leading to an overestimation of the extension.

[23] The accuracy of the best fit reconstruction result depends on two major influences. The first of these is the crustal thickness grid, which influences the calculated standard deviation. The crustal thickness grid southeast of New Zealand depicts all tectonic features (e.g., Great South Basin or Bounty Platform) that can be seen in the bathymetry or are known by previous surveys. Northwest of New Zealand the grid has a distinctly lower resolution due to being less surveyed, and yet covers far more tectonic complexity. Small-scale variability in the grid should not affect the standard deviation in unperturbed crustal thickness, as this is calculated in a large window. The second influence is that of the window itself (Figures 6a, 8, and 9). On one hand, the window should cover a region that is as large as possible; but on the other hand it is limited to areas affected by the rotation being tested. As long as this window comprises the main tectonic features affected by the extension, the values of the standard deviation seem to be robust and the position of the rotation pole producing its minimum did not vary by more than ~2–3 degrees. The standard deviation rises by 3% within an area of 3–4 degrees in longitude and 3–5 degrees in latitude (Figure 10). Finally, this type of best fit plate reconstruction cannot provide any age control. For this reason, it

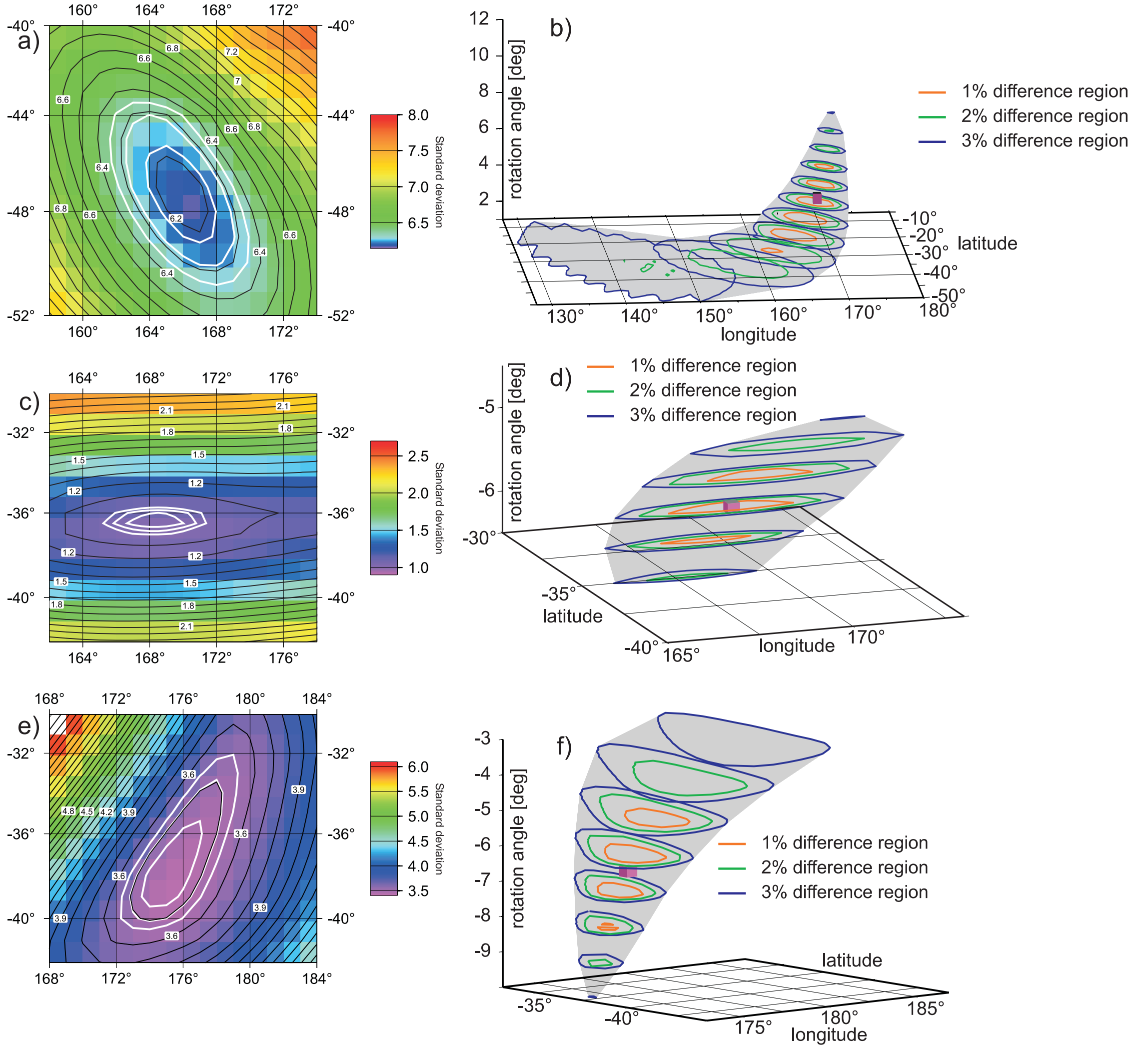

Figure 10. (a) Standard deviations of crustal thickness for the Campbell Plateau rotation. The pole was varied in 1° steps in latitude and longitude; the rotation angle was 6.25°. Contour interval is 0.1. (b) Three percent error region. The grey hull and the blue rings enclose all rotation poles that differ less than 3% in standard deviation from the best fit pole, green rings enclose the 2% region, and orange rings enclose the 1% region. Mauve cube marks the best fit pole. (c and d) Same as Figures 10a and 10b but for the Norfolk Ridge rotation. Rotation angle is 5.5°. (e and f) Same as Figures 10a and 10b but for the Reinga Ridge. Rotation angle is 6.4°.

is useful to complement the results of such a reconstruction with the results of reconstructions that constrain ages.

6. Application to Zealandia

