Validation of tectonic reconstructions by crustal volume balance: New Zealand through the Cenozoic

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ABSTRACT

We describe a procedure that allows us to quantitatively test hypotheses about the tectonic evolution of a region, including areas for which there is little or no geologic record, and apply it to the Pacific-Australian plate boundary in the New Zealand region since 65 Ma. The derived models are a first attempt to quantify the effects of the development of the modern plate boundary on four major components of the tectonic evolution of New Zealand, i.e., sedimentation, paleogeography, growth of crustal root, and nonrigid deformation. The technique balances total rock volume through time using estimates of these factors. Although the solutions are nonunique, the uncertainties in each factor can be estimated and used to define the models. The plate reconstructions we present are minor modifications of earlier work, developed to test whether those proposed reconstructions are self-consistent and consistent with present-day crustal structure and sediment distribution. They are digital and geographically referenced, and they have the advantage that new data can be readily incorporated and new concepts tested against several criteria. The model of the evolution of New Zealand's crustal root is new and incorporates a previously unpublished compilation.

The models show that rock redistribution is accounted for by erosion and sedimentation during the period 65–25 Ma. The Pacific-Australian plate boundary began propagating through New Zealand ca. 45 Ma. In these models, development of the boundary has no effect on nonrigid deformation until ca. 25 Ma. That time marked the start of a significant increase in land area, and of the nonrigid deformation of a large region in the center of the New Zealand continent. Since ca. 20 Ma, ~575,000 km^3 of sediments were deposited in basins around New Zealand, and a crustal root with a volume of ~2,200,000 km^3 is interpreted to have developed beneath the landmass. A large area in the center of Late Cretaceous and Tertiary reconstructions of the New Zealand region, inferred from outcrop, well, and seismic reflection data, deformed, eroded, and was eventually amalgamated within the continental crust of New Zealand, a redistribution of ~3,080,000 km^3 of rock (at 0% porosity).

Keywords: tectonic models, plate tectonics, sediment budget, mass balance, New Zealand.

INTRODUCTION

The geologic record shows that the distribution of rocks in the New Zealand region has changed dramatically during the Cenozoic, in part due to large-scale nonrigid deformation. All recent tectonic reconstructions of New Zealand (e.g., Walcott, 1984; Holt and Stern, 1994; King, 2000a) show a radical reconfiguration of fragments of present-day New Zealand distributed around a large region that is not recognized in the geologic record. In this paper we refer to this region as the central deformed region. The original shape and extent of this region, its relationship with the rest of New Zealand, and where the rocks that formed it have gone are not well known.

The technique presented in this paper provides limitations on the original plate configuration, and allows us to make testable predictions about the tectonic evolution of New Zealand. We assume that the total mass of the crust in the New Zealand region has been constant, and use plate tectonic reconstructions, paleogeography, and calculated sediment volumes to infer changes in mass distribution during the Cenozoic, after the separation of New Zealand from Gondwana. The method helps validate plate tectonic and paleogeographic models, the most significant results relating to predictions about the timing and nature of deformation of geographic areas for which there is little or no geologic record, and to changes in crustal thickness through time. We discuss the uncertainties associated with each of the input data sources, and the effect they have on the results.

New Zealand is an ideal setting to undertake this type of study because it has been on an active, evolving plate boundary for ~40 m.y., and has been isolated from tectonic and sedimentological influences of other plate boundaries. Where it passes through New Zealand, the boundary between the Pacific and Australian plates is relatively well defined along the Hikurangi subduction zone, Alpine fault, and Puysegur subduction zone (Fig. 1). The present-day relative motion between the plates is well documented (e.g., De Mets et al., 1990, 1994), and although the majority of the modern deformation occurs near the plate boundary (e.g., Walcott, 1978, 1984, 1998; Beavan and Haines, 2001), as much as 50% of the total Eocene–Holocene plate displacement was accommodated by crustal shear distributed over an area tens to several hundred kilometers wide (Sutherland, 1999).

To test plate reconstructions of New Zealand over the past 65 m.y., we quantify the present-day volume and distribution of sediments and crust, and combine them in a feedback process with relatively sparse knowledge of paleogeography and tectonic evolution of the region. Our reconstructions are first-order, digital, geographically referenced models of the evolution of the New Zealand region that incorporate both rigid block motions and nonrigid deformation. They are designed to quantitatively test hypotheses and to be readily updated with new information.

The technique may be applicable in other regions where plate collision occurs, allowing similar predictions about the changing locations, orientations, and shapes of tectonic elements that are poorly defined by geology. It may be difficult to use this technique in areas where the assumption of constant mass is not valid, i.e., where sediments may be derived from outside

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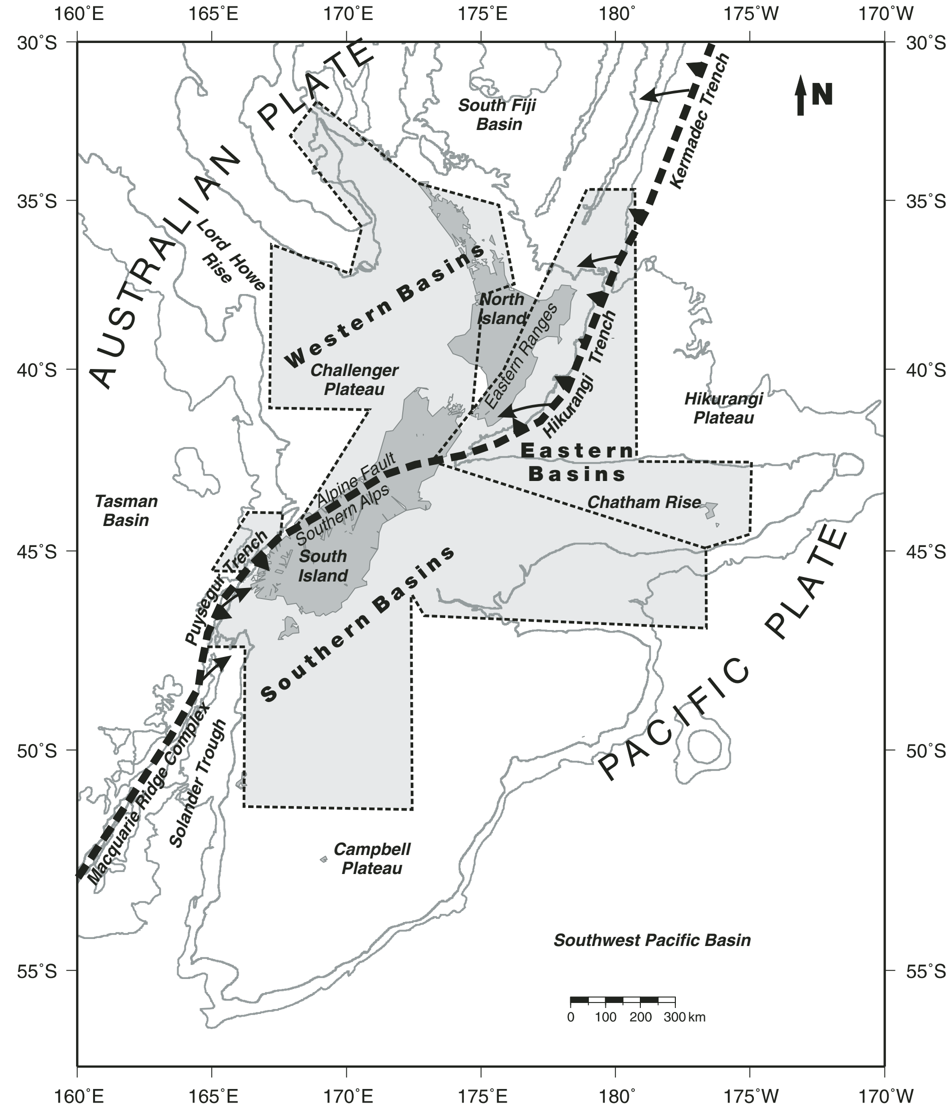


