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Key Points:

- Revised Cenozoic dextral displacement on New Zealand's Alpine Fault >700 km
- >94% of relative plate motion through continental lithosphere focused in a 10 km wide zone
- Rifting in Antarctica results in >225 km of Late Cretaceous sinistral motion through Zealandia

Supporting Information:

- Supporting Information S1

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Focusing of relative plate motion at a continental transform fault: Cenozoic dextral displacement >700 km on New Zealand's Alpine Fault, reversing >225 km of Late Cretaceous sinistral motion

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Abstract The widely accepted ~450 km Cenozoic dextral strike-slip displacement on New Zealand's Alpine Fault is large for continental strike-slip faults, but it is still less than 60% of the Cenozoic relative plate motion between the Australian and Pacific plates through Zealandia, with the remaining motion assumed to be taken up by rotation and displacement on other faults in a zone up to 300 km wide. We show here that the 450 km total displacement across the Alpine Fault is an artifact of assumptions about the geometry of New Zealand's basement terranes in the Eocene, and the actual Cenozoic dextral displacement across the active trace is greater than 665 km, with more than 700 km (and <785 km since 25 Ma) occurring in a narrow zone less than 10 km wide. This way, the Alpine Fault has accommodated almost all (>94%) of the relative plate motion in the last 25 Ma at an average rate in excess of 28 mm/yr. It reverses more than 225 km (and <300 km) of sinistral shear through Zealandia in the Late Cretaceous, when Zealandia lay on the margin of Gondwana, providing a direct constraint on the kinematics of extension between East and West Antarctica at this time.

1. Introduction

Zealandia straddles the boundary between the Australian and Pacific plates (Figures 1 and 2). Today, relative plate motion in the southern part of the New Zealand region is essentially parallel to the Alpine Fault (~38 mm/yr) with a small component of orthogonal convergence (<9 mm/yr), determined from GPS measurements [*Beavan et al.*, 2002]. The Holocene slip rate on the Alpine Fault is ~30 mm/yr [*Norris and Cooper*, 2001; *Barth et al.*, 2014], indicating that the fault is currently taking up ~80% of the relative plate motion. Figure 3 illustrates two models for the accommodation of the long term Cenozoic relative plate motion. The widely accepted view is that linear basement terranes were contiguous across Zealandia in the early Cenozoic, and so plate motion was taken up by a combination of dextral offset of these terranes across the Alpine Fault (~450 km) and deformation in a broad region several hundred kilometers wide; the latter occurring as distortion and clockwise sigmoidal bending about a vertical axis of the basement terranes on both sides of the Alpine Fault [*Lamb*, 2011] (Figures 1 and 3a). This way, the plate-boundary as a whole, where it passes through continental lithosphere, has been regarded as a fluid-like channel, up to 300 km wide, with a bulk power law rheology [*Molnar et al.*, 1999; *Moore et al.*, 2002; *Zietlow et al.*, 2014; *Lamb*, 2015].

In this paper, we present data that support an alternative view of Cenozoic deformation in New Zealand, in which the geometry of the curved basement terranes has remained virtually unchanged in the Cenozoic, and almost all the relative plate motion has been taken up in a narrow zone, less than 10 km wide, along the Alpine Fault (Figure 3b). This requires a large initial sinistral offset of the basement terranes in the early Cenozoic at the inception of the plate boundary through New Zealand (Figure 3b).

2. Cenozoic Plate Reconstructions

A knowledge of the Cenozoic relative plate motions between the Australian and Pacific plates is crucial for understanding deformation in New Zealand. Since the Late Oligocene (~25 Ma) there has been no sea floor spreading directly between the Australian and Pacific plates, and so relative plate motions are calculated from

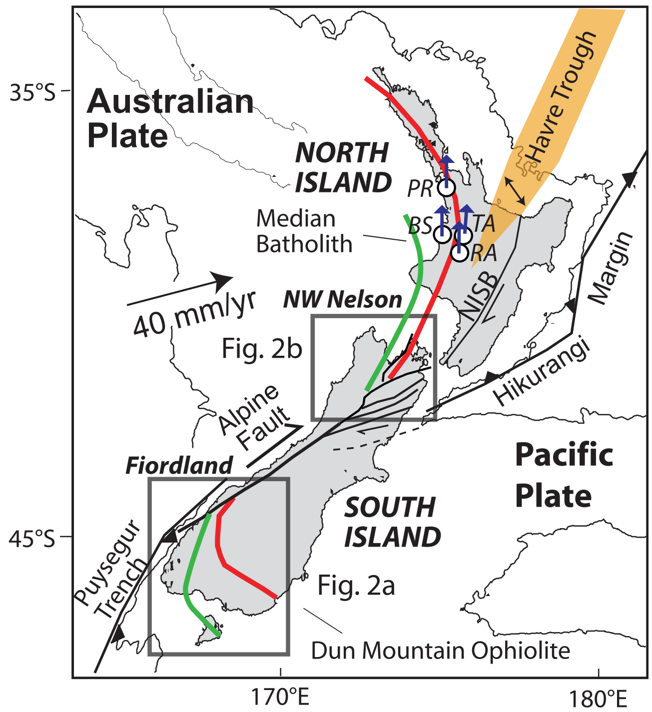

Figure 1. General location and tectonic setting of the plate-boundary between the Australian and Pacific plates through North and South Islands of New Zealand. Pacific Plate is being subducted beneath North Island along the Hikurangi Margin, and Australian Plate is being subducted beneath Fiordland in the Puysegur Trench. This two subduction zones are linked by a transform zone through continental lithosphere, with >75% motion taken up on the Alpine Fault. Also shown are the trends of prominent basement terranes; red line = Dun Mt-Maitai Terrane, green line = Median Batholith (Darran Igneous suite). Note the ~90° swing in the trend of both these terranes toward the Alpine Fault. Boxes show location of geological maps in Figures 2a (Fiordland) and 2b (NW Nelson) of matching basement units and Cenozoic cover sequences in southern and northern South Island. Black circles show paleomagnetic localities (see Table 1) in Eocene to Early Miocene cover sequences in western North Island, indicating negligible vertical axis rotation with respect to the Australian Plate (blue arrows show mean rotation anomaly).

global plate circuits [*Cande and Stock*, 2004a, 2004b]. These are well constrained from sea floor magnetic anomalies between the Australian, Pacific and Antarctic Plates, but prior to this, there was also motion between East and West Antarctica [*Cande and Stock*, 2004a, 2004b, *Granot et al.*, 2013].

The recognition of Paleogene oceanic crust between the Australian and Pacific plates to the south of New Zealand, in the Emerald Basin, together with distinctive segments of the complementary rift margins, magnetic anomalies and fracture zones, tightly constrains the full finite Cenozoic reconstruction [*Sutherland*, 1995; *Keller*, 2004; *Barker et al.*, 2008]. This finite reconstruction is certainly younger than the youngest oceanic crust in the Tasman sea (~52 Ma) [*Cande and Stock*, 2004b], because the initial rift margin in the New Zealand region (Resolution Ridge) cuts across this oceanic fabric. Most workers use a nominal age of ~45 Ma, consistent with magnetic anomaly data [*Sutherland*, 1995; *Keller*, 2004; *Barker et al.*, 2008], and also coincident with the onset of rift tectonics in the New Zealand region itself [*King*, 2000].

Three estimates of the 45 Ma plate reconstruction [*Sutherland*, 1995; *Keller*, 2004; *Barker et al.*, 2008] are identical within error with a finite Euler pole to the south of New Zealand (178°E, −49.7°N). These show that the northwestern part of South Island (NW Nelson) lay to the south of South Island (Figure 4b), with a ~48° anticlockwise rotation of the Australian plate with respect to the Pacific Plate. This way, the western edge of East Zealandia (Campbell Plateau) was juxtaposed with the continental lithosphere that is northwest of the Alpine Fault today (Figure 4b).

The Alpine Fault itself is widely regarded to have been active since *at least* the latest Oligocene [*Carter and Norris*, 1976; *King*, 2000]. At this time (~25 Ma) sea floor magnetic anomalies show that relative plate motion became mainly transcurrent after an earlier rift phase, coinciding with a marked change in the Pacific-Antarctic plate motion (Figure 4c) [*Sutherland*, 1995; *Cande and Stock*, 2004a, 2004b; *Croon et al.*, 2008]. The stress field suggested by the intrusion of a widespread lamprophyre dyke swarm at 20–25 Ma is also consistent with predominantly strike-slip motion at this time (Figure 2a) [*Cooper et al.*, 1987]. The total dextral relative plate motion parallel to the Alpine Fault since 25 Ma is 770 ± 15 km (Figure 4c) [*Cande and Stock*, 2004a, 2004b; *Lamb et al.*, 2015].

3. New Zealand Basement Terranes

The Paleozoic to Mesozoic geological evolution of the New Zealand involved the progressive accretion of terrains along the subducting margin of Gondwana [*Mortimer*, 2014]. Today, these terrains form linear belts, up to a few tens of km wide, that extend for 100s to >1000 km through Zealandia, although bent and dextrally offset in onshore New Zealand (Figures 1 and 2) [*Mortimer*, 2014].