[24] We varied the position of the rotation pole systematically in intervals of 5° in longitude and/or latitude, grazing all nodes between 80°N and 80°S, and the rotation angle in steps of 2.5° in order to find the rotations that yield the lowest standard deviations within a certain window (Figures 8 and 9). In a second and third iteration, the search region was divided more finely into cells of 1° and 0.1° in longitude and latitude and 1° and 0.05° (for the Campbell Plateau) or 0.1° (for Norfolk and Reinga ridges) in rotation angle. The lowest standard deviation for the Campbell Plateau reconstruction reached 6.1588 km (compared to 6.5745 km before the rotation), for the Norfolk Ridge the lowest standard deviation was 0.9963 km (3.1462 km before rotation) and for the Reinga Ridge it was 3.4336 km (4.1301 km before rotation; Figure 9).

[25] The right-handed rotation of the Campbell Plateau relative to a fixed Chatham Rise about a pole at 166°E, 47.5°S and an angle of 6.25° leads to a minimum standard deviation in the window (Figure 8). The rotation pole lies at the margin of

Table 2. Rotation Poles[a]

Area	Lon	Lat	Angle
Campbell Plateau (this work) w/ respect to Chatham Rise	166.0	−47.5	6.25
Campbell Plateau preferred rotation [*Larter et al.*, 2002] w/ respect to Chatham Rise	129.68	−42.79	5.31
Campbell Plateau rejected rotation [*Larter et al.*, 2002] w/ respect to Chatham Rise	167.32	−53.23	11.31
Bollons Seamount w/ respect to Chatham Rise [*Eagles et al.*, 2004]	152.96	−50.48	10.74
Reinga Ridge w/ respect to Lord Howe Rise (this work)	174.9	−38.2	6.4
Norfolk Ridge w/ respect to Lord Howe Rise (this work)	168.4	−36.4	5.5
Norfolk Ridge w/respect to Reinga Ridge (this work)	33.02	39.18	−1.06

[a] The finite rotation poles of this work are calculated with the standard deviation of the crustal thickness after the reconstruction. Positive angles indicate counterclockwise rotations when viewed from above the surface of the Earth and going back in time.

Campbell Plateau, near the Solander Trough (Table 2). As the pole is close to the rotated plate, relative motion in the plate boundary region has a small translational and a large rotational part. Sample trajectories of points near the edges of the Campbell Plateau and Bounty Platform (Figure 11) indicate that, relative to a fixed Chatham Rise, points at the Campbell Plateau margins covered a distance of 57 km in the Great South Basin area, 87 km near the Inner Bounty Trough, 103 km near the Middle Bounty Trough and 112 km near the Outer Bounty Trough.