Figure 1. Location map showing present-day land area and bathymetric contours (gray, CANZ, 1997). The present-day boundary between the Australian and Pacific plates (bold dashed line with arrows indicating relative plate motion is from De Mets et al., 1994) follows the Kermadec Trench, Hikurangi Trough, Alpine fault, Puysegur Trench, and Maquarie Ridge Complex. Major sedimentary basins are named and a dashed line delineates the areas analyzed in detail by this study.

the region of interest, or where extensive volcanism or underplating has added mass.

GEOLOGICAL BACKGROUND

The New Zealand margin has been extensively studied, and geophysical data acquired from both sides of the plate boundary can be used to estimate sediment volumes and crustal thickness. The broad aspects of the tectonic history of the region are well understood in terms of relative plate motion (Walcott, 1978, 1984; Sutherland, 1995; Cande and Stock, 2004), history of mountain building (Walcott, 1998; Gerbault et al., 2003; Scherwath et al., 2003; Henrys et al., 2004; Van Avendonk et al., 2004), and present-day geodetic strain (Walcott, 1984; Beavan and Haines, 2001; Wallace et al., 2004). There are, however, still large uncertainties in the past configuration of the plate boundary and the associated patterns of deformation, uplift, and erosion.

All plate reconstructions indicate that during the Cretaceous (ca. 85 Ma) the block of continental crust that includes New Zealand rifted from Gondwana. Seafloor spreading in the Tasman Sea continued until the early Paleocene (e.g., Gaina et al., 1998), and is still active along the Pacific-Antarctic Ridge south of New Zealand. Propagation of the modern plate boundary through New Zealand began in the Eocene (e.g., Carter and Norris, 1976; Sutherland, 1995; Cande and Stock, 2004). In the south, extension in the Emerald Basin evolved into strike-slip movement and oblique convergence; in the north, oblique convergence and subduction have been occurring for at least 25 m.y. (Walcott, 1984; Holt and Stern, 1994). More than 450 km of dextral movement occurred on or adjacent to the Alpine fault during the Cenozoic (Wellman, 1956; Sutherland, 1999). Movement on the Alpine fault occurred in association with westward-directed subduction that developed at the Kermadec Trench and Hikurangi Trough, east of the North Island, and northeastward-directed subduction at the Puysegur Trench, southwest of New Zealand (Fig. 1). Between these subduction zones, continental crust of the Chatham Rise and the Hikurangi Plateau large igneous province are colliding with continental crust of the Challenger Plateau and associated parts of the North and South Islands (Fig. 1). Oblique compression across the plate margin is marked by deformation along the Alpine fault and uplift of the Southern Alps in the South Island (Norris et al., 1990), the eastern ranges of the North Island (Nicol and Beavan, 2003), and the offshore East Coast fold and thrust belt (Davey and Stern, 1990).

The shape of New Zealand has changed markedly since the breakup of Gondwana in the Cretaceous (Walcott, 1978, 1984; Holt and Stern, 1994; Kamp, 1986; King, 2000a). Paleogeographic interpretations based on outcrop, well, and seismic reflection data indicate that the land area decreased during the Late Cretaceous and early Cenozoic as New Zealand subsided in response to post-breakup lithospheric cooling. Land area increased from the early Miocene, after the formation of the convergent plate boundary through New Zealand. The corresponding Cretaceous to Holocene sedimentary succession can be summarized as a first-order transgressive-regressive megasequence, with maximum marine flooding and widespread deposition of carbonate sediments in the late Oligocene (King, 2000b). Large volumes of sediment derived from the submerging and emerging land were deposited in basins around New Zealand (Stagpoole et al., 2002). The process continues today, with high rates of uplift (~10 mm/yr; Wellman, 1979) countered by high rates of erosion (Adams, 1980; Gomez et al., 2001).

METHOD

The analysis in this paper assumes that the New Zealand region is a closed system in terms of crustal material, including clastic sediments. We assume that the distribution of the rocks has changed, but the total mass has been constant for the past 65 m.y. The distribution of rocks has been affected by erosion and sedimentation, and by tectonic activity that has altered the crustal structure and changed the topography of the land surface. This closed-system assumption allows calculations of the distributions of mass (e.g., crust and sediment thickness) that provide constraints on the evolution of areas deformed or redistributed by tectonic activity.

The volume calculation in our model balanced four factors through time: (1) observed sediment volume, calculated from regional subsurface mapping and compacted to zero porosity; (2) change in land area due to erosion and subsidence, calculated from regional paleogeographic analysis; (3) crustal volume, i.e., the present volume inferred from seismic tomography; and (4) continental area not preserved in the geologic record, i.e., the original area defined by the location of rigid blocks used in tectonic reconstructions (central deformed region).

In the volume balance calculations, sediment and crustal volume (including paleotopography) are calculated at nine time steps from the present day to the beginning of the Cenozoic (65 Ma), prior to the development of the convergent margin through New Zealand.

The present-day distribution of sediments is delimited by decades of systematic regional subsurface mapping of all the major sedimentary basins. New Zealand has been isolated from other sources of clastic sediment and there is no evidence that significantly large volumes (>100,000 km^3) of rock have been lost to the system by subduction. If significant volumes of sediment have been subducted, then much of this material would be included in the crustal component of our model. This would not change the overall result, but would influence inferences about the rates of erosion, deposition, uplift, and subsidence. Our calculations indicate that the effects of thermal subsidence, sea-level change, and uplift due to magmatism are an order of magnitude less than other factors considered in the volume balance and are within the uncertainty bounds of those factors.

New Zealand's present-day crustal structure is defined by seismic tomography studies (described in the following). The submarine plateaus around New Zealand are at similar water depths, have similar crustal thicknesses, and have been relatively stable throughout the Cenozoic (e.g., Adams, 1962; Shor et al., 1971; Solomon and Biehler, 1969; Woodward and Wood, 2000; Wood and Woodward, 2002), indicating that a simple uniform initial crustal model for the New Zealand region is a reasonable first-order approximation for the starting point of the region's evolution.