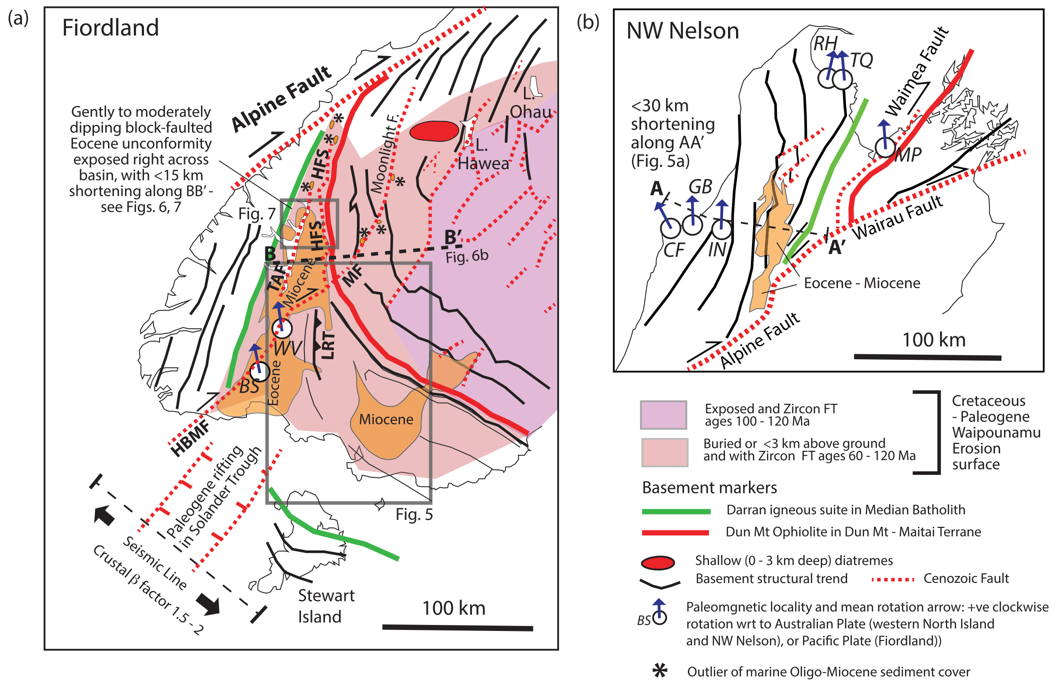

Figure 2. Maps showing matching basement terranes on either side of the Alpine Fault. Black circles show paleomagnetic localities (see Table 1) in Eocene to mid Miocene cover sequences, indicating negligible vertical axis rotation with respect to the Australian or Pacific Plate (blue arrows show mean rotation anomaly). (a) Detailed map of basement trends in Fiordland, in southern South Island (see box in Figure 1). See Figures 5–7 for detailed cross sections and geological maps. Also note unconformably overlying Marine to terrestrial Eocene-Miocene cover sequences, mainly in the Te Anau and Waiau basins of Fiordland, and the Late Cretaceous-Paleogene Waipounamu Erosion Surface. Note also the location of shallow diatremes [*Cooper et al*., 1987; *Craw*, 1995], and mainly marine Eocene-Oligocene outliers. The following faults are discussed in this study: HFS = Hollyford Fault System, HBMF = Hauroko-Blackmount-Moonlight Fault Zone, MF = Moonlight Fault, TAF = Te Anau Fault, LRT = Letham Ridge Thrust. Paleogene rifting in the Solander Trough has resulted in <35 km of extension, which decreases to the north, accommodating <10° of total post-Eocene clockwise rotation about a vertical axis of the Median Batholith in Fiordland relative to the Pacific Plate. (b) Map showing Median Batholith and Dun Mt Ophiolite in NW Nelson (see box in Figure 1), to the NW of the Alpine Fault, where they trend NE to NNE. There has been ~30 km shortening with respect to Australian plate along line AA' [*Ghisetti and Sibson*, 2006] (Figure 6a).

3.1. Median Batholith and Dun Mountain—Maitai Terranes

The Dun Mountain-Maitai Terrane (including the Dun Mountain Ophiolite Belt) forms a belt of Permian upturned oceanic crust and mantle [*Turnbull*, 2000], and where not exposed is defined by the prominent Stokes magnetic anomaly. The Median Batholith is a terrane consisting of subduction-related mafic to granitic plutons of mainly Late Jurassic to Mid Cretaceous age, which have a strong internal structural grain, defined by elongate intrusive units [*Allibone et al*., 2009; *Turnbull et al*., 2010]. These terranes are clearly identifiable on both sides of the Alpine Fault (Figures 1 and 2). In addition, again on both sides of the Alpine Fault, the structural separation between them decreases from ~100 km to ~20 km as the fault is approached, so that the offset across the Alpine Fault of the Median Batholith is similar (±20 km) to that for the Dun Mountain-Maitai Terrane (Figure 1).

In southern South Island (Stewart Island and Fiordland), the Median Batholith can be traced as an essentially continuous unit with a ~90° bend (Figure 2a). Here almost all the internal faulting predates the intrusive contacts of the younger (Early to Mid Cretaceous granites) unfoliated members of the suite [*Allibone et al*., 2009], and younger offsets are generally less than a few kilometres. In Fiordland, it has behaved as a more-or-less rigid but tilted block (Figure 2a) [*Turnbull*, 2000; *Turnbull et al*., 2010]. Profiles of zircon fission track ages across the Median Batholith show progressively younger ages toward the NW, in a direction more-or-less orthogonal to the structural trend, ranging from ~90 Ma to <25 Ma [*Sutherland et al*., 2009] and indicating Cenozoic block tilting of 6–10°, tilted to the SE. Cenozoic internal distortion, particularly involving elongations parallel to the trend of the batholith is small to negligible, involving elongations <1.1 (Figure 2a) [*Rattenbury et al*., 1998; *Turnbull et al*., 2010].

Fiordland forms a contiguous part of the New Zealand orocline (Figure 2a) [*Turnbull et al*., 2010; *Mortimer*, 2014], and cannot be treated as an allochthonous block that was displaced 100s kilometres, as was often

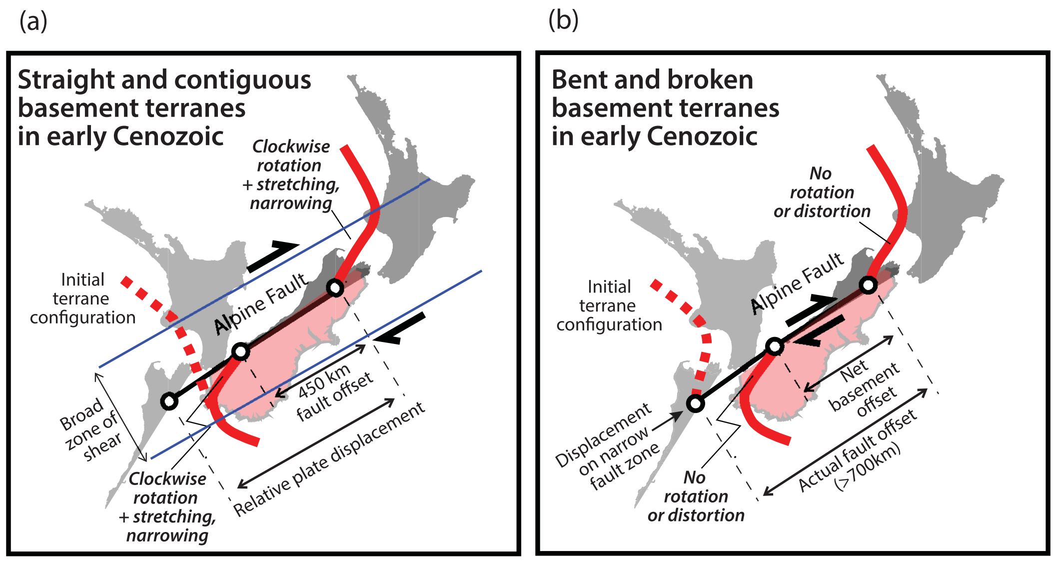

Figure 3. Generalized maps of New Zealand region showing two models for accommodation of Cenozoic relative plate displacement. (a) The generally accepted view is that basement terranes (thick or dashed red lines) through New Zealand formed nearly straight and contiguous belts in the early Cenozoic, and were subsequently offset ~450 km across the Alpine Fault, and rotated clockwise relative to either the Australian or Pacific Plates in a broad zone of dextral shear. This model requires evidence for large-scale tectonic rotation up to ~90° clockwise, and many tens of kilometers of shortening and strike-slip between the terranes, as well as substantial stretching along their length. (b) If the basement terranes acquired their geometry before Alpine Fault movement, then they did not undergo subsequent tectonic rotation, shortening or stretching, and the observed offset across the fault is a net displacement, with a much larger actual displacement in a narrow fault zone determined by the relative plate motion. In this case, the terranes in the early Cenozoic were sinistrally displaced across the Alpine Fault.

assumed in earlier plate reconstructions in which there has been tens to hundreds of kilometres of total strike-slip displacement on the Te Anau, Hollyford and Hauroko-Blackmount-Moonlight Faults (Figure 2a) [*King*, 2000]. If the two sides of the New Zealand region are fitted back to the ~45 Ma reconstruction (Figure 4b), then the basement terranes can only have been contiguous across the plate-boundary at this time if they have subsequently rotated ~90° clockwise about a vertical axis. In fact, plate reconstructions require