[26] The crustal thickness of Campbell Plateau prior to the rotation was about 20–24 km. As Campbell Plateau was rotated and crustal thickness should only change at its margins, the plateau is supposed to have the same thickness after the rotation. A small area south of Stewart Island, however, is 24 km thick and suggests a slight overlap (Figure 8). In the regions of the former Bounty Trough, the rotation implies that crustal thickness changed from 17–24 km before extension to 10–18 km afterward. A similar change in crustal thickness can be observed for the Great South Basin and the Challenger Plateau, where the reconstructed thickness is in general 20 –22 km compared to ~16 km prior to the reconstruction. Small areas in both basins have a thickness of only 18 km and a few patches reach 24 km. In general, the crustal thickness in southeastern Zealandia is well balanced within the range 18–24 km. Using the rotation parameters of *Eagles et al.* [2004], Bollons Seamounts does not fit well to the Bounty Platform, because Bounty Platform's margin is constrained by few data only. With its narrow COTZ, the rotation poles for relative motions of Bollons Seamount are well constrained by conventional plate tectonic reconstructions [*Eagles et al.*, 2004].

[27] The rotation of the Norfolk Ridge closes the New Caledonia Basin entirely and leads to a uniform reconstructed crustal thickness with little variation. The Norfolk Ridge and the Middle Lord Howe Rise between 25°S and 31°S keep their thicknesses of 18–20 km, which are the same as that of the closed New Caledonia Basin. The result for the southern New Caledonia Basin and the Challenger Plateau is less convincing. The southern New Caledonia Basin can be closed to a large extent, but not entirely, although the thickness increased from a minimum of 11 km before reconstruction to at least ~14–15 km with a mean thickness of ~20 km afterward. The rotation of the West Norfolk Ridge has resulted in one small region's thickness increasing to 36 km from 26 km, showing that this solution is not the optimum for this area. The results might be further improved if

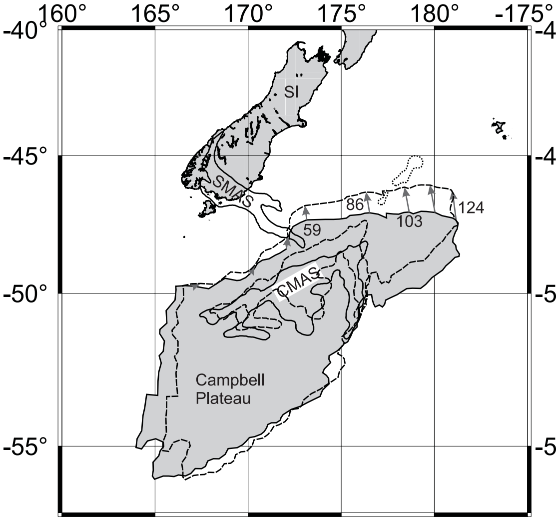

Figure 11. Main magnetic anomaly systems of the Campbell Plateau before and after the rotation. Bold black lines outline the Campbell Plateau and Campbell Magnetic Anomaly System (CMAS) in its present position; dashed lines outline both after the rotation. Dotted lines are magnetic anomalies of the Bounty Trough interpreted as extensional features. Bold black line at the South Island of New Zealand (SI) is the Stokes Magnetic Anomaly System (SMAS).

the West Norfolk Ridge were to be considered as part of an independently rotating plate. As the data coverage is too sparse, however, it was impossible to divide the grid into smaller regions that would allow such an analysis for the West Norfolk and Reinga ridges.

7. Discussion

[28] The motion of the Campbell Plateau relative to a fixed Chatham Rise presented in this paper has a larger rotational and a smaller translational component compared to the reconstruction presented by *Larter et al.* [2002], because our rotation pole lies at the margin of the Campbell Plateau, while previous poles were located within Australia (Table 2). The distances (80 –110 km) covered by points at the Campbell Plateau margin are only one third (Bounty Trough) of the distances (300–330 km) proposed by *Larter et al.* [2002] or suggested by *Kamp* [1986]. In both cases, the assumption was made that Bounty Trough and the Great South Basin were underlain by oceanic crust and had a narrow continent-ocean transition zone. *Larter et al.* [2002] interpreted the COTZs of Campbell Plateau and Chatham Rise as sharply defined in *Sandwell and Smith*'s [1997] satellite-derived free-air gravity data.