TABLE 1. TOTAL SOLID VOLUME (VOLUME AT 0% POROSITY) OF CLASTIC AND CARBONATE SEDIMENT DEPOSITED AROUND NEW ZEALAND THROUGH TIME

Age (Ma)	Clastic sediment volume in western basins (km^3)	Clastic sediment volume in eastern basins (km^3)	Clastic sediment volume in southern basins (km^3)	Clastic sediment volume in all basins (km^3)	Clastic uncertainty (km^3)
0–5	123300	85400	33400	242100	66600
5–10	59500	31700	20200	111400	34700
10–15	63000	33400	18200	114600	37500
15–20	53700	35700	17100	106500	35000
20–25	41400	37000	16000	94400	35100
25–40	58200	46500	40300	145000	54800
40–55	62000	48400	63600	174000	52400
55–65	44900	31900	74500	151300	57300
Total	506000	350000	283300	1139300	373400

Age (Ma)	Carbonate sediment volume in western basins (km^3)	Carbonate sediment volume in eastern basins (km^3)	Carbonate sediment volume in southern basins (km^3)	Carbonate sediment volume in all basins (km^3)	Carbonate uncertainty (km^3)
0–5	32,500	7300	13,200	53,000	28,700
5–10	20,900	5600	8300	34,800	19,200
10–15	24,800	5700	8700	39,200	21,400
15–20	22,400	6000	8500	36,900	20,300
20–25	24,200	6200	8900	39,300	21,600
25–40	34,600	6000	24,100	64,700	34,200
40–55	20,900	6000	28,100	55,000	29,400
55–65	12,600	4000	58,100	74,700	38,600
Total	192,900	46,800	157,900	397,600	213,400

Note: Volumes of biogenic siliceous sediments and organic matter (mostly coal) are minor in comparison to carbonate and are considered to be much less than the uncertainty in the volume of carbonate. See Figure 1 for location of basins.

Volume calculations were made on grids of sediment isopachs and paleotopography for time steps through the Cenozoic, and on the present-day shape of the crustal root. Grids had a 4 km cell size and volume calculations used generic mapping tools software (GMT; Wessel and Smith, 1995). The calculations assume similar particle densities for the components. This tends to overestimate the volume above sea level (at zero porosity) and underestimate the volume in the crustal root, but the errors (estimated to be ~5%–10%) are significantly less than the uncertainty in the volume of each component.

Sediment volumes (excluding carbonate sediments) for each time step have an estimated uncertainty of 30%, based on the distribution and quality of seismic data and assumptions made about sediment type, porosity, and erosion (Table 1). The volume of crust above sea level has an estimated uncertainty of 25% at each time step, based on assumptions about the paleotopography and the location of the shoreline (Table 2). The present-day volume in the crustal root has an estimated uncertainty of 25%, based on assumptions about the initial crustal structure and other factors such as Cenozoic underplating of mantle material associated with volcanism.

Sediment Volume

Regional interpretations of Cretaceous and Cenozoic sediment distribution and thickness have been compiled for all the major sedimentary basins and some of the more remote areas in the New Zealand region (Cahill, 1995; Cook et al., 1999; Davy, 1993; Field et al., 1989, 1997; Herzer et al., 1997; Gillies and Davey, 1986; Isaac et al., 1994; King and Thrasher, 1996; Nathan et al., 1986; Turnbull et al., 1993; Wood et al., 1989; Wood, 1993). Sediment volumes (at 0% porosity) as a function of time were estimated by removing the carbonate and organic components, the effect of porosity inferred from a regional porosity-depth relationship, and in some areas the effects of erosion and reworking.

Basins with petroleum potential have reasonably comprehensive coverage of seismic reflection data. In these areas the stratigraphic interpretations are usually tied to wells and are

TABLE 2. NEW ZEALAND LAND AREA THROUGH TIME, SUBDIVIDED INTO AREAS OF EROSION AND ONSHORE DEPOSITION

Age (Ma)	Erosion area (km^2)	Onshore deposition (km^2)	Total onshore (km^2)
0	207,811		207,811
5	235,000	55,000	290,000
10	210,000	70,000	280,000
16	230,000	35,000	265,000
20	175,000	20,000	195,000
25	100,000	0	100,000
40	320,000	125,000	445,000
56	605,000	125,000	730,000
65	800,000	230,000	1,030,000

Note: Derived from King (2000a, 2000b).

relatively robust. In the more remote parts of the New Zealand region, the data coverage is often sparse, and the distribution, age, and nature of sediments are relatively poorly defined. Areas such as the Solander Trough, South Fiji Basin, and outer parts of the Campbell Plateau (Fig. 1) have not been systematically mapped and are not included in volume estimates. These areas have been remote from sources of clastic sediment for most of the past 40 m.y., and their omission is unlikely to significantly alter the results.

The volume of the clastic and carbonate components of the sediments (at 0% porosity) in the New Zealand region is presented in Table 1. Paleogeographic interpretations (where available) calibrated to wells were used to define the spatial distribution of lithologies, and thus estimate the clastic, carbonate, and organic-matter content of each grid cell. Diagenesis and deposition of biogenic siliceous sediments were considered negligible on a basin-wide scale. Comparison of paleogeographic interpretations with well and outcrop data indicates that uncertainties in the volumes of carbonate and organic matter on a basin-wide scale are typically ~±30%. In areas where well data are scarce the uncertainties are greater.

In areas where paleogeographic interpretations are not available, the interpretation of lithology content was based on Deep Sea Drilling Project and/or Ocean Drilling Program data (DSDP Legs 21 and 29, and ODP Leg 181). Carbonate volume estimates in these areas are assigned an uncertainty of ±80% in the eastern basins because of the lack well data, and a ±50% uncertainty in other regions (Table 1).

Crustal Structure and Volume

New Zealand is part of a large continental block that separated from Gondwana in the Cretaceous (e.g., Weissel et al., 1977). Most of this continental block (the Challenger Plateau–Lord Howe Rise, Campbell Plateau, Chatham Rise; Fig. 1) is in water depths between 500 and 1000 m and has a crustal thickness of 20–30 km (e.g., Adams, 1962; Shor et al., 1971; Solomon and Biehler, 1969; Woodward and Wood, 2000; Wood and Woodward, 2002). In contrast, the crust close to the present-day plate boundary is as thick as 45 km (e.g., Scherwath et al., 2003). This thickened crust under New Zealand is a result of compression across the evolving plate margin during the Cenozoic. Plate reconstructions (e.g., Walcott, 1984; Holt and Stern, 1994; King, 2000a, 2000b) and our model indicate that much of the material in the root came from redistribution of crust that originally formed the central deformed region (discussed in more detail in the following). Regional geological studies and plate reconstructions indicate that formation of the crustal root began ca. 20 Ma, when compression along the plate margin began to increase, although the rate of root growth increased greatly after ca. 10 Ma (e.g., Kamp, 1986; Holt and Stern, 1994; Rait et al., 1991; Walcott, 1998).