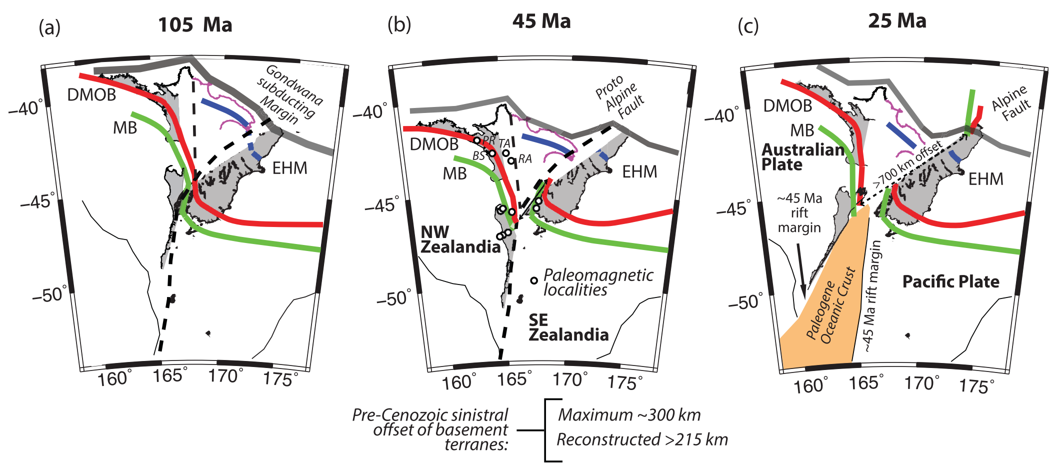

Figure 4. Reconstructions of New Zealand (Zealandia) basement markers (a) in the early Late Cretaceous (~105 Ma), (b) at the inception of the plate-boundary in the Eocene (~45 Ma, note paleomagnetic localities for constraining tectonic rotations (see text)), and (c) at the initiation of dextral motion on the Alpine Fault (~25 Ma) when relative plate motion became predominantly dextral shear parallel to the fault–– note oceanic crust created during Paleogene sea floor spreading between the Australian and Pacific Plates, and remnant ~45 Ma rift margins. The identification of essentially undeformed basement markers in the Median Batholith (MB, thick green line), in both Fiordland region (southern South Island) and NW Nelson (northwestern South Island), creates a "space" problem if they were contiguous at ~45 Ma. Instead, they are inferred to have had >215 km sinistral offset at this time, as a result of sinistral shear prior to this between NW and SE Zealandia. The same displacement history applies to the Dun Mt Ophiolite in the Dun Mt-Maitai Terrane (DMOB, red line), and possibly Esk Head Melange (EHM, blue line). Thus, the total displacement in a narrow fault zone <10 km wide along the Alpine Fault, since ~25 Ma, taking account of the maximum plausible bending of the basement terranes (see text) is >700 km.

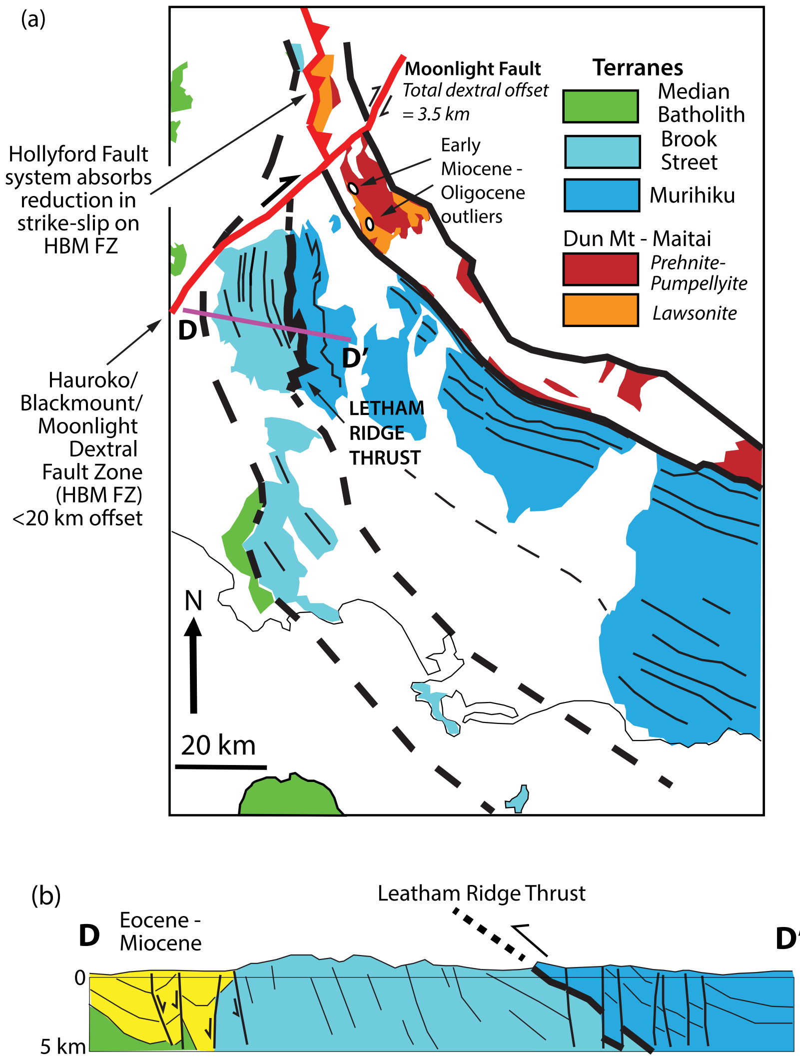

Figure 5. (a) Geological map of southern South Island showing outcrop of basement terranes (Dun Mountain-Maitai, Murihiku, Brook Street, Median Batholith [*Turnbull and Allibone*, 2003]). See box in Figure 2a for location. White areas are regions of outcrop of Eocene–– Recent cover sequences. The structural trend of the basement terranes curves round from ~WNW-ESE trend in the east to N-S farther west. This curvature in the Brook Street terrane must be a pre-Eocene feature, because it is associated with pinching out of the Murihiku terrane toward the west along the Letham Ridge Thrust, which is unconformably overlain by Eocene cover sequences. Eocene and Oligocene cover sequences to the east and south of the Letham Ridge Thrust dip at low angles, and deformation consists of relatively minor normal faulting. Note the relatively minor dextral strike-slip offset (<5 km) of the Dun Mountain-Maitai terrane by the Moonlight Fault segment of the Hauroko-Blackmount-Moonlight Fault system (HBM Fz). The inferred dextral strike-slip on the HBM Fz farther to the southwest is <20 km, requiring most of this slip to be transferred to the Hollyford Fault system. Also note the abrupt change from Prehnite-Pumpellyite facies metamorphism to Lawsonite in the Dun Mt-Maitai terrane, unconformably overlain by unmetamorphosed Early Miocene to Oligocene sediments [*Landis*, 1974; *Turnbull*, 2000]. (b) Cross-section through the Brook Street and Murihiku terranes across the Letham Ridge Thrust, along line DD' in Figure 5a. Note the low angle nature of the thrust, with a displacement ≫10 km.

virtually all the clockwise vertical axis rotation to have occurred in the last 25 Ma, given the relative position of the basement terranes on the Australian and Pacific plates at this time (Figure 4c) [*Cande and Stock*, 2004a; *Lamb et al.*, 2015]. This reconstruction (Figure 4c) also requires the terranes to have been stretched along their length by a factor of 2–4. Thus, there is a "space" problem, because the geological observations show that strain on this scale did not occur during the Cenozoic [*Allibone et al.*, 2009; *Turnbull et al.*, 2010].

3.2. Mesozoic Basement Curvature in Southern South Island

Between the Median Batholith and Dun Mountain-Maitai terranes are two other basement terranes called the Brook Street and Murihiku terranes which mainly consist of Permian to Jurassic marine and marginal marine sedimentary together with volcanic and intrusive units (Figure 5).

Table 1. Palaeomagnetic Vertical Axis Rotation Data for Sites in Western North Island, NW Nelson and Fiordland, New Zealand, Listed by Latitude (See Figures 1, 2 and 4 for locations)

Locality[a]	Age Ma	Lat. N (°)	Long. E (°)	Pol[b]	N ep/gc[c]	D_o[d] (°)	I_o[d] (°)	α_{95}[d] (°)	D_x[e] (°)	I_x[e] (°)	R[f] (°)	Ref[g]
Western North Island												
Ponganui Road (PR)				N	14/0	29	−59	4				
	∼35	−37.39	174.82									1
				All	14	29	−59	4	30	−65	−1 ± 7	
Bexley Station (BS)												
	∼35	−38.65	174.73	R	9/20	211	67	5				1, 4
		−38.65	174.73	All	29	31	−67	5	31	−66	−1 ± 11	
Taumaranui (TA)												
	∼25	−38.94	175.18	R	6/23	209	52	5				1,4
				All	29	29	−52	5	25	−65	4 ± 9	
Raurimu (RA)												
	∼20	−39.11	175.38	R	6/28	204	52	2				1,4
				All	34	24	−52	2	22	−65	2 ± 4	
North West Nelson, South Island												
Rangihaeata Head (RH)				N	7/0	45	−70	8				
	∼35	−40.81	172.8									2
				All	7	45	−70	8	32	−68	13 ± 22	
Tarakohe Quarry (TQ)	17.5 ±1			N	55/0	15	−64	3				
		−40.83	175.9	R	65/0	196	61	2				2
				All	120	15	−63	2	20	−66	−5 ± 4	
Magazine Point (MP)												
	∼30	−41.27	173.26	R	9/22	205	69					1, 2
		−41.28	173.25	All	31	25	−69	4	29	−68	−4 ± 11	
Cape Foulwind (CF)				N	4/0	352	−48	14				
	∼10	−41.75	171.5	R	1/6	145	64	25				2
				All	11	345	−57	14	13	−66	−28 ± 26	
Gibson's Beach (GB)												
	∼34	−41.75	171.48	R	59/0	210	49	7				2
				All	59	30	−49	7	32	69	−2 ± 10	
Inangahua (IN)	36 ±1			N	10/0	38	−65	5				
		−41.84	171.93	R	10/0	211	60	3				1, 2
				All	20	34	−63	3	32	−69	2 ± 6	
Fiordland, South Island												
Waiau Valley (WV)	12 ±2											
		−45.72	167.67	R	4/7	169	64	6				1,4
				All	11	349	−64	6	355	−67	−6 ± 10	
Bryce Burn (BB)	15 ±1			N	80	345	−57	3				
		−45.95	167.57	R	64	165	55	6				3
				All	144	345	−56	4	355	−67	−10 ± 8	

[a]Palaeomagnetic sample locality with two letter code in brackets––see Figures 1, 2 and 4 for locations for locations.
[b]Magnetic polarity (N = normal, R = reversed).
[c]Number of specimens (ep = end point directions, gc = great circles or remagnetization planes [*McFadden and McElhinny*, 1988]).
[d]Mean declination and inclination, and radius of 95% cone of confidence (a95) after tilt correction.
[e]Expected declination and inclination for Australian Plate (all localities except BB and WV) or Pacific Plate (BB and WV localities) [*Veevers and Li*, 1991; *Beaman et al.*, 2007].
[f]Vertical axis rotation anomaly (+ve clockwise) and 95% uncertainty with respect to Australian or Pacific Plate (see notes e and g)
[g]References (1 = *Mumme and Walcott* [1985]; 2 = *Turner et al.* [2007, 2012]; 3 = *Ohneiser et al.* [2008]; 4 = data reanalyzed in this study).