[29] *Larter et al.* [2002] presented two solutions for the best fit of Chatham Rise to Marie Byrd Land. The rotation pole in their first, rejected, model differs only by a few degrees in latitude and longitude to our pole, but has a larger rotation angle (11.3° instead of 6.25°). *Larter et al.*'s [2002] preferred pole differs by tens of degrees in latitude and longitude. It is possible that our rotation angle is slightly too small because it neglects intrusions in the Bounty Trough, while the angle of *Larter et al.* [2002] is likely to be too large due to their assumption of narrow COBs of Marie Byrd Land and Chatham Rise.

[30] Our plate-kinematic reconstruction has many implications for geophysical observations in Zealandia itself. It has been suggested that the two major magnetic anomaly systems of southeast Zealandia, the Stokes Magnetic Anomaly System (SMAS) and the Campbell Magnetic Anomaly System (CMAS) are parts of an originally continuous system offset by ~300 km of dextral shear [*Davey and Christoffel*, 1978; *Kamp*, 1986; *Sutherland*, 1999], that has been related to the opening of the Bounty Trough. *Sutherland* [1999] suggested instead that the dextral offset may have occurred prior to 90 Ma, possibly in Permian times. It is possible, however, that the sources of SMAS and CMAS are not identical, because the styles of the magnetic anomalies differ and the CMAS could be related to underplating beneath the Campbell Plateau (Grobys et al., submitted manuscript, 2007). Our reconstruction limits the dextral offset of the CMAS relative to SMAS to just a few kilometers in the time between 90 Ma and 83 Ma. This observation rules out the idea that CMAS and SMAS were a single connected magnetic anomaly system at the time of the onset of Bounty Trough opening. With these data, we cannot conclude whether or not both anomaly systems had a common origin and displacement from one another that occurred at much earlier times.

[31] In the Middle Bounty Trough, synthetic flow lines describing our rotation strike subperpendicular to the gravity anomalies seen there (Figure 11). Our reconstruction explains the gravity patterns in the Middle Bounty Trough representing extensional structures [*Grobys et al.*, 2007] caused by incipient seafloor spreading. They interpreted the Middle Bounty Trough as the locus of incipient seafloor spreading, while the Outer Bounty Trough was underlain by oceanic crust [*Davy*, 1993] and the Inner Bounty Trough was not enough extended to produce oceanic crust. Our reconstruction postulates a rotational motion of the Campbell Plateau relative to a fixed Chatham Rise that is consistent with this progression. This motion leads to an extension of ~87 km in the Inner Bounty Trough, ~100–110 km in the Middle Bounty Trough and ~115–125 km in the Outer Bounty Trough. With the crustal properties of the crust in the Campbell Plateau-Chatham Rise area, the amount of extension necessary to start seafloor spreading can be determined as ~110 km, and the β-factor as ~2.7 [*Grobys et al.*, 2007].

[32] We calculated extension of 85–121 km in the segment of the New Caledonia Basin between 29°S and 25°S, increasing northward, and a maximum extension of ~105 km for the rotation of the Reinga Ridge decreasing to almost 0 km near the coastline of the North Island. Extension rates in the middle New Caledonia Basin were higher than those that formed oceanic crust in the Bounty Trough, and in view of the fact that the initial crustal thickness is ~4 km less, oceanic crust ought to have appeared earlier in the New Caledonia Basin, presumably after about 80–85 km of extension. This means that at 29°S, (present-day coordinates) seafloor spreading could have started and, at 25°S, ~35 km of

oceanic crust could have formed. *Lafoy et al.* [2005b] postulated ~120 km of oceanic crust beneath the New Caledonia Basin at 24°–25°S, which is equal to the total amount of extension we calculate for the central New Caledonia Basin. It is possible that the crust interpreted as oceanic crust is highly thinned and intruded continental crust similar to the crust of the Inner Bounty Trough and only parts of this consist of oceanic crust.

