Cenozoic distributed rotational deformation, South Island, New Zealand

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[1] New structural and paleomagnetic data from the Marlborough region, New Zealand, provide better constraints on the timing of the formation of the South Island orocline. These data indicate that approximately 100° of clockwise bending of the crust has occurred across this part of the plate boundary zone during the Neogene, most of which took place between the early and late Miocene (circa 25–8 Ma), implying that distributed shear has been an important mechanism in the accommodation of Neogene finite strain. A simple kinematic model suggests that this distributed deformation has been accommodated by the rotation of elongate blocks parallel to the main fabric, in response to continuous deformation in the underlying lithospheric mantle beneath. After the introduction of a significant convergent component to the plate motion in the late Miocene, distributed deformation may have ceased to play such a significant role in the central Marlborough fault zone, with motion becoming concentrated on the Marlborough faults themselves. In the northeastern part of Marlborough, however, an extra clockwise rotation of ∼35° has occurred since this time, which might be explained by the reorganization of the crust into more equidimensional blocks where they terminate against the Hikurangi margin.

INDEX TERMS: 8102 Tectonophysics: Continental contractional orogenic belts; 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 8099 Structural Geology: General or miscellaneous; 9399 Information Related to Geographic Region: General or miscellaneous; 9604 Information Related to Geologic Time: Cenozoic; KEYWORDS: New Zealand, tectonics, orocline, distributed deformation, paleomagnetism, Cenozoic.


1. Introduction

[2] There are very few places in continental lithosphere where geological markers can be used to determine the full finite displacement across the boundary zone between two tectonic plates. There are even fewer places where this pattern of finite motion can be compared directly with the active deformation in the same plate boundary zone. New Zealand, which straddles the boundary between the Australian and Pacific plates, is probably unique in this respect: there are a wealth of geodetic observations, as well as prominent geological and bathymetric features, that can be matched or traced across the deforming zone. All of these geological markers could potentially provide an opportunity to compare the long-term (>1 Myr) brittle and ductile distribution of deformation with the short-term elastic and anelastic (≪1 Myr) strains. Such a comparison is capable of placing powerful constraints on the rheology of the continental lithosphere and defining more general relationships between the elastic, brittle, and ductile behavior of rocks. However, for this to be successful, good constraints are required on both the timing and displacement field of the finite deformation.

[3] GPS velocity profiles in South Island show that the instantaneous relative plate motion is distributed across a zone between 80 km and 180 km wide [Beavan et al., 1999; Bourne et al., 1998], and is predominantly strike-slip in nature. The full history of relative plate motion, determined from seafloor magnetic anomalies, extends back into the early Cenozoic. However, it has proved difficult to determine how much of the observed finite strain in the plate boundary zone actually occurred within this time frame [Norris, 1979; Kamp, 1987; Bradshaw et al., 1996; Sutherland, 1999]. In addition, rigid-body rotations about a vertical axis are likely to have been an important component of the displacement field, but cannot always be constrained by the structural patterns alone. These problems must be solved before full advantage can be taken of New Zealand as a natural laboratory to improve our understanding of continental dynamics.

[4] In this study, we present two new data sets to help quantify the total Cenozoic distributed deformation in the Marlborough region, at the northern end of South Island, New Zealand. We have mapped out the apparent curvature of structural trends in the basement rock across the plate boundary zone, by averaging bedding orientations and identifying strike ridge traces. We also present new paleomagnetic rotation data from the same region, which document significant vertical axis rotations of crustal blocks since the early Miocene.

[5] We argue that the good correlation between these data sets provides constraints on both the timing and displacement field of rotation in South Island. Our results suggest that a predominantly simple-shear displacement field across...
The short-dashed line marks the Esk Head subterrane. The shows the general geometry of the New Zealand orocline. the Junction Magnetic Anomaly of the Maitai terrane, which marked by thick solid lines. The long-dashed line represents northern end to the Hikurangi subduction zone by the occurs along the Alpine fault, which is connected at its line. In the South Island, oblique continental collision crust are marked approximately by the (AUS) and Pacific (PAC) plates. Regions of continental boundary zone between the obliquely converging Australian [Sutherland, 1995, 1999; Sutherland et al., 2000]. The central segment of this fault shows an oblique-reverse displacement, with a late Quaternary slip rate of 20–30 mm/yr [e.g., Berryman et al., 1992; Sutherland and Norris, 1995]. Offset of the Maitai basement terrain, including the Junction Magnetic Anomaly, across the fault, indicates a total right-lateral displacement of 460 km (Figure 1). At its northern end, the Alpine fault is connected to the Hikurangi subduction zone by a series of strike-slip faults referred to as the Marlborough fault zone (MFZ).