At least 60° of the curvature in the Brook Street terrane, where it swings round from an approximately WNW to N-trend (in the Takitimu Mountains), must be a pre-Eocene feature, because it is associated with pinching out of the Murihiku terrane toward the west along the Letham Ridge Thrust (Figures 2a, 5a, 5b, and 8) [*Turnbull and Allibone*, 2003]—the main movement on the Letham Ridge Thrust is thought to have initiated in the Late Jurassic to Early Cretaceous, although minor movement occurred in the Late Cretaceous, resulting in local overriding of Late Cretaceous marginal marine sediments (Ohai Group) that rest unconformably on both Brook Street and Murihiku terrane rocks [*Landis et al.*, 1999]. Laterally continuous Eocene and Oligocene cover sequences to the east and south of the outcrop of the Letham Ridge Thrust dip at low angles, again resting unconformably on both Brook Street and Murihiku Terrane units, indicating that movement on the thrust had ceased by this time. Cenozoic deformation here consists of relatively minor normal faulting, and could not accommodate significant bending of the basement terranes. This is supported by the palaeomagnetic data (see section 4) from more intensely deformed middle Miocene sequences on the west and southwest margins of the north trending block of Brook Street terrane, which show negligible, or very small anticlockwise (<10°) rotation, relative to the Pacific Plate (Table 1 and Figure 2a).

The pre-Eocene curvature of the terranes is also associated with an abrupt east to west change from Prehnite-Pumpellyite metamorphic facies in the Dun Mt-Maitai terrane to Lawsonite bearing rocks farther west, unconformably overlain by unmetamorphosed Early Miocene to Oligocene sedimentary outliers (Figure 5a) [*Landis*, 1974; *Turnbull*, 2000; *Turnbull and Allibone*, 2003], suggesting that the Letham Ridge Thrust extended roughly due north, forming the western boundary of the Dun Mt-Maitai terrane and accommodating Mesozoic exhumation of this terrane. Further evidence that terranes in southern South Island, where they trend ~N-S today, had a similar configuration in the Mesozoic is indicated by the N to NNE trend of steeply dipping schist units in the Rakaia terrane much farther east, outcropping around Lakes Hawea and Ohau (Figure 2a). This is in the vicinity of where the regional Late Cretaceous-Paleogene Waipounamu Erosion Surface is well preserved, and zircon fission track ages in basement rocks are >80 Ma, indicating that Cenozoic erosion and fault displacements, together with associated bending of the terranes, must be relatively small (Figure 2a) [*Tippett and Kamp*, 1993; E. Warren-Smith, personal communication, 2016).

4. Palaeomagnetic Data

We have reanalyzed available paleomagnetic data from Eocene (~36 Ma) to mid Miocene (~12 Ma) sedimentary cover sequences that unconformably overly the basement terranes, using a combined analysis of end point vectors and remagnetization planes to obtain the best estimate of the direction of primary magnetization at each site (Table 1) [*McFadden and McElhinny*, 1988; *Mumme and Walcott*, 1985; *Ohneiser et al.*, 2008; *Turner et al.*, 2007, 2012]. As a further test of primary magnetization, almost all sites showed reversed magnetic polarities, with close to expected inclinations (taking account of compaction induced inclination flattening in fine grained sediments), given the age and site location, after correcting for the tilt of the beds (Table 1) [*Veevers and Li*, 1991; *Beaman et al.*, 2007]. See supporting information Figure S1 for stereoplots of tilt corrected primary magnetizations reanalyzed in this study.

Ten localities in the western North Island and NW Nelson, spanning the curvature of basement terranes, all show negligible tectonic rotation with respect to the Australian Plate (Figures 1 and 2b, and 4b; Table 1 and supporting information Figure S1) [*Mumme and Walcott*, 1985; *Turner et al.*, 2012]. In Fiordland, a large-scale magneto-stratigraphic study of a 14–16 Ma and ~650 m thick sedimentary sequence indicates a small *anticlockwise* rotation ($-10° \pm 8°$) relative to the Pacific plate (site BB in Figure 2a, Table 1) [*Ohneiser et al.*, 2008]. About 30 km farther north, ~12 Ma mudstones give a compatible result ($-6 \pm 10°$, site WV in Figure 2a, Table 1 supporting information Figure S1) [*Mumme and Walcott*, 1985; this study].

These data effectively rule out significant clockwise tectonic rotation of the Median Batholith and Dun Mountain-Maitai Terrane on the northwestern side of the Alpine Fault, in NW Nelson, since the inception of the Cenozoic plate boundary (Figures 2b and 4b). In southern Fiordland, the paleomagnetic data show that any clockwise tectonic rotation must be older than ~15 Ma, and the intense local shortening here since ~15 Ma, particularly in the region adjacent to the Hauroko-Blackmount-Moonlight Faults (Figure 2a, see section 5.1), has not accommodated this rotation.

5. Cenozoic Deformation

Another way to constrain the amount of Cenozoic rotation of the underlying basement terranes is to quantify horizontal shortening and shear in the Eocene to Miocene cover sequences, in the context of kinematic models of rotation. The regional Cenozoic evolution of the New Zealand plate boundary involved rifting in the Paleogene, associated with sea floor spreading in the Emerald basin to the south of New Zealand, with development of thick normal-fault bounded sedimentary basins in what is today NW Nelson and Fiordland (Figure 2) [*Norris et al.*, 1978; *Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993; *Sutherland*, 1995]. In the latest Oligocene, the plate boundary in southern South Island became mainly dextral strike-slip, with an increasing component of compression toward the present [*Norris et al.*, 1978; *Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993; *Sutherland*, 1995; *Cande and Stock*, 2004a; *Lamb et al.*, 2015].

Given that the palaeomagnetic data (section 4) rule out significant Cenozoic clockwise rotation of the basement terranes to the NW of the Alpine Fault, in NW Nelson, the focus of the following analysis is southern

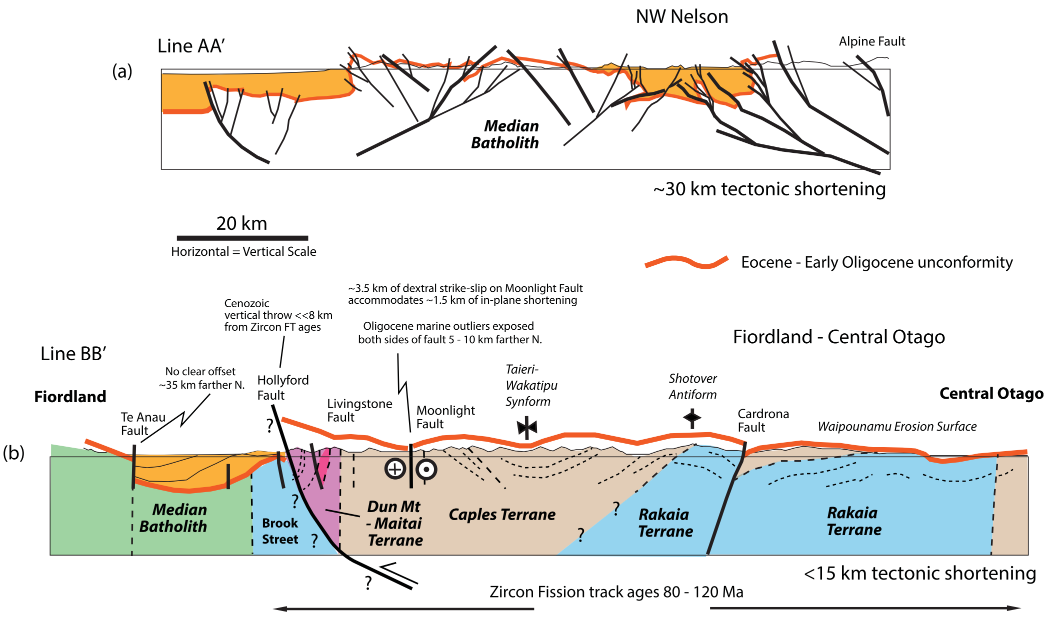

Figure 6. Cross sections through (a) NW Nelson (line AA', taken from *Ghisetti and Sibson* [2006]) and (b) Fiordland-Central Otago (line BB' based on *Turnbull* [2000])––note the inferred displacement on the Hollyford Fault system, which juxtaposes Dun Mountain-Maitai terrane with Brook Street terrane. See Figures 2a and 2b for lines of cross sections. The Eocene-Early Oligocene unconformity between basement and overlying mainly marine Eocene-Miocene cover sequences can be traced right across the regions, forming a clear structural marker. Typical spacing of major Cenozoic faults is 10–20 km. Total shortening along line AA' in NW Nelson is $\sim$30 km, and $<$15 km along line BB' in Fiordland-southern South Island, with $<$10 km shortening along BB' between the basement markers in Median Batholith and Dun Mt-Maitai terranes.

South Island, to the SE of the Alpine Fault. This is where virtually all the Cenozoic rotation and distortion of the basement terranes, amounting to $\sim$300 km of dextral shear (see below), would need to have occurred *if* the terranes where originally contiguous across the Alpine Fault in the Eocene, at the time of the initiation of the plate-boundary through Zealandia. We show that the observed Cenozoic deformation falls far short of that required to accommodate this dextral shear.