We used results from seismic tomography studies (Eberhart-Phillips and Reyners, 1997, 2001; Eberhart-Phillips and Bannister, 2002; Eberhart-Phillips et al., 2005; Reyners et al., 1999, 2006) to infer the present-day thickness of the crust beneath New Zealand (Fig. 2). The depth to rocks with a P-wave velocity of 7.5 km/s was mapped, and velocity anomalies related to underplating and subduction (D. Eberhart-Phillips, 2005, personal commun.) were removed. Although this is not a direct measure of crustal thickness, the result agrees with other studies based on interpretation of seismic reflection and/or refraction data (Stern and Davey, 1987; Scherwath et al., 2003; Henrys et al., 2004; Van Avendonk et al., 2004).

An initial crustal thickness of 28 km for the New Zealand landmass (including the central deformed region) prior to formation of the margin through New Zealand is used in the mass balance. The choice of 28 km is a consequence of the configurations of the 65 Ma plate reconstruction and of the present-day crustal root. Areas thicker than 28 km (shaded in Fig. 2) are assumed to be the product of crustal thickening. The 28 km thickness is toward the upper end of the range of thickness estimates for the submerged plateaus in the broader New Zealand region, and is in good agreement with thickness measurements from offshore central New Zealand (Holt and Stern, 1984). Plate tectonic and paleogeographic reconstructions indicate that the New Zealand landmass was relatively large and probably close to isostatic equilibrium at 65 Ma, and a crustal thickness somewhat greater than that of the surrounding plateaus is reasonable.

A thickness much different than 28 km requires significant changes to the configuration of the present-day root and/or the positions of the fragments of present-day New Zealand that determine the extent of the central deformed region in plate reconstructions. Because there are no mass losses or gains in our model and the other components are largely accounted for, there is a correlation between the rock volume of the central deformed region and of the continental root. For example, if the initial crustal thickness is assumed to be 25 km, then the increase in crustal root volume requires a 60% increase in the area of the central deformed region, an interpretation difficult to support with current paleogeographic and tectonic models.

Given an initial crustal thickness of 28 km, the present-day volume of the New Zealand continental root is estimated to be ~2,200,000 km^3. Prior to 20 Ma, the other components account for mass changes and there is no need to model an increase in the volume of the crustal root. Our model predicts that between 20 and 16 Ma the crustal root grew by 25,000 km^3/m.y., between 16 and 10 Ma by 83,000 km^3/m.y., between 10 and 5 Ma by 200,000 km^3/m.y., and between 5 Ma and now by 140,000 km^3/m.y.

A ±1 km uncertainty in the original average crustal thickness leads to ±15% variation in the volume of the crustal root. Additional uncertainties relate to the accuracy of the crustal thickness map and the possible inclusion of zones of crustal underplating in the calculations. The assumed uncertainty in volume of the crustal material redistributed during the formation of the present-day plate boundary through New Zealand is ±25%.

Paleogeography, Tectonic Elements, and Topographic Volume

Paleogeographic reconstructions (modified from King, 2000a, 2000b) are combined with tectonic models to quantify the New Zealand land area through time (Figs. 3 and 4; Table 2). The reconstructions use rotation poles from Cande and Stock (2004) and assume that the Pacific plate is fixed.

For these reconstructions the New Zealand region is subdivided into five tectonic elements: the Pacific plate, the Australian plate (including the West Coast of the South Island and western North Island), the east coast of the North Island, and the Marlborough and Fiordland areas of the South Island. The east coast of the North Island, Marlborough, and Fiordland are known to have deformed nonrigidly (e.g., Walcott, 1984, 1987; Lamb and Bibby, 1989; King, 2000a, 2000b), but in these first-order reconstructions they are treated as rigid blocks. Their motions are adapted from those of King (2000a, 2000b; P. King and R. Sutherland, 2005, personal commun.) to maintain the rock mass balance and produce smooth tectonic trajectories relative to the Pacific plate. The central, triangular-shaped region in the 40 Ma plate configuration is interpreted to have been radically deformed during plate boundary evolution, and the rocks redistributed as sediments, crustal root, and topography (Figs. 3, 4, and 5).

The volume of rock above sea level is calculated by assuming a distribution of elevations similar to that of present-day New Zealand. Elevations were certainly different from this in the past, but comparison of these results with those obtained using a distribution of elevations similar to that of present-day Australia, perhaps typical of New Zealand in the early and mid-Cenozoic, showed that the difference in volume was within the margin of uncertainties.