Plate reconstructions show that in the last 45 Ma there has been a total of 860±100 km of essentially strike-slip offset across the New Zealand region, implying that the Alpine fault has accommodated just over half of the relative plate motion during this time [Sutherland, 1995, 1999]. Regional-scale bending of the basement terrains is observed on either side of the Alpine fault, in a zone between 250 and 300 km wide. This geometry could be explained in terms of ~170 km of right lateral shear south of the Alpine fault, and as much as ~400 km offset across the whole plate boundary, which would account for the “missing” relative plate motion [e.g., Molnar et al., 1975; Norris, 1979; Sutherland, 1999]. In addition, Molnar et al. [1999] concluded from the pattern of seismic anisotropy (shear wave splitting data) beneath the South Island that distributed shear had occurred in the underlying lithospheric mantle, over a similar length scale to the surface regional-scale bending of the basement terranes. However, there is no general consensus on the exact timing of either the surface or mantle deformation. Some authors [Kamp, 1987; Bradshaw et al., 1996] have argued that the curved geometry of the basement terrains is a relict of the Mesozoic evolution of New Zealand, and has nothing to do with Cenozoic plate motion. To clarify the deformational history of the South Island of New Zealand, it is important to determine the actual finite Cenozoic strains and displacements in the plate boundary zone.

2.2. Marlborough Fault Zone (MFZ)

In this study, we focus on the plate boundary zone at the northern end of the South Island. Here, deformation is currently accommodated by the four major strike-slip faults in the MFZ (Wairau, Awatere, Clarence and Hope faults; see Figure 3). Estimates of late Quaternary slip rates vary from 20–30 mm/yr on the Hope fault [Cowan, 1990; Van Dissen and Yeats, 1991] to 4–6 mm/yr on the Wairau fault [Berryman et al., 1992]. The cumulative slip rate, when compared with geodetic measurements, suggests that these faults account, within error, for all of the current relative plate motion [Holt and Haines, 1995; Bourne et al., 1998]. The finite offsets on individual faults (except the Wairau) are less than about 35 km [Little and Jones, 1998], with a probable cumulative offset of 55 to 65 km [Reay, 1993; Wood et al., 1994].

The Wairau fault, which is the northernmost of the Marlborough faults, represents the continuation of the Alpine fault through this region. It has been inferred that the Alpine and proto-Wairau faults have been the main locus of strike-slip motion for the bulk of the history of the New Zealand plate boundary zone. The initiation of the rest
of the MFZ occurred at a relatively late stage, during the onset of continental collision in South Island in the late Miocene [Anderson et al., 1993; Little and Jones, 1998]. At their present rates of motion, the strike-slip faults in the MFZ could easily have achieved their finite offsets in much less than 5 Myr. However, there is evidence for widespread folding and thrusting in the MFZ region, probably related to subduction along the Hikurangi margin, at least as early as the early Miocene [Lamb and Bibby, 1989; Rait et al., 1990].

[10] The stratigraphy of the northeastern South Island consists of Mesozoic basement rock, referred to as the Torlesse terrane or supergroup, which is unconformably overlain by a Late Cretaceous to Recent cover sequence. The Late Cretaceous to Miocene sequence, outcropping in a region extending from south of the Wairau fault to south of the Hope fault, consists of fine-grained, deep water, marine sediments including the Amuri limestone, which are overlain by a markedly course-grained sedimentary facies, starting with the Great Marlborough conglomerate. The Great Marlborough conglomerate was deposited in a near shelf submarine fan [Lewis et al., 1980] and contains reworked clasts of older parts of the cover sequence. This change from fine to course-grained facies appears to record an increase in tectonic activity in the Marlborough region in early Miocene times [Lamb and Bibby, 1989; Rait et al., 1990].