5.1. Cenozoic Strike Slip and Thrusting in Fiordland

The Hauroko-Blackmount-Moonlight Fault system is the most important zone of Cenozoic faulting in central and southern Fiordland (Figure 2a) [*Norris et al*., 1978]. It separates the Cenozoic sequences into two distinct basins, referred to as the Te Anau (in the vicinity of Lake Te Anau) and Waiau (farther south) basins, and individual formations do not appear to be continuous between the basins, with distinct source areas [*Norris et al*., 1978; *Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993; *Zink*, 2000; *Zink and Norris*, 2004]—it possible that the Hauroko-Blackmount-Moonlight Fault system follows a Mesozoic basement structure, reactivated during Early Cenozoic rifting with a large vertical throw $>$5 km [*Norris and Turnbull*, 1993; *Zink*, 2000]. However, the principal Neogene deformation is dextral-strike slip, with a component of shortening, although the displacement is poorly determined; provenance studies of Eocene to Oligocene sediments have been used to suggest a dextral displacement $\sim$20 km [*Norris et al*., 1978; *Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993]. In fact, this must be an upper limit, unless there was an original sinistral offset of basement markers in the Median Batholith (Figure 2a). At the northeastern end of the fault zone, along the Moonlight Fault segment, the Dun Mountain-Maitai terrane is offset dextrally $<$5 km, indicating that a larger displacement farther to the southwest must be absorbed by shortening in the Waiau and Te Anau basins (Figure 5) [*Norris et al*., 1978; *Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993].

Along the eastern margin of the Te Anau Basin (Figure 2a), Cenozoic sediments as young as $\sim$10 Ma, and in a zone up to 5 km wide, locally have a subvertical dip, thrust over by the adjacent Dun Mountain-Maitai terrane. At the northern end of Lake Te Anau, the basal Eocene unconformity, together with three formations of the overlying Eocene Annick Group (Figure 7a), can be traced more-or-less continuously across the region, dipping at moderate to low angles above the steeply dipping units of the Median Batholith in the west and the Brook Street terrane in the east (see line BB' in Figures 2a and 6b, line CC' in Figure 7)

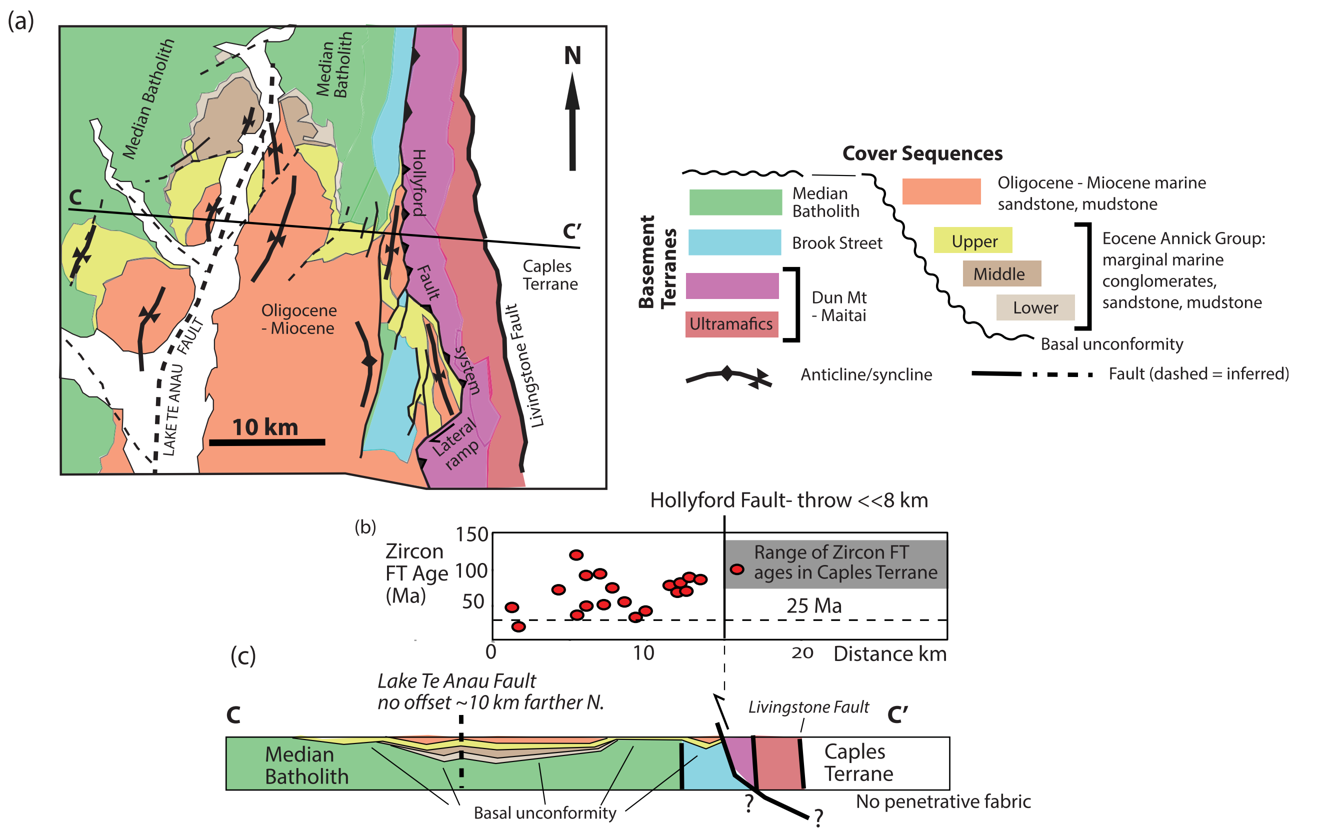

Figure 7. (a) Detailed map of marine to marginal marine Eocene and Oligocene cover sequences (based on *Turnbull* [2000]), which unconformably overly basement terranes around Lake Te Anau in Fiordland (see Figure 2a for map location). Note that Te Anau Fault, which has been thought to structurally separate Fiordland from the rest of South Island, has essentially no offset at the northern end where there is lateral continuity across the region of individual formations in the Eocene Annick Group and Oligocene-Miocene sequences. Thus, the only major Cenozoic structural break here must be the contact between the Brook Street and Dun Mountain-Maitai terranes, along the Hollyford Fault system. Note the presence of a lateral ramp on the Hollyford Fault system, constraining displacement to have a dextral oblique component. (b and c) Summary cross-section along line CC′ in Figure 7a, showing variation in zircon fission track ages across northern Fiordland, plotted as a swath for the transects extending north of line CC′ (data from *Sutherland et al.* [2009]). The relative low grade and shallow depth of Cenozoic erosion of the Dun Mountain-Maitai Terrane, in the hanging wall of the Hollyford Fault system, combined with continuity of Cenozoic cover sequences in the footwall, constrain total horizontal post-Eocene motion between the Median Batholith and Dun Mt-Maitai terranes to <10 km of both strike-slip and horizontal shortening.

[*Turnbull*, 2000; *Zink*, 2000; *Zink and Norris*, 2004; *Turnbull et al.*, 2010]; gentle to moderately dipping unconformable outliers can be found all the way north to the Alpine Fault itself (Figure 2a) [*Turnbull*, 2000].

These relations constrain the major Cenozoic structural break through this part of Fiordland to be a steeply east-dipping thrust contact (which we refer to as the Hollyford Fault system) juxtaposing steeply dipping Brook Street terrane, and its much more shallowly dipping Eocene and younger unconformable cover, with the steeply dipping western margin of the Dun Mountain-Maitai terrane (Figures 2a, 5a, 6b, and 7). In addition, the continuity of the Eocene cover sequences indicates that Cenozoic strike-slip displacement here, between the Median Batholith and Brook Street terrane, must be small ($\ll$10 km), unless all strike-slip predated any tilting of the cover sequences, which seems implausible (Figure 7).

5.2. Hollyford Fault System

The Hollyford Fault system has a segmented geometry, with north-trending thrust segments linked by roughly NE trending strike-slip or lateral ramp segments (Figures 2a, 5a, 6b, 7a, and 8b) [*Turnbull*, 2000], indicating dextral motion with a strong component of thrusting in a direction subparallel to the Hauroko-Blackmount-Moonlight (HBM) Fault strike-slip system, associated with ~N-trending folding in the footwall. This thrust must be the major Cenozoic structure that absorbs strike-slip on the HBM Fault system (Figures 5a, 7a, and 8b) [*Norris et al.*, 1978; *Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993; *Zink and Norris*, 2004]—the decrease in the width of the north-trending Brook Street terrane across the Moonlight Fault, from 15 to 20 km in the south to <5 km about ~25 km farther north (Figure 5a), is consistent with the displacement required on the Hollyford Fault system and associated footwall structures to accommodate the