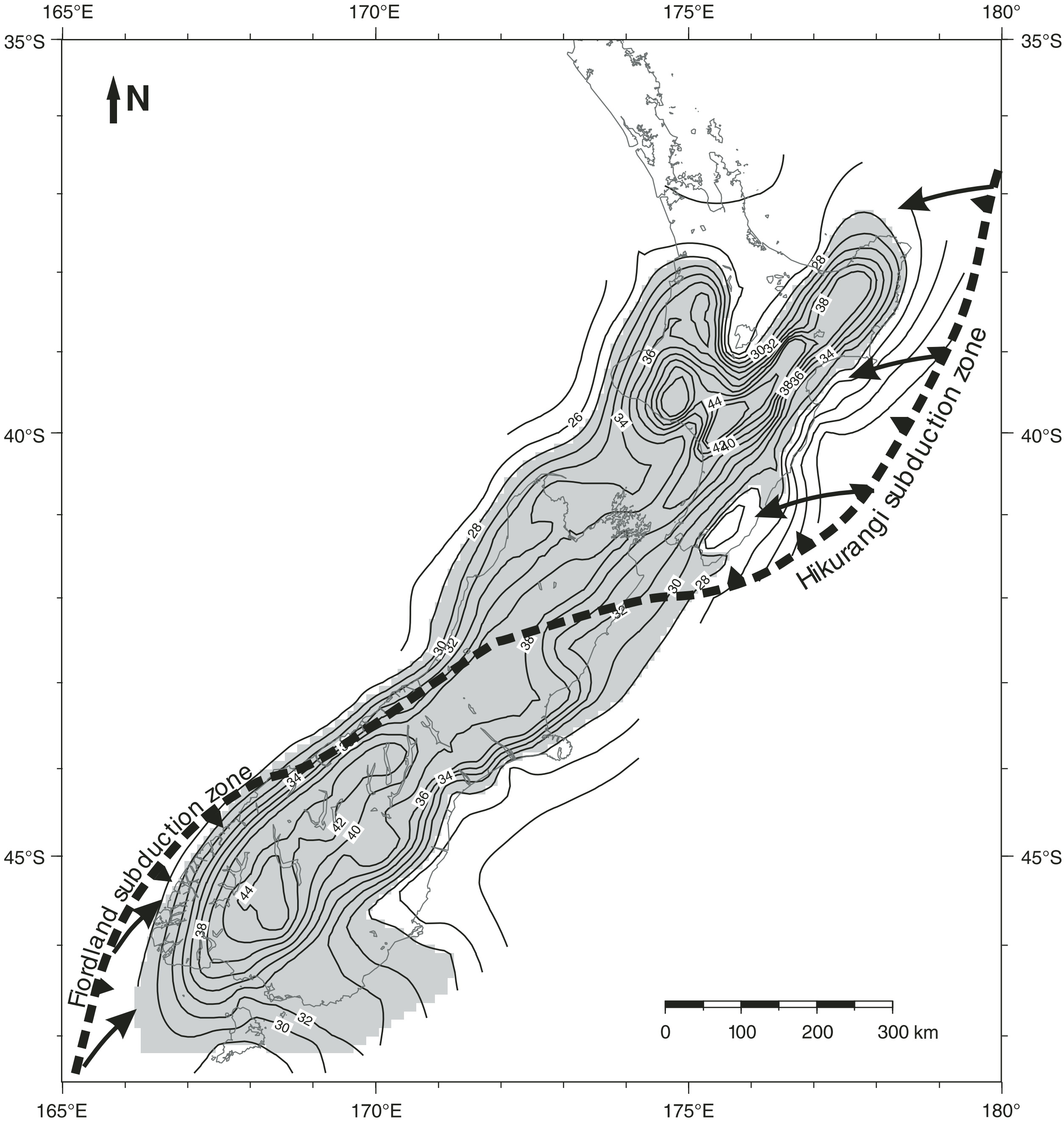


Figure 2. Map showing crustal thickness (km) beneath New Zealand inferred from seismic tomography (depth to rocks with P-wave velocity of 7.5 km/s). The area of crust thicker than 28 km is shaded gray, and dashed line indicates the present-day position of the plate boundary through New Zealand. Arrows indicate the relative plate motion.

The location of the shoreline is more critical than the elevation profile. Uncertainty of 10–20 km in the location of the shoreline, expected for this scale of mapping, leads to 20%–30% variation in land area. The assumed uncertainty in the land area for each paleogeographic reconstruction is generally ~±15%, but is larger during middle Cenozoic time, when the land area was small (<200,000 km^2).

Plate Boundary Evolution

The plate boundary through New Zealand has been the locus of deformation related to movement of the Australian and Pacific plates for the past 45 m.y. (e.g., Carter and Norris, 1976; Kamp, 1986; King, 2000a). The nature and location of deformation have changed as the boundary evolved (Figs. 4 and 5). In Figure 5, large black arrows depict the predicted motion during each time interval for two points on the Australian plate. For example, for the period 40–25 Ma the tail of the vector is located at the point's location at 40 Ma, and the head of the vector is at its location at 25 Ma.

Most modern reconstructions of New Zealand (e.g., Walcott, 1987; Holt and Stern, 1994; King, 2000a) show a configuration of the major

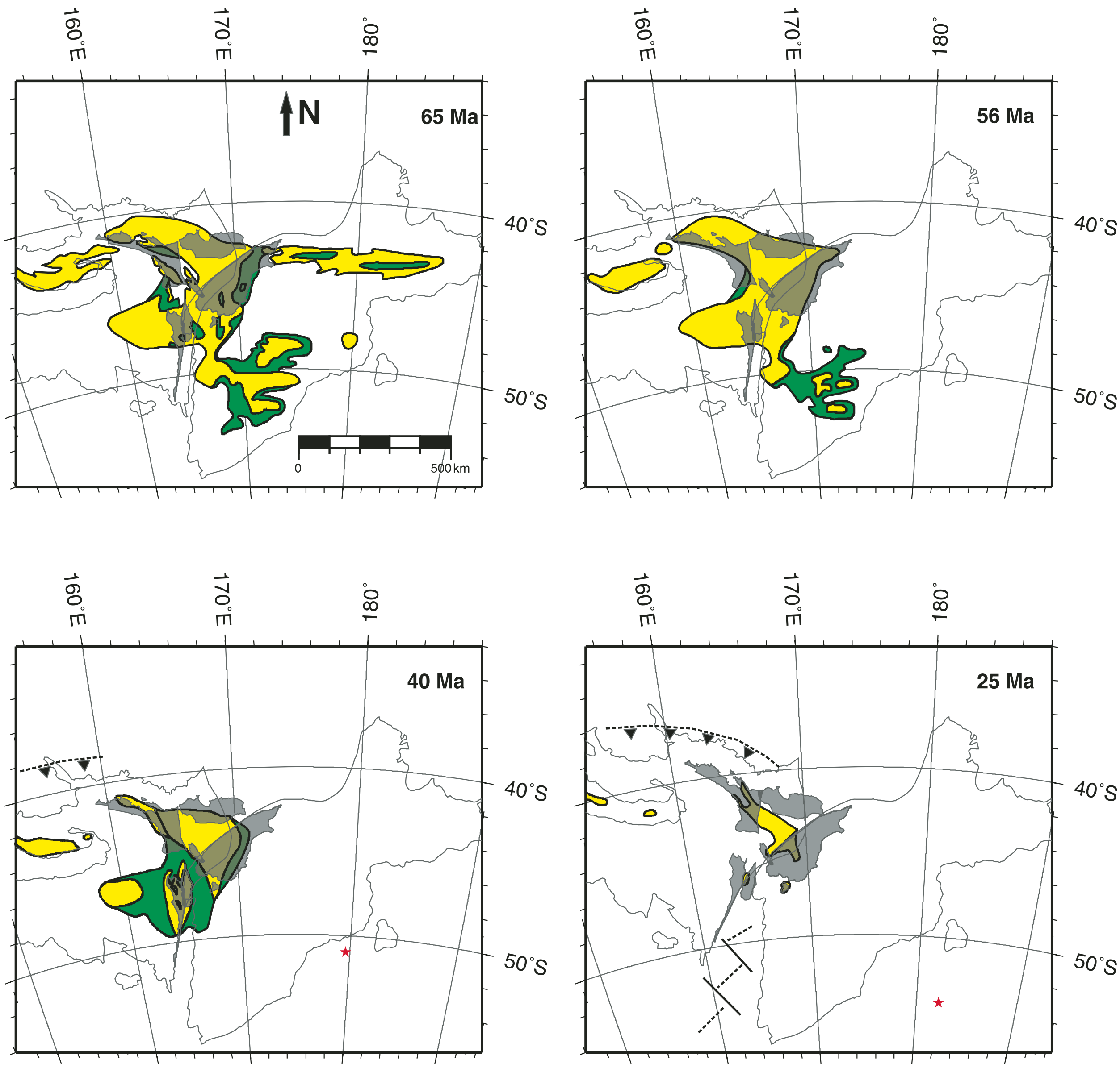


Figure 3. Paleogeography interpreted for the period 65–25 Ma (adapted from King, 2000a, 2000b). Yellow indicates areas of erosion, green indicates areas of onshore deposition, and dark gray areas are locations of major fragments of present-day New Zealand landmass. Dashed lines indicate the development of the plate margin through New Zealand. The red star indicates the location of the finite rotation pole of the Australian plate relative to the Pacific plate.