[11] Previous paleomagnetic work [Walcott et al., 1981; Mumme and Walcott, 1985; Roberts, 1992; Vickery and Lamb, 1995; Little and Roberts, 1997] has mainly focused on the coastal region, where suitable rock units are well exposed. Details of these published results, including the site ages and rotation anomalies, are given in Table 1. These studies suggest that there have been large (>10⁵) clockwise rotations of crustal blocks about vertical axes during the last 50 Myr, and most likely in the last 25 Myr. Various models have been proposed to explain this, which involve two main phases of deformation. The younger, post 8 Ma rotation is generally agreed to be due to block rotations about vertical axes between the strike-slip faults. The cause of the older phase, before 8 Ma, is much less clear. Little and Roberts [1997] propose that the older deformation was the consequence of another phase of block rotations between the northeastern ends of the major strike-slip faults in early to middle Miocene times. In contrast, Vickery and Lamb [1995] suggest that early rotation was coeval with more regional thrusting in the Marlborough region associated with the subduction of the Pacific plate, and driven by the rotation of the whole subducted margin about a hinge at its south termination, where the continental crust of the Chatham Rise intersects the plate boundary zone.

### Table 1. Summary of Published Paleomagnetic Data

<table>
<thead>
<tr>
<th>Location</th>
<th>Label</th>
<th>Approximate Age, Myr</th>
<th>Declination Anomaly</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Awatere Dykes</td>
<td>GS1</td>
<td>80</td>
<td>22 ± 15</td>
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<td>59</td>
<td>138 ± 6</td>
<td>4</td>
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<tr>
<td>Woodside Creek</td>
<td>WC2</td>
<td>59</td>
<td>146 ± 11</td>
<td>4</td>
</tr>
<tr>
<td>Ward-Cape Campbell</td>
<td>BB</td>
<td>30</td>
<td>135 ± 17</td>
<td>4</td>
</tr>
<tr>
<td>Silver Springs</td>
<td>SS</td>
<td>20</td>
<td>122 ± 12</td>
<td>4</td>
</tr>
<tr>
<td>Deadman Stream</td>
<td>DS</td>
<td>18</td>
<td>99 ± 10</td>
<td>2</td>
</tr>
<tr>
<td>Kekerengu-washdyke</td>
<td>HC3</td>
<td>17</td>
<td>106 ± 15</td>
<td>4</td>
</tr>
<tr>
<td>Heavers Creek</td>
<td>HC2</td>
<td>17</td>
<td>121 ± 55</td>
<td>4</td>
</tr>
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<td>Waihopai Valley</td>
<td>WV</td>
<td>8</td>
<td>20 ± 4</td>
<td>3</td>
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<tr>
<td>Boundary Stream</td>
<td>BS</td>
<td>8</td>
<td>17 ± 13</td>
<td>3</td>
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<tr>
<td>Fuchsia Creek</td>
<td>FC</td>
<td>5.5</td>
<td>0 ± 11</td>
<td>5</td>
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<td>Cape Campbell</td>
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<td>5.4</td>
<td>24 ± 9</td>
<td>1</td>
</tr>
<tr>
<td>Needles Creek</td>
<td>NC</td>
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<td>Upton Brook</td>
<td>UB</td>
<td>4.8</td>
<td>32 ± 3</td>
<td>3</td>
</tr>
<tr>
<td>Blind River</td>
<td>BR</td>
<td>4.8</td>
<td>33 ± 3</td>
<td>3</td>
</tr>
<tr>
<td>Richmond Brook</td>
<td>RB</td>
<td>4.2</td>
<td>32 ± 7</td>
<td>3</td>
</tr>
<tr>
<td>Swamp Stream</td>
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<td>CS</td>
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<td>−5 ± 4</td>
<td>3</td>
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</table>

*For locality locations, see Figure 6. References are as follows: 1, Walcott et al. [1981]; 2, Mumme and Walcott [1985]; 3, Roberts [1992]; 4, Vickery [1994]; 5, Little and Roberts [1997].