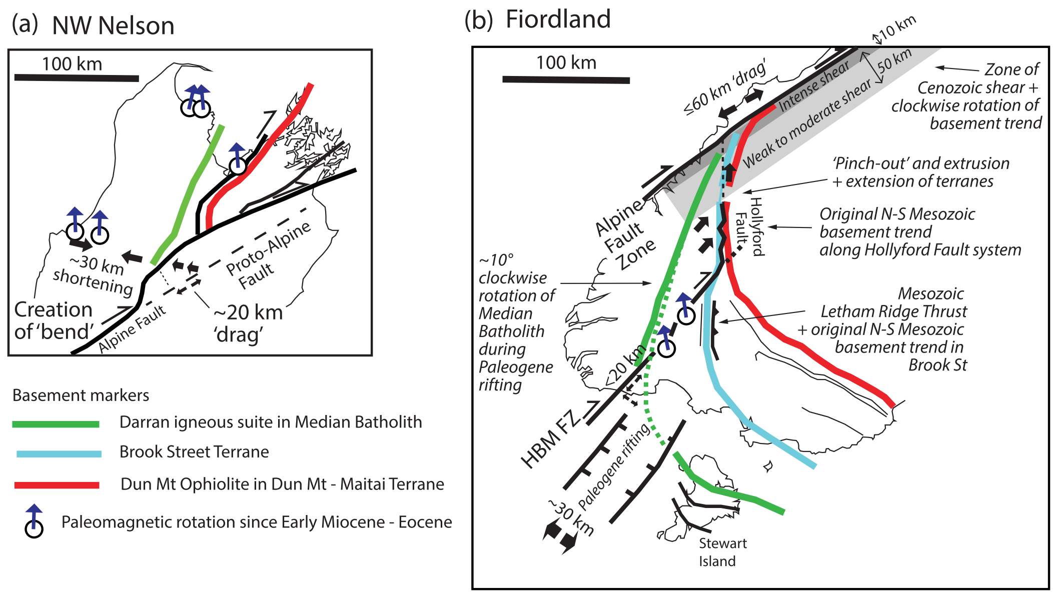

Figure 8. Simplified maps of NW Nelson and Fiordland, summarizing structural and paleomagnetic constraints on the timing of bending of the basement terranes, and Cenozoic displacements associated with dextral shear along the Alpine Fault (see Figure 1 for locations of Figures 8a and 8b). (a) Shortening across NW Nelson accommodates ~20 km of Cenozoic relative plate motion parallel to the Alpine Fault. This shortening has resulted in a progressive westward migration of the northern end of the Alpine Fault, creating the prominent "bend" in the fault, with negligible rotation of basement terranes. (b) Clockwise Cenozoic rotation of terranes in Fiordland is constrained to occur within a zone extending up to 50 km from the Alpine Fault, with significant extension along the length of the terranes. At greater distances, based on estimates of shortening and strike-slip between the terranes in the context of block rotation models, together with paleomagnetic data (see text), the terranes have undergone negligible rotation during the Cenozoic, retaining their present day curvature. Thus, the geometry of the pre-Eocene Letham Ridge Thrust together with trend of the Brook Street terrane, and truncation of the Murihiku terrane farther east (see Figure 5), shows that at least 60° of the curvature (in particular, that for the Brook Street Terrane) must be pre-Cenozoic. The northward projection of the Letham Ridge Thrust, together with the kinematics of displacement on the Hauroko-Blackmount-Moonlight Fault system (HBM Fz) and Hollyford Fault system can be simply explained if the N-S trend of the terranes north of the Letham Ridge Thrust is also an original Mesozoic feature. Taken together, these observations show that the maximum Cenozoic relative plate motion parallel to the Alpine Fault accommodated by distributed deformation away from the Alpine Fault is ≤60 km, with most of this occurring within 10 km of the fault. However, ~10° clockwise rotation of the Median Baltholith is likely to be a result of Paleogene rifting, with increasing extension to the south.

reduction in inferred dextral strike-slip toward the NE along the Hauroko-Blackmount-Moonlight Fault system [*Norris et al*., 1978; *Norris and Carter*, 1980, 1982; *Norris and Turnbull*, 1993].

However, a number of observations indicate that the Cenozoic thrust displacement on the Hollyford Fault system is much less than 8 km, and so there may have been 5–10 km of pre-Cenozoic thrusting along the eastern boundary of the Dun Mountain-Maitai terrane, presumably associated with Mesozoic motion on the Letham Ridge Thrust (Figures 5 and 8b). Thus, Cenozoic unroofing of both the Dun Mountain- Maitai terrane, and adjacent Caples Terrane sediments, is certainly ≪8 km, because the Caples Terrane, outcropping only ~5 km to the east, does not contain a penetrative fabric, and is at the shallowest erosional level for this terrane, with Late Cretaceous zircon fission track ages (Figure 7b) [*Mortimer*, 2003]. Importantly, there is no marked change in zircon fission track ages across the northern extension of the Hollyford Fault system, with ages >70 Ma extending >15 km into the footwall (Figures 2a and 7b) [*Sutherland et al*., 2009], indicating the Cenozoic throw on the fault must be much less than the thickness of the zircon partial annealing zone (≪8 km for 25°C/km geotherm); given the steep dip of both the Hollyford Fault system and Dun Mountain-Maitai rocks in the hanging wall, the throw will be a maximum estimate of the shortening accommodated by displacement on the fault (Figures 6b and 7c).

In northern Fiordland, the Brook Street terrane and part of the Dun Mountain-Maitai terrane nearly pinch-out entirely, but thicken again adjacent to the Alpine Fault to a width of ~10 km where their trend is rotated round 10°–30° clockwise compared to the "pinch-out" region farther south; the similarity of fission track ages across the terranes (Figure 2a) [*Sutherland et al*., 2009] indicates that this lateral thinning or "pinch-out" is most plausibly a result of Cenozoic strike-slip motion and northward extrusion along the northern part of the Hollyford Fault system and Livingstone Faults (Figures 2a and 8b) [*Norris et al*., 1978;

Norris and Carter, 1980, 1982; *Norris and Turnbull*, 1993], accommodating ~25 km of stretching of the terranes along their length together with ~10 km of narrowing of their combined width. The amount of narrowing here is comparable to the plausible Cenozoic shortening farther south, accommodated on the southern part of the Hollyford Fault system between the Brook Street and Dun Mountain-Maitai terranes.

5.3. Cenozoic Deformation East of Fiordland

East of the Dun Mountain-Maita terrane, the Moonlight Fault is the most important Cenozoic fault, swinging round from a ~NE trend where it cuts the Dun Mountain-Maitai terrane, to ~NNE trend farther north, upthrown to the west (Figure 2a) [*Norris et al.*, 1978; *Turnbull*, 2000]. The maximum Cenozoic throw on the fault is near its northern end. This is constrained to be 5–10 km by the change in structural thickness of the schists [*Mortimer*, 2003], together with zircon fission track ages >60 Ma [*Tippet and Kamp*, 1993], and similar metabasite units [*Craw*, 1995; *Turnbull*, 2000] in both the footwall and hanging wall. Slivers of Oligocene marine sediments are found locally in the footwall, adjacent to the fault. West of the Moonlight Fault (Figure 2a) [*Turnbull*, 2000], the schists are folded into N to NE trending open synclines and anticlines (interlimb angles 90–100°, Figure 2a) [*Turnbull*, 2000; *Rattenbury et al.*, 2010], which are likely to be, at least in part, Cenozoic in age [*Cooper et al.*, 1987; *Craw*, 1995]. Simple strain calculations indicate that all these structures together, given their geometry, cannot accommodate more than 30 km of Cenozoic shortening across this region, but this shortening could have helped to accommodate both local Cenozoic clockwise bending of the basement terranes (see section 5.4, Figure 8b) and the component of plate convergence orthogonal to the Alpine Fault [*Lamb et al.*, 2015].

East of the Moonlight Fault (Figure 2a), Cenozoic deformation right across southern South Island, is also characterized by local open and upright folding in the schistosity of the underlying schists associated with high angle reverse faults spaced ~10 km (accommodating <15 km shortening in total for line BB′ in Figures 2a and 6b) [*Craw*, 1995; *Turnbull*, 2000; *Norris*, 2004]. Displacements on major Cenozoic faults here are predominantly dip slip, and the offsets are constrained by the relatively small changes in erosion level, indicated by the preservation of the extensive Late Cretaceous-Paleogene Waipounamu Erosion Surface [*Landis et al.*, 2008], as well as shallow level (<3 km depth) Oligocene-Early Miocene diatremes (Figure 2a) [*Cooper et al.*, 1987; *Craw*, 1995], outliers of marine Paleogene sediments (Figure 2a) [*Turnbull*, 2000; *Turnbull et al.*, 2010], and fission track zircon ages 60–120 Ma (Figures 2a and 6b) [*Tippett and Kamp*, 1993].

5.4. Kinematic Rotation Models

We can compare the observed Cenozoic deformation with that required by kinematic rotation models for bending of the basement terranes. We consider the kinematic consequences of two end-member models that involve rotation of linear markers as either a slat or trellis arrangement, or as stacked dominoes. Thus, a slat model for clockwise rotation of the terranes requires *sinistral* strike-slip parallel to the terrane boundaries and shortening across their width (Figure 9a), whereas a domino-type rotation requires only *sinistral* strike-slip (Figure 9b).

5.4.1. Basement Rotation to the SE of the Alpine Fault

For Fiordland, given the present day geometry of the Median Batholith and Dun Mountain—Maitai terranes (Figure 1c) where they are ~N-trending, 10° of clockwise rotation would require ~12 km of cumulative sinistral strike-slip and ~18 km of shortening *between* these terranes for the trellis or slat model (total displacement ~22 km), and ~34 km of sinistral strike-slip for the domino model (see Figures 9a and 9b, using an appropriate hinge line spacing W ~ 125 km). Given the constraints on Cenozoic shortening and strike-slip between the Median Batholith and Dun Mountain-Maitai terranes in northern Fiordland, at the northern end of the Te Anau basin (outlined in sections 5.1–5.3) these results certainly limit Cenozoic tectonic rotation of the terranes here to less than 10° clockwise.