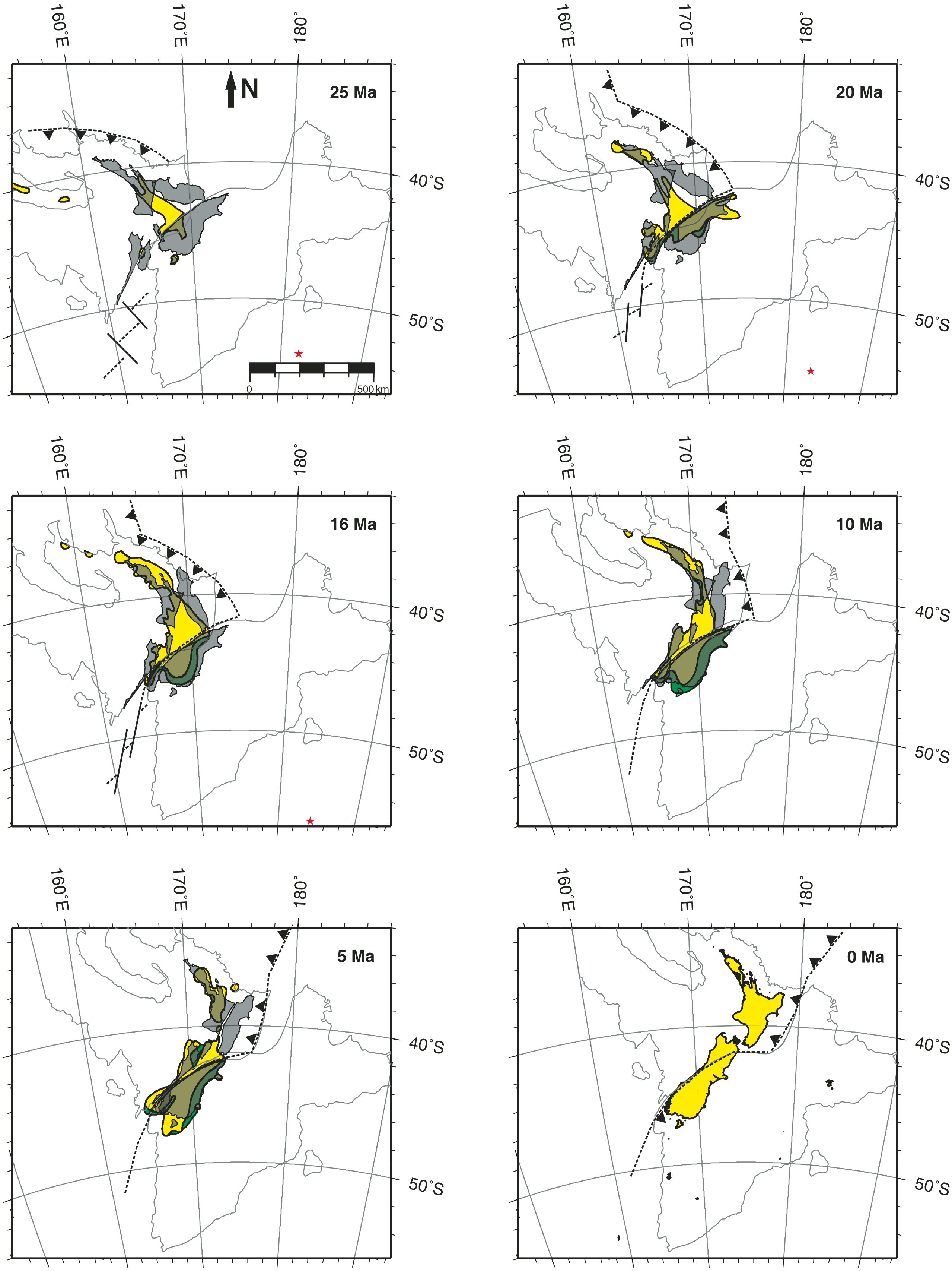
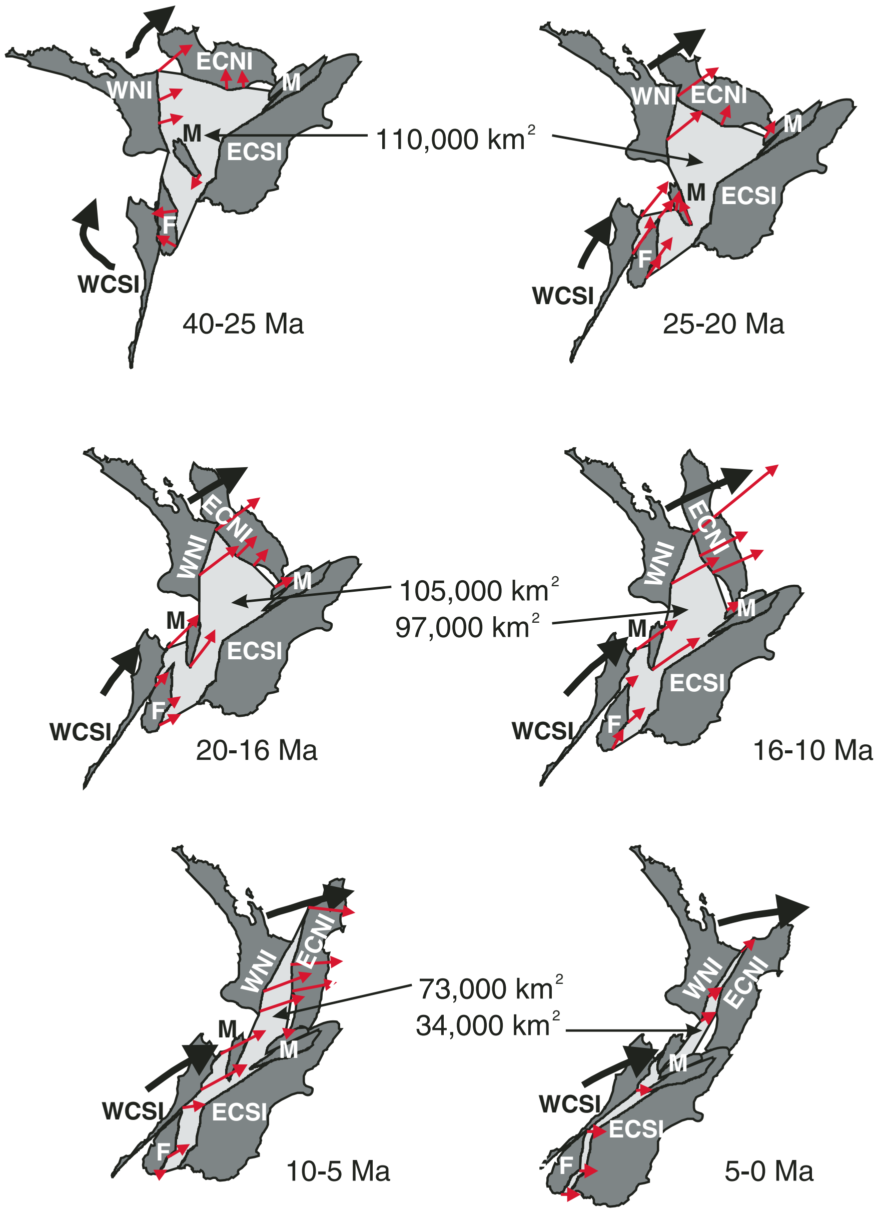


Figure 4. Paleogeography interpreted for the period 25–0 Ma (adapted from King, 2000a, 2000b). The shading, lines, and red star are as in Figure 3.