[33] The calculated rotation between the Norfolk and Reinga ridges shows extension backward in time as the Norfolk Ridge is rotated away from the Reinga Ridge. In our reconstruction we separated the two microplates along the Vening Meinesz Fracture Zone [*Herzer and Mascle*, 1996], but we considered Lord Howe Rise as a single block. It has been shown that the Lord Howe Rise consists of at least two blocks and must be treated separately from the Challenger Plateau [*Gaina et al.*, 1998a]. To do this, *Lafoy et al.* [2005a] continued the Vening Meinesz Fracture Zone into Lord Howe Rise. These observations imply that the underlap between Reinga Ridge and Norfolk Ridge could be reduced if a segmentation of the Lord Howe Rise was introduced into our reconstruction. Another further reduction of the underlap could be yield by a separation of the Reinga Ridge microplate into West Norfolk Ridge and Reinga Ridge microplates, as our reconstruction shows an overlap of the West Norfolk Ridge and the northern tip of the Challenger Plateau.

8. Conclusion

[34] With this work, we presented the first crustal thickness map of Zealandia based on seismic and gravity data. This map shows well the main features of the microcontinent and outlines the region's basins and plateaus. It indicates a rather uniform crustal thickness of the plateaus of ~20–24 km and of 10–14 km in the basins. We developed a crustal thickness balancing method to constrain finite rotations for describing the extension of continental crust. In regions of two or more neighboring plates, the crust was divided in overlapping parts. The plates were rotated, crustal thickness was added up and the standard deviation of the new crustal thickness grid was calculated within a significant window. We defined the best fit reconstruction as the one with a minimum standard deviation. Reconstructions on the basis of crustal thickness balancing are a powerful tool to produce paleotectonic maps in areas of crustal thinning where magnetic spreading anomalies are absent. The derivation of the rotation parameters is confined by the accuracy of the crustal thickness map and the assumption that the crustal thickness in this region was uniform before the breakup.

[35] In Zealandia, the motion of the Campbell Plateau opens the Bounty Trough, the Canterbury Basin, and the Great South Basin simultaneously. The gravity anomalies in the Middle Bounty Trough are confirmed as the expressions of en echelon extensional features formed at the locus of nascent seafloor spreading. The rotational motion of the Campbell Plateau also rules out the possibility that the Stokes Magnetic Anomaly System and the Campbell Magnetic Anomaly System were a single anomaly system until the separation of Zealandia and Antarctica at 90–83 Ma. It rather confirms the hypothesis that an earlier event, maybe in Permian times, offset the two anomaly systems or that the anomaly systems have different origins.

[36] Our reconstruction of the New Caledonia Basin region shows an extension of 120 km at most. A comparison with the Bounty Trough extension suggests that a maximum of 35 km, if any, of oceanic crust could have been built in the New Caledonia Basin. It seems possible that the New Caledonia Basin is underlain by highly extended and intruded continental crust similar to that beneath the Bounty Trough. The reconstruction of the southernmost New Caledonia Basin supported the necessity of a Lord Howe Rise that consists of several independently rotated pieces. Treating the West Norfolk Ridge as a separate microplate is necessary to reduce the misfit of plate reconstructions in the southernmost New Caledonia Basin. However, this needs to be verified by a significant improvement in crustal thickness measurements.

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References

Auzende, J.-M., S. Van de Beuque, G. Dickens, C. Francois, Y. Lafoy, O. Voutay, and N. F. Exon (2000), Deep sea diapirs and bottom simulating reflector in Fairway Basin (SW Pacific), *Mar. Geophys. Res.*, *21*, 579–587.

Beanland, S., and J. Haines (1998), The kinematics of active deformation in the North Island, New Zealand, determined from geological strain rates, *N. Z. J. Geol. Geophys.*, *41*, 311–323.

Bradshaw, J. D. (1989), Cretaceous geotectonic patterns in the New Zealand region, *Tectonics*, *8*, 803–820.

Cande, S. C., and J. Stock (2004a), Cenozoic reconstructions of the Australia-New Zealand-South Pacific sector of Antarctica, in *The Cenozoic Southern Ocean: Tectonics, Sedimentation and Climate Change Between Australia and Antarctica*, *Geophys. Monogr. Ser.*, vol. 151, edited by N. F. Exon, J. P. Kennett, and M. Malone, J., pp. 5–18, AGU, Washington, D. C.

Cande, S. C., and J. Stock (2004b), Pacific-Antarctic-Australia motion and the formation of the Macquarie Plate, *Geophys. J. Int.*, *157*(1), 399–414, doi:10.1111/j.1365-246X.2004.02224.x.