In fact, the evidence is for a *dextral*, rather than a sinistral Cenozoic component of strike-slip along the southern part of the Hollyford Fault system, where the Brook Street terrane and overlying Eocene sedimentary cover are juxtaposed with the Dun Mountain-Maitai terrane, with a displacement vector subparallel to the trend of the dextral Hauroko-Blackmount-Moonlight Fault system (Figures 2a, 5a, and 8b)—this is a powerful argument that Cenozoic clockwise rotation of the terranes here was negligible (given the requirement for sinistral strike-slip in the slat and domino models (Figures 9a and 9b)), and so the N-S orientation of the terranes must be a Mesozoic feature predating the Cenozoic plate-boundary zone. This conclusion is supported by the fact that the Mesozoic trend of the Brook Street terrane farther south, where it is

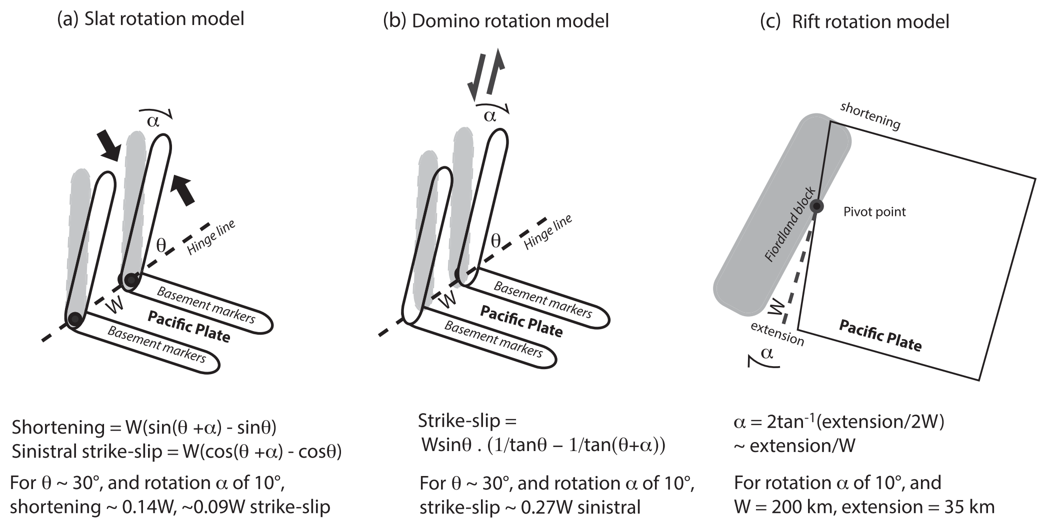

Figure 9. Generalised end-member block kinematic models for clockwise rotation of basement terranes, applicable to Fiordland and southern Island (see Figure 2a). (a) Slat type clockwise rotation with no length change parallel to the hinge line, and shortening and sinistral strike-slip between terranes. (b) Domino type clockwise rotation with sinistral strike-slip along basement terrane boundaries. (c) Rift model, with clockwise rotation of Fiordland block accommodated by gradients of extension and shortening relative to Pacific Plate.

overthrust by Murihiku terrane on the Mesozoic Letham Ridge Thrust, is also N-S (see section 3.1, Figures 7 and 8b). If anything, the evidence points to a small anticlockwise rotation ($\sim$5°) of the terranes in Fiordland during the Neogene, as indicated by the paleomagnetic data (section 4, Table 1). Thus, the footprint of Cenozoic clockwise rotation and shear is restricted to the clockwise swing of the terranes toward the Alpine Fault, farther north, so that they deviate from their original N-S trend, also involving local stretching and thinning along their length and folding in the schists farther east (Figures 2a and 8b). In this case, the point of "pinch-out" of the Brook Street and Dun Mountain Ophiolite defines the "hinge" of clockwise rotation and shear associated with Cenozoic relative plate motion through Zealandia (Figure 8b).

Rotation of the Median Batholith in Fiordland could also be accommodated by gradients of extension and shortening (rift model, Figure 9c). The crustal structure at the southern end of the Solander Trough indicates Cenozoic crustal thinning, requiring stretching $\sim$30 km (β factor 1.5–2 across $\sim$70 km, Figure 1c) [*Melhuish et al*., 1999]. This extension drops to effectively zero about $\sim$200 km farther north (Figures 6 and 7) [*Turnbull*, 2000; *Zink*, 2000], accommodating since the Eocene a total clockwise vertical-axis rigid body rotation less than 10° of the Median Batholith relative to farther east (Figure 9c). This rotation explains the slightly clockwise obliquity of the structural trend (N to NNE-trending) of the Median Batholith here compared to the N-S trend of the Dun Mountain-Maitai terrane (Figures 2a and 8b). Since the Miocene, with the onset of subduction along the Puysegur trench, the Solander Trough has undergone some shortening, reversing some of the motion of early Cenozoic normal faults [*Melhuish et al*., 1999], and possibly causing the small anticlockwise rotation indicated by palaeomagnetic data (Figure 2a and Table 1).

5.4.2. Basement Rotation to the NW of the Alpine Fault

The rotation model for NW Nelson, similar to the rift model in Fiordland but involving gradients shortening, also limits Cenozoic rotation of the terranes on the NW side of the Alpine Fault to less than 10° clockwise. Well-constrained balanced cross-sections indicate that the total horizontal displacement of the Median Batholith in NW Nelson, relative to the Australian Plate, is $\leq$30 km (see line AA′ in Figures 2b and 6a) [*Rattenbury et al*., 1998; *Nathan et al*., 2002; *Ghisetti and Sibson*, 2006]. This shortening has resulted in a westward migration of the northern end of the Alpine Fault, creating the prominent "bend" in the fault (Figure 8a).

6. Implications for Cenozoic Displacement on the Alpine Fault

The previous structural and paleomagnetic analysis (summarized in Figure 8) shows Cenozoic dextral shear in the regions either side of the Alpine Fault has not been accommodated by significant rotation of the basement terranes in NW Nelson ($<$10° clockwise), and at least 60° of the curvature of the basement terranes in Fiordland and southern South Island is pre-Eocene in age. Significant Cenozoic bending of the basement terranes is restricted to a region within 50 km (and most intense within 10 km) of the Alpine Fault in southern South Island, marked by the onset of stretching along their length and local "pinch-out" of the Brook Street and Dun Mountain-Maitai terranes (Figure 8). In other words, the null rotation basement trend in southern South Island for the Cenozoic is N-S, and not the WNW-ESE trend farther away from the Alpine Fault as has been generally assumed. This constrains the total amount of distributed Cenozoic dextral shear to less than 80 km with $\sim$20 km to the NW of the Alpine Fault (NW Nelson), and $<$60 km to the SE (southern South Island) of the fault (Figure 8). This is large compared to displacement on major strike-slip faults elsewhere in the world [*Darin and Dorsey*, 2013; *Lanphere*, 1978; *Searle* 1996, 2006; *Searle et al.*, 2010; *Sengör*, 1979; *Yin et al.*, 2002], but small compared to that required by the Cenozoic relative plate motions through Zealandia.

The relative plate displacement in the last 25 Ma, when the motion was subparallel to the Alpine Fault, is 770 $\pm$ 15 km [*Cande and Stock*, 2004; *Lamb et al.*, 2015]. Thus, displacement on the active fault trace, as opposed to distributed deformation either side ($<$80 km of dextral shear, with $\sim$25 km focused in a zone within 10 km of the Alpine Fault), must be greater than 675 km since 25 Ma (taking account of the uncertainty in the plate motion) for $\sim$500 km segment of the plate-boundary, with more than 700 km occurring within a zone less than 10 km wide (Figures 3b, 4c and 8b). This way, an initial sinistral offset of the basement terrains in the early Cenozoic, greater than 215 km, was turned into a $\sim$450 km net dextral offset (Figures 3b, 4b, and 4c).

The Alpine Fault has accommodated more than 94% of the relative plate motion since 25 Ma, with an average slip rate is in excess of 28 mm/yr. However, at the northeastern termination of the Alpine Fault, at the southern end of the Hikurangi Margin where the crust is underlain by subducted Pacific Plate (Figure 1), displacement was taken up by substantial clockwise rotation in the Neogene [*Lamb*, 2011]. Here paleomagnetic data indicate up to $\sim$140° clockwise rotation of the intervening fault blocks about a vertical axis, acting as a hinge for 60°–90° of clockwise rotation of the whole Hikurangi Margin in the last 25 Ma (Figures 4b and 4c, summarized in *Lamb* [2011]). Thus, the age of vertical axis rotation in the New Zealand region varies from Mesozoic in the continental part of the plate boundary, to Neogene farther north along the subducting margin.

7. Pre-Eocene Deformation of Basement Terrains

If Cenozoic displacement on the Alpine Fault has reversed more than 225 km of sinistral displacement of the basement terrains, it is important to ask when and why this initial sinistral offset occurred. It must be younger than $\sim$105 Ma, when the youngest granites in the Median Batholith where emplaced [*Kimbrough et al.*, 1994; *Allibone et al.*, 2009]—at this time Zealandia was still part of the margin of Gondwana, with Southeast Zealandia (Campbell Plateau) joined to Marie Byrd Land in West Antarctica (Figure 10a) [*Lawver et al.*, 1992]. It probably predates separation of Zealandia from Gondwana at $\sim$85 Ma (Figure 10b), but could be as young as 70 Ma when a continuous continental margin to southern Zealandia first formed [*Cande and Stock*, 2004b]. This constrains the displacement to the time period 105–70 Ma, when there was significant motion between East and West Antarctica, an early phase of uplift of the Transantarctic Mountains, and slow sinistral strike-slip motion between Tasmania and East Antarctica, and metamorphism in southern South Island [*Lawver et al.*, 1992; *Fitzgerald*, 2002; *Siddoway et al.*, 2004; *Kula et al.*, 2007].