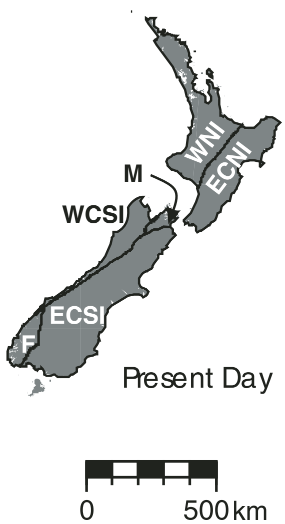


Figure 5. Tectonic reconstructions modified from King (2000b) showing the location of the major blocks at the start of each time step (WNI—western North Island, ECNI—east coast North Island, M—Marlborough, WCSI—west coast South Island, ECSI—east coast South Island, F—Fiordland). Black arrows show the predicted plate motion using rotation poles of Cande and Stock (2004) (Pacific plate is fixed) during each time interval for two points on the Australian plate. The red arrows point from the location of each block at the start of the time step to the location at the end of the period. Volume numbers refer to the central deformed region (light gray) that changes shape and reduces in size from 40 Ma.

plate fragments similar to that in the 65–40 Ma models in Figure 4. The reconstructions require a triangular-shaped central region surrounded by the rigid blocks of the eastern North and South Islands, western North and South Islands, Marlborough, and Fiordland. In our reconstructions (Fig. 5) the triangular region changes shape, reduces in size, and eventually disappears during the subsequent 40 m.y. of tectonic evolution. This transformation represents crustal material being deformed, eroded, and amalgamated within the continental crust of New Zealand. It is beyond the scope of this paper to predict the flow path of individual particles of this crustal material as it is redistributed from the central deformed region into the crustal root, topography, and sediments, but the models can be tested with field observations and the tectonic framework can be refined.

The oroclinal bending of basement terranes, the distribution of large areas of shearing, and the pattern of uplift and thickening of the crust indicate that the zone of deformation extends beyond the central deformed region and that at least some of the rigid blocks in the model have deformed internally. However, the rock volume represented in each block has been constant, and the assumption of rigid blocks does not significantly affect our conclusions.

Our model, like most modern plate reconstructions, predicts an increase in the amount of shortening across the plate margin since 16 Ma (Fig. 5). In northern New Zealand (between the east coast of the North Island and western North Island) the reconstruction shows ~160 km of shortening between 16 and 10 Ma, ~60 km between 10 and 5 Ma, and ~45 km between 5 Ma and the present. To a first order, and given the uncertainties in the data, the model agrees with observed shortening on the east coast of the North Island (17–34 km since 5 Ma; Nicol and Beaven, 2003).

South of New Zealand, the plate boundary was characterized by seafloor spreading and strike-slip motion until at least 11 Ma (e.g., Lamarche et al., 1997). Oblique subduction of oceanic crust and compression across the plate boundary were probably active by ca. 7 Ma (e.g., Davey and Smith, 1983). Our model (Fig. 5) shows considerable shortening, particularly since 16 Ma, as the blocks of western New Zealand approached eastern New Zealand. Shortening between the Fiordland block and the east coast of the South Island is predicted to be ~35 km between 16 and 10 Ma, ~50 km between 10 and 5 Ma, and ~25 km between 5 Ma and the present. The model is consistent with estimates by others of 50–100 km of convergence between the Pacific and Australian plates across the Alpine fault in the past 10 m.y. (e.g., Allis,

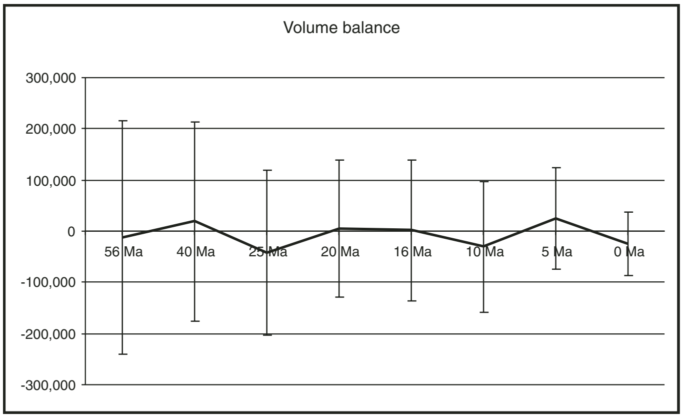
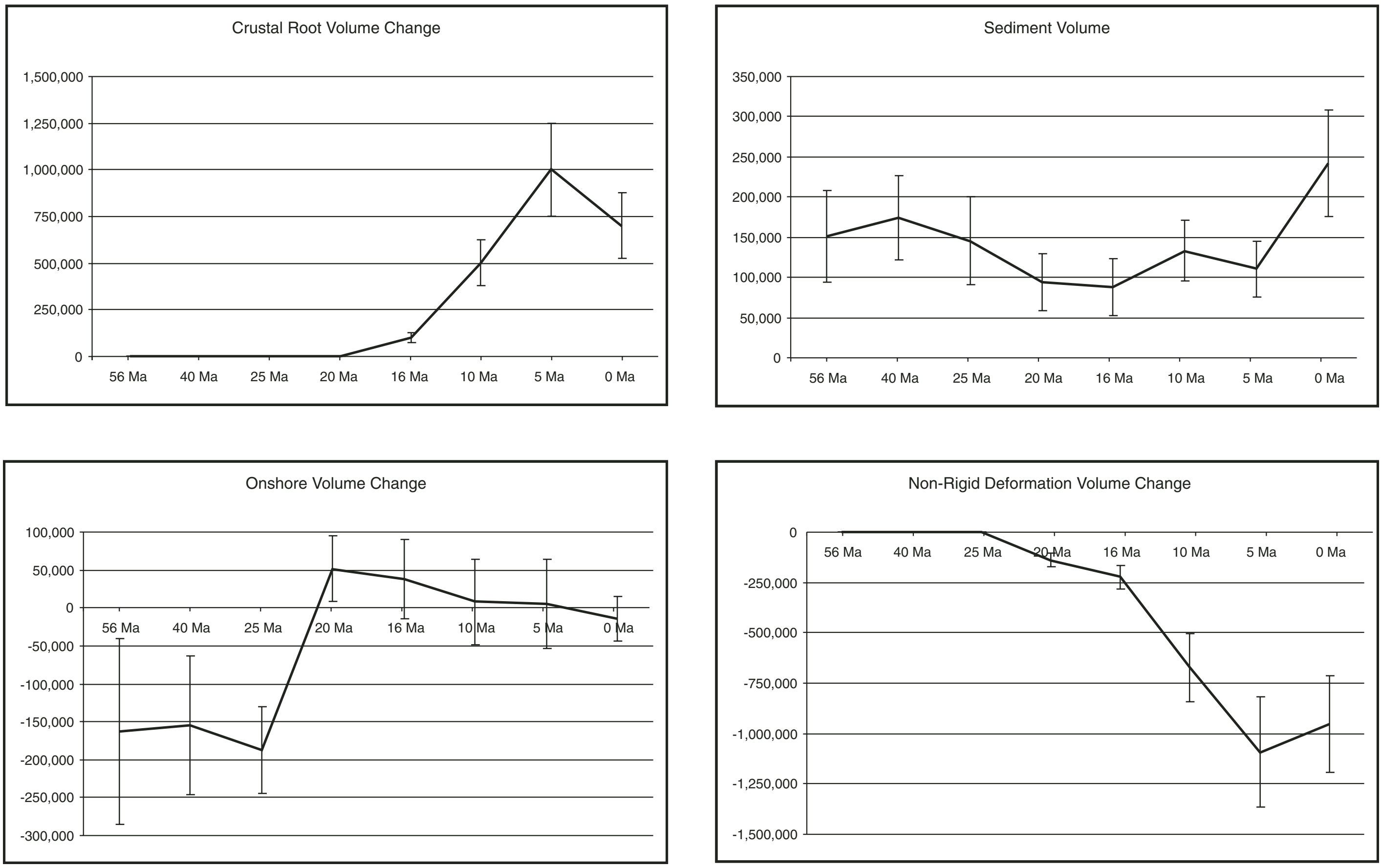