Cook, R. A., R. Sutherland, H. Zhu, R. Funnel, and S. D. Killops (1999), *Cretaceous-Cenozoic Geology and Petroleum Systems of the Great South Basin, New Zealand*, 188 pp., Inst. of Geol. and Nucl. Sci. Ltd., Lower Hutt, New Zealand.

Davey, F. J. (1977), Marine seismic measurements in the New Zealand Region, *N. Z. J. Geol. Geophys.*, *20*, 719–777.

Davey, F. J., and D. A. Christoffel (1978), Magnetic anomalies across Campbell Plateau, New Zealand, *Earth Planet. Sci. Lett.*, *41*, 14–20.

Davy, B. (1993), The Bounty Trough: Basement structure influences on sedimentary basin evolution, in *South Pacific Sedimentary Basins of the World*, edited by P. F. Ballance, pp. 69–92, Elsevier Sci., Amsterdam.

Davy, B. (2006), Bollons Seamount and early New Zealand–Antarctic seafloor spreading, *Geochem. Geophys. Geosyst.*, *7*, Q06021, doi:10.1029/2005GC001191.

Davy, B., and R. Wood (1994), Gravity and magnetic modelling of the Hikurangi Plateau, *Mar. Geol.*, *118*, 139–151.

DiVinere, D, V. Kent, and I. W. D. Dalziel (1995), Early cretaceous paleomagnetic results from Marie Byrd Land, West Antarctica: Implications for the Wedellia collage of crustal blocks, *J. Geophys. Res.*, *100*, 8133–8152.

Eagles, G., K. Gohl, and R. D. Larter (2004), High-resolution animated tectonic reconstruction of the South Pacific and West Antarctic Margin, *Geochem. Geophys. Geosyst.*, *5*, Q07002, doi:10.1029/2003GC000657.

Forster, M. A., and G. S. Lister (2003), Cretaceous metamorphic core complexes in the Otago Schist, New Zealand, *Aust. J. Earth Sci.*, *50*(2), 181–198, doi:10.1046/j.1440-0952.2003.00986.x.

Gaina, C., D. R. Müller, J.-Y. Royer, J. Stock, J. Hardebeck, and P. A. Symonds (1998a), The tectonic history of the Tasman Sea: A puzzle with 13 pieces, *J. Geophys. Res.*, *103*, 12,413–12,433.

Gaina, C., W. R. Roest, R. D. Müller, and P. A. Symonds (1998b), The opening of the Tasman Sea: A gravity anomaly animation, *Earth Interact.*, *2*, 1–23.

Godfrey, N. J., F. J. Davey, T. Stern, and D. Okaya (2001), Crustal structure and thermal anomalies of the Dunedin Region, South Island, New Zealand, *J. Geophys. Res.*, *106*, 30,835–30,848.

Grobys, J. W. G., K. Gohl, B. Davy, G. Uenzelmann-Neben, T. Deen, and D. Barker (2007), Is the Bounty Trough off eastern New Zealand an aborted rift?, *J. Geophys. Res.*, *112*, B03103, doi:10.1029/2005JB004229.

Herzer, R., and J. Mascle (1996), Anatomy of a continental-backarc transform: The Vening Meinesz fracture zone northwest of New Zealand, *Mar. Geophys. Res.*, *18*, 401–427.

Herzer, R., et al. (1997), Seismic stratigraphy and structural history of the Reinga Basin and its margins, southern Norfolk Ridge System, *N. Z. J. Geol. Geophys.*, *40*, 425–451.

Jongsma, D., and J. C. Mutter (1978), Non-axial breaching of a rift valley: Evidence from the Lord Howe Rise and the Southeastern Australian Margin, *Earth Planet. Sci. Lett.*, *39*, 226–234.

Kamp, P. J. J. (1986), Late Cretaceous-Cenozoic tectonic development of the southwest Pacific region, *Tectonophysics*, *121*, 225–251.

King, P. R. (2000), Tectonic reconstructions of New Zealand: 40 Ma to the present, *N. Z. J. Geol. Geophys.*, *43*, 611–638.

Kohler, M. D., and D. Eberhart-Phillips (2002), Three-dimensional lithospheric structure below the New Zealand Southern Alps, *J. Geophys. Res.*, *107*(B10), 2225, doi:10.1029/2001JB000182.