Total stretching in the Ross Sea area, between East and West Antarctica, is poorly determined, but could be up to 400 km, based on the crustal thickness variations [*Fitzgerald*, 2002]. Thus, if Zealandia was located at a triple junction in the Late Cretaceous (Figure 10b), motion between East Antarctica, West Antarctica (Marie Byrd Land) and Australia could have been accommodated in the New Zealand region as a sinistral transform, terminating the extension between East and West Antarctica and offsetting the basement terrains $>$225 km. We test this idea by calculating possible Euler Pole solutions (Table 2 and Figure 10) for the period 105–85 Ma, given our estimated $\sim$250 km sinistral offset (12.5 mm/yr over 20 Myrs) through Zealandia, together with a plausible 50–100 km displacement of Australia with respect to East Antarctica deduced from sea floor magnetic anomalies and fracture zones between Australia and East Antarctica [*Lawver et al.*, 1992; *Cande and Stock*, 2004b]. This way, we have a direct measure of the Late Cretaceous rifting between East and West Antarctica (Figure 10b)—100–150 km of subsequent Paleogene extension in the Ross Sea area was oblique to this [*Cande et al.*, 2000; *Cande and Stock*, 2004b; *Granot et al.*, 2013]. The main curvature of the basement

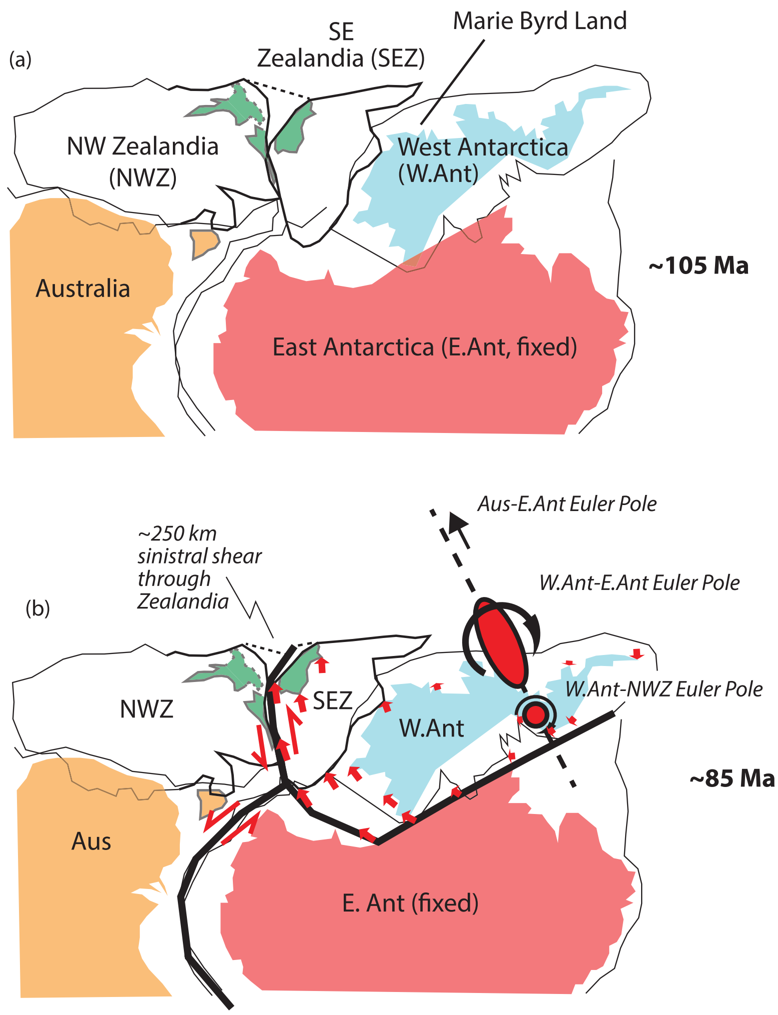

Figure 10. (a and b) Reconstructions of the margin of Gondwana in the New Zealand region in the Late Cretaceous, based on a fit of the continental margins of Australia, Zealandia, East Antarctica (treated as fixed) and West Antarctica (Marie Byrd Land) at ~105 Ma, taking account of 100–150 km of Cenozoic motion between East and West Antarctica in the Ross Sea region [*Lawver et al*., 1992; *Cande and Stock*, 2004b; *Granot et al*., 2013], showing how oblique rifting in the Late Cretaceous between East and West Antarctica could result in >215 km (and <300 km) of sinistral strike-slip through Zealandia (between NW and SE Zealandia), with a small amount of sinistral motion between Australia and East Antarctica, as part of a triple junction that formed during the early stages of the break-up of Gondwana in this region. Possible Euler poles for relevant plate pairs are also shown, given ~250 km offset through Zealandia and 50–100 km displacement of Australia with respect to East Antarctica (see Table 2). Red arrows in Figure 10b show motion of West Antarctica and SE Zealandia with respect to East Antarctica for solution with 75 km displacement between Australia and East Antarctica.

Table 2. Euler Pole Solutions for Plate Pairs in the East Antarctica, West Antarctica, SE Zealandia, NW Zealandia, Australia Plate Circuit in the Late Cretaceous (~85 Ma, in a Frame of Reference Fixed to East Antarctica Today, But Reconstructed Zealandia (See Figure 10)

Plate Pair[a]	Model[b]	Lat. N (°)	Long. E (°)	Angle[c] (°)
Aus-E.Ant	50 km	13.1	−170.5	−0.44
E.Ant-W.Ant	50 km	−73.3	−112.3	−6.44
W.Ant-NWZ	50 km	−75	−100	−6.5
Aus-E.Ant	100 km	13.1	−170.5	−0.88
E.Ant-W.Ant	100 km	−70.7	−122.5	−6.46
W.Ant-NWZ	100 km	−75	−100	−6.5

[a]Aus = Australian Plate, E.Ant = East Antarctica (fixed), W.Ant = West Antarctica (Marie Byrd Land and SE Zealandia), NWZ = NW Zealandia.
[b]Total sinistral transform displacement between Australia and East Antarctica during the Late Cretaceous.
[c]Euler rotation angle (+ve clockwise).

terrains must have occurred even earlier (Figure 4a), possibly as an original feature of subduction and accretion of basement terrains along the margin of Gondwana.

At ~70 Ma, with the creation of extensive oceanic crust right along the margins of Marie Byrd Land and Australia [*Cande and Stock*, 2004b], Zealandia drifted away, opening up the Tasman Sea. When relative motion between the Australian and Pacific plates initiated in the New Zealand region at ~45 Ma, a zone of deformation, with slightly thicker crust, as well as oroclinal bending of the basement terrains and a Late Cretaceous sinistral offset, was already present in what is today the land area of New Zealand, eventually becoming the locus of the plate boundary zone since the Eocene when the region was reactivated first by rifting and then dextral motion on the Alpine Fault.

8. Discussion

This previous analysis demonstrates that plate boundaries through continental lithosphere on time scales of 10s of millions of years, at least in the crust, need not form wide zones of distributed deformation. Instead, they can share features of oceanic lithosphere, where the relative plate motion is taken up in narrow transform fault zones, and as in the oceans, these zones in the continents can be long-lived features, with histories spanning 10s to 100s of millions of years.

Counter-intuitively, it may be the weakness of continental crust that allows such long-lived and intense focusing of deformation. To achieve more than 700 km of displacement in the last 25 Ma, the Alpine Fault has maintained a high average slip rate comparable to the present day rate of ~30 mm/yr [*Norris and Cooper*, 2001; *Barth et al*., 2014], suggesting that the nature of the fault—in particular, the shear strength and/or geometry—has not changed significantly throughout this period. Other well documented examples of active major continental strike-slip faults, such as the San Andreas, Dead Sea, Denali, Karakoram, Altyn Tagh, North Anatolian, Red River Faults [*Darin and Dorsey*, 2013; Lanphere, 1977; *Searle*, 1996, 2006; *Searle et al*., 2010; *Sengör*, 1979; *Yin et al*., 2002], have either much lower average slip rates (<10 mm/yr) and/or much shorter displacement histories (≤10 Ma).

This mode of deformation needs to be taken into account when interpreting the rheology of the continental lithosphere at depth from seismic anisotropy. For example, a progressive swing in the fast SkS splitting direction toward parallelism with the Alpine Fault is observed in a zone up to 600 km wide, more-or-less centred on the Alpine Fault, and this has been attributed to distributed mantle lithospheric shear associated with Cenozoic relative plate motion between the Australian and Pacific plates [*Molnar et al*., 1999; *Moore et al*., 2002; *Little et al*., 2002; *Zietlow et al*., 2014]. However, given the evidence in this study that Cenozoic finite crustal shear away from the Alpine Fault is small, a much wider distribution of deeper lithospheric strain requires a special mechanism. One possible mechanism for distributing lower lithospheric Cenozoic strain on the Pacific side of the Alpine Fault over a much wider area than that in the crust could be related to an observed flattening of the Alpine Fault in the mid to lower crust, so that Australian Plate underlies Pacific Plate in much of southern South Island [*Lamb et al*., 2015]. However, it remains unclear how to interpret the seismic anisotropy on the Australian side of the Alpine Fault.

Finally, the ~250 km Late Cretaceous sinistral offset through Zealandia provides a direct measure of motion between East and West Antarctica at this time, as well as the shape of Zealandia that fitted with Marie Byrd Land in the Ross Sea region of Antarctica. Although it has been long clear that there was tectonic activity in the Ross Sea region of Antarctica at this time, there is no consensus on the amount and kinematics of this deformation [*Fitzgerald*, 2002; *Siddoway et al*., 2004]. Our Late Cretaceous Euler pole (243°E, −72°N) for West Antarctica with respect to East Antarctica constrains the motion to ≤250 km, involving both extension and a sinistral component of shear. The Euler pole appears to have subsequently migrated southward, so that motion between West and East Antarctica in the Paleogene involved extension in the Ross Sea and Adare basin oblique to the Late Cretaceous motion, with rotation about an Euler pole at ~200°E, −85°N [*Granot et al*., 2013].

9. Conclusions

This paper reevaluates the Cenozoic displacement history on the Alpine Fault, with conclusions summarized below.

We show that the widely accepted 450 km Cenozoic strike-slip displacement along the Alpine Fault is an artifact of assumptions about the geometry of New Zealand's basement terranes in the Eocene, and the actual Cenozoic dextral displacement across the active trace is greater than 675 km, with more than 700 km (<785 km) occurring since 25 Ma in a narrow zone less than 10 km wide and accommodating more than 94% of the relative plate motion at an average rate about 28 mm/yr.

Our revised displacement history for the Alpine Fault indicates that almost all the relative plate motion in a plate boundary through continental lithosphere can be focused in a narrow fault zone over periods of 10s of millions of years.

In addition, the displacement reverses more than 225 km (and <300 km) of sinistral shear through Zealandia in the Late Cretaceous, as a consequence of intra-continental rifting between East and West Antarctica when Zealandia lay on the margin of Gondwana. The Late Cretaceous sinistral displacement provides a direct constraint on the kinematics of extension between East and West Antarctica at this time.

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