Figure 6. Top: Rock volume balance and uncertainties. Bottom: Components of the balance, i.e., the nonrigid deformation of the central deformed region (total ~3,080,000 km³), growth of the crustal root (total ~2,200,000 km³), sediment deposition (total ~1,140,000 km³), and change in land area (total ~560,000 km³). Note that values are rates of change and that the plots have different vertical scales.



1986; Norris et al., 1990; Walcott, 1998). How this convergence may have been accommodated needs to be tested by field observations.

DISCUSSION AND CONCLUSIONS

The models in this paper are a first attempt to quantify the major effects of the development of the modern plate boundary through New Zealand.

Quantification of sedimentation, crustal structure, and paleogeography for the past 65 m.y. indicates that the total volume of rock that needs to be accounted for in the New Zealand region is ~3,600,000 km³. The major components of this rock volume at 65 Ma are the triangular-shaped central region (~3,080,000 km³) and volume above sea level (~560,000 km³). The present-day components are the crustal root (~2,200,000 km³), sediment volume (~1,140,000 km³), and volume above sea level (~140,000 km³). We assume that the volume of the rigid blocks remains constant. Figure 6 shows the rate of change of these four components at each time in the models, and the total volume balance. The volume balance varies by ±50,000 km³ for each time step, <2% of the total volume of rocks considered.

The solution is not unique, and in our model the evolution of New Zealand is primarily dependent on the initial assumptions of structure and configuration of the New Zealand continental block prior to the development of the modern plate margin, and on the volume of the present-day continental root. Significant changes to either of these components would result in correspondingly large changes in the results of our analysis.

The locations of the major crustal blocks and the configuration of the deformed area at 40 Ma are based on recent plate reconstructions, iteratively modified to preserve continuity of major structural features and to balance the change in rock volume. The starting locations of the plate fragments at each time step were based on King's (2000b) reconstruction, reflecting the known configurations of the major geologic units, tectonic structures, and paleogeographic features. Relatively small translations and rotations were applied to the blocks to produce smooth changes in the volume of the central deformed region, consistent with the other factors in the mass balance, and smooth trajectories for each block relative to the Pacific plate.

The models assume simple, regular motions relative to the Pacific plate for the rigid blocks (Fig. 5). For example, the east coast of the North Island moves ~100 km northeast in the period 40–16 Ma, and then moves ~100 km east and rotates ~50° clockwise since 16 Ma relative to the western North Island. This is compatible with paleomagnetic data from the area that suggest there has been as much as ~50° rotation since ca. 20 Ma (Andy Nicol, 2005, personal commun.). The measured amount of rotation is locally quite variable, indicating that the east coast of the North Island has internally deformed and that the rigid block assumption, though correct at a regional scale (500–1000 km), is not valid on a local scale (50–100 km).

In the reconstructions (Fig. 5), Marlborough rotates slightly clockwise in the period 40–25 Ma, and then rotates ~70° clockwise and moves ~500 km northeast between 25 Ma and the present. Fiordland rotates ~20° clockwise in the period 40–25 Ma, and then moves ~200 km northeast between 25 Ma and the present. As with the east coast of the North Island, these motions are simple, first-order approximations of the block motions, but will not be applicable at a local scale where variable amounts of internal deformation have occurred (e.g., Lamb and Bibby, 1989).

Figure 6 summarizes the modeled deformation and history. New Zealand was relatively stable during the period 65–25 Ma. Sedimentation during that period was very similar to the estimated reduction in volume of the landmass. The sedimentation rate dropped from ~17,000 km^3/m.y. to ~10,000 km^3/m.y. as the land area and topography were reduced by subsidence and erosion. Initiation of the modern plate boundary at 40 Ma had little immediate effect on the first-order structures of the region. Sedimentation and erosion continued to be nearly in balance at this time, and there is no need to model changes in volume in either the central deformed region or the crustal root.

The first manifestation of the modern plate boundary in this model is an increase in onshore area and decrease in area of the central deformed region during the period 25–20 Ma. The plate motion vectors in Figure 5 show that contraction was most likely accommodated along the subduction zone northeast of New Zealand (Fig. 4), consistent with little or no growth of a crustal root. Because the onshore area change is established by the paleogeography, growth of a crustal root during this time would require greater loss of area of the central deformed region. This is possible, but would require significant changes to the motions of the rigid blocks. For example, more rapid motion of the Fiordland and/or Marlborough blocks relative to the Pacific plate would decrease the volume of the central deformed region (Fig. 5). The sedimentation rate increased during this period to ~19,000 km^3/m.y.

The tempo of change increased after 20 Ma, with the greatest volume changes during the period 10–5 Ma. During this period the crustal root grew at the rate of ~190,000 km^3/m.y. and the volume of the central deformed region decreased by ~220,000 km^3/m.y. Estimates of rates of crustal root growth and change in area of the central deformed region decline slightly for the past 5 m.y., but this is not conclusive given the uncertainties of the model. The sedimentation rate increased from ~22,000 km^3/m.y. in the period 10–5 Ma to almost 50,000 km^3/m.y. today.

The technique described in this paper offers a means to test first-order plate reconstructions through study of the interaction of the major components of the mass balance. We demonstrate that plate reconstructions of the region are compatible with our present-day knowledge of New Zealand geology, and make testable predictions about the deformation process. Improvements in knowledge of the components of the system, such as more detailed maps of sediment distribution and crustal structure, could easily be incorporated and used to refine the results.

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