Lafoy, Y., I. Brodien, R. Vially, and N. F. Exon (2005a), Structure of the Basin and Ridge System west of New Caledonia (southwest Pacific): A synthesis, *Mar. Geophys. Res*, *26*(1), 37–50, doi:10.1007/s11001-005-5184-5.

Lafoy, Y., L. Géli, F. Klingelhoefer, R. Vially, B. Sichler, and H. Nouzé (2005b), Discovery of continental stretching and oceanic spreading in the Tasman Sea, *Eos Trans. AGU*, *86*(10), 101.

Laird, M. G. (1993), *Cretaceous Continental Rifts: New Zealand Region*, pp. 37–49, Elsevier Sci., Amsterdam.

Larter, R. D., A. P. Cunningham, P. F. Barker, K. Gohl, and F. O. Nitsche (2002), Tectonic evolution of the Pacific margin of Antarctica: 1. Late Cretaceous tectonic reconstructions, *J. Geophys. Res.*, *107*(B12), 2345, doi:10.1029/2000JB000052.

Louden, K. E., and D. Chian (1999), The deep structure of non-volcanic rifted continental margins, *Philos. Trans. R. Soc. London, Ser. A*, *357*, 767–805.

Luyendyk, B. P. (1995), Hypothesis for Cretaceous rifting of east Gondwana caused by subducted slab capture, *Geology*, *23*, 373–376.

Luyendyk, B. P., S. Cisowski, C. Smith, S. Richard, and D. L. Kimbrough (1996), Paleomagnetic study of the northern Ford Ranges, western Marie Byrd Land, West Antarctica: Motion between West and East Antarctica, *Tectonics*, *15*, 122–141.

McKenzie, D. (1978), Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett.*, *40*, 25–32.

Mechie, J., G. R. Keller, C. Prodehl, M. A. Khan, and S. J. Gaciri (1997), A model for the structure, composition and evolution of the Kenya rift, *Tectonophysics*, *278*, 95–119.

Mortimer, N., F. J. Davey, A. Melhuish, J. Yu, and N. J. Godfrey (2002), Geological interpretation of a deep seismic reflection profile across the Eastern Province and Median Batholith, New Zealand: Crustal architecture of an extended Phanerozoic convergent orogen, *N. Z. J. Geol. Geophys.*, *45*, 349–363.

Mortimer, N., K. Hoernle, F. Hauff, J. M. Palin, W. J. Dunlap, R. Werner, and K. Faure (2006), New constraints on the age and evolution of the Wishbone Ridge, southwest Pacific Cretaceous microplates, and Zealandia–West Antarctic breakup, *Geology*, *34*(3), 185–188, doi:10.1030/G22168.1.

Mukasa, S. B., and I. W. D. Dalziel (2000), Marie Byrd Land, West Antarctica: Evolution of Gondwana's Pacific margin constrained by zircon U-Pb geochronology and feldspar common-Pb isotopic compositions, *Geol. Soc. Am. Bull.*, *112*, 611–627.

Müller, R. D., C. Gaina, and S. Clark (2000), Seafloor Spreading around Australia, in *Billion-Year Earth History of Australia and Neighbours in Gondwanaland*, edited by J. J. Veevers, pp. 18–25, Dept. of Earth and Planet. Sci., Macquarie Univ., GEMOC Press, Sydney, Australia.

Reyners, M., and H. Cowan (1993), The transition from subduction to continental collision: Crustal structure in the North Canterbury region, New Zealand, *Geophys. J. Int.*, *115*, 1124–1136.

Sandwell, D. T., and W. H. F. Smith (1997), Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956–1962.

Scherwath, M., T. Stern, F. Davey, D. Okaya, W. S. Holbrook, R. Davies, and S. Kleffmann (2003), Lithospheric structure across oblique continental collision in New Zealand from wide-angle *P* wave modeling, *J. Geophys. Res.*, *108*(B12), 2566, doi:10.1029/2002JB002286.

Shor, G. G. J., H. K. Kirk, and H. W. Menard (1971), Crustal structure of the Melanesian area, *J. Geophys. Res.*, *76*, 2562–2586.

Smith, W. H. F., and D. T. Sandwell (1997), Marine gravity anomaly from Geosat and ERS 1 satellite altimetry, *J. Geophys. Res.*, *102*, 10,039–10,054.

Smith, W. H. F., and P. Wessel (1990), Gridding with continuous curvature splines in tension, *Geophysics*, *55*, 29–305.

Spell, T. L., L. McDougall, and A. J. Tulloch (2000), Thermochronologic constraints on the breakup of the Pacific Gondwana margin: The Paparoa core complex, South Island, New Zealand, *Tectonics*, *19*, 433–451.

Sutherland, R. (1995), The Australia-Pacific boundary and Cenozoic plate motions in the SW Pacific: Some constraints from Geosat data, *Tectonics*, *14*, 819–831.

Sutherland, R. (1999), Basement geology and tectonic development of the greater New Zealand region: An interpretation from regional magnetic data, *Tectonophysics*, *308*(3), 341–362, doi:10.1016/S0040-1951 (99)00108-0.

Uruski, C. (2003), Cretaceous paleogeography of the Taranaki Basin, paper presented at Geological Society of New Zealand Inc 2003 Annual Conference, Geological Society of New Zealand miscellaneous publication, Univ. of Otago, Dunedin, New Zealand.

Uruski, C., and R. Wood (1991), A new look at the New Caledonia Basin, an extension of the Taranaki Basin, offshore North Island, New Zealand, *Mar. Pet. Geol.*, *8*, 379–391.

Van Avendonk, H. J. A., W. S. Holbrook, D. Okaya, J. K. Austin, F. Davey, and T. Stern (2004), Continental crust under compression: A seismic refraction study of South Island Geophysical Transect I, South Island, New Zealand, *J. Geophys. Res.*, *109*, B06302, doi:10.1029/2003JB002790.

Van de Beuque, S., J.-M. Auzende, Y. Lafoy, G. Bernandel, A. Nercessian, M. Régnier, R. Sykes, and N. F. Exon (1998), Transect sismique continu entre l'arc des Nouvelle-Hébrides et la marge orientale de l'Australie: Programme FAUST (French Australian Seismic Transect), *C. R. Acad. Sci., Ser. II*, *327*, 761–768.

Vially, R., Y. Lafoy, J.-M. Auzende, and R. France (2003), Petroleum potential of New Caledonia and its offshore basins, paper presented at AAPG International Conference, Am. Assoc. of Pet. Geol., Barcelona, Spain, 21–24 Sept.

Voss, M., and W. Jokat (2007), Continent-ocean transition and voluminous magmatic underplating derived from P-wave velocity modelling of the East Greenland continental margin, *Geophys. J. Int.*, *170*, 580–604, doi:10.1111/j.1365-246X.2007.03438.x.

Wandres, A. M., and J. D. Bradshaw (2005), New Zealand tectonostratigraphy and implications from conglomeratic rocks for the configuration of the SW Pacific margin of Gondwana, *Geol. Soc. Spec. Publ.*, *246*, 179–216.

Wernicke, B., and B. C. Burchfiel (1982), Modes of extensional tectonics, *J. Struct. Geol.*, *4*, 105–115.

Wessel, P., and W. H. F. Smith (1998), New, improved version of Generic Mapping Tools released, *Eos Trans. AGU*, *79*, 579.

Wood, R., and V. Stagpoole (2007), Validation of tectonic reconstructions by crustal volume balance: New Zealand through the Cenozoic, *Geol. Soc. Am. Bull.*, *119*(7–8), 933–943, doi:10.1130/B26018.1.

Wood, R., and D. J. Woodward (2002), Sediment thickness and crustal structure of offshore western New Zealand from 3-D gravity modelling, *N. Z. J. Geol. Geophys.*, *45*, 243–255.

Woodward, D. J., and T. Hunt (1971), Crustal structure across the Tasman Sea, *N. Z. J. Geol. Geophys.*, *14*, 39–45.

Worthington, T. J., R. Hekinian, P. Stoffers, T. Kuhn, and F. Hauff (2006), Osbourn Trough: Structure, geochemistry and implications of a mid-Cretaceous paleospreading ridge in the South Pacific, *Earth Planet. Sci. Lett.*, *245*(3–4), 685–701, doi:10.1016/j.epsl.2006.03.018.