### 3. Structural Data

#### 3.1. Deformation of the Torlesse Terrane or Supergroup

[13] The basement rock at the eastern end of the MFZ consists solely of the Mesozoic Pahua subterrane of the Torlesse terrane. This is a highly deformed and mildly metamorphosed subduction-accretion complex of Late Jurassic to Early Cretaceous age [MacKinnon, 1983; Silberling et al., 1988], which is dominated by lithic and quartzo-feldspathic alternating sandstone and siltstone, with minor occurrences of basaltic lavas and associated tuffs. A great deal of faulting and tight to isoclinal folding is evident at outcrop scale, though over larger areas, the Torlesse rocks have a remarkably consistent average strike pattern with near-vertical dips. This consistency allows large-scale variations in the structural trend to be easily identified and mapped.

[14] Measurements of the orientation of bedding in the Torlesse terrane were made in a swath running perpendicular to the general trend of the main faults, extending across the central MFZ (this study and database held at the Institute of Geological and Nuclear Sciences, New Zealand).

### 3.2. Averaging of Structural Data

[15] Bedding orientations were sampled by averaging between 5 and 566 measurements in domains about 5 km across, yielding both a mean bedding orientation and...
confidence limits [Fisher, 1953]. The dips of the averaged bedding measurements, in almost all cases, lie within 25° of the vertical. Representative stereoplots and a summary of the results are shown in Figure 2.

3.3. Remote Sensing of the Structural Grain

[16] The analysis of satellite imagery can be used to augment the field studies of the rock structure. Black and white Landsat 7 pictures, with a 15 m resolution, clearly show prominent linear features running across the landscape, mapped on the ground as strike ridges (Figure 3 [Reay, 1993; Warren, 1995]). In addition, a 25 m digital elevation model has been used to further estimate the average structural grain, identified by topography and rivers. Rivers and streams often follow the less-resistant rock units, cutting valleys which trend parallel to the main structure.

3.4. Patterns of Deformation

[17] It is clear from Figure 3, that on a length scale similar to the width of the plate boundary zone, the structural trends of the Torlesse terrain define a curve. To
the south of the plate boundary zone, in the underformed the Pacific plate, the bedding strikes \(\sim 110^\circ\). Further north, near the Wairau fault, this strike has swung around to \(\sim 020^\circ\). This indicates that although no distinct marker terrane is present within the study area, the structural data presented here quantifies the geometry of the large-scale crustal bending seen elsewhere across the plate boundary zone. Given the subvertical dip of the average bedding, this change in orientation can be interpreted in terms of a vertical axis rotation. From the reference frame of the undeformed Pacific plate (to which all published palaeomagnetic rotations are referenced), this equates to \(\sim 100^\circ\) of clockwise rotation across a distance of about 120 km.

Previous palaeomagnetic and structural studies [Lamb, 1988; Lamb and Bibby, 1989; Vickery and Lamb, 1995; Little and Roberts, 1997] have shown that there appears to be a sharp change in structural regime between main central part of the fault zone and its northeast corner, where the faults terminate against the Hikurangi margin. Little and Roberts [1997] identified a distinct change in trend of the subvertical structural grain across this boundary, involving a swing in the average strike from 020° to 055° (Figure 3). The structural grain is continuous across the boundary, implying that the NE region has undergone a further 35° of clockwise rotation [Little and Roberts, 1997]. Much larger local bending can be observed here in the orientation of the late Cretaceous to Cenozoic cover sequences, involving swings in strike up to 100°, but these cannot be interpreted solely in terms of vertical axis rotation because they are part of moderately plunging (~30°) fold structures [Vickery, 1994].

4. Paleomagnetic Data

4.1. Sample Localities

Samples were collected for paleomagnetic analyses from 10 localities in Marlborough. Only three of these, from the coastal regions south of the Hope fault, are discussed further because they yielded stable end-point magnetizations (see Figure 6 for locations). Samples were collected from indurated and well-bedded white micritic limestones that form part of the Late Cretaceous to late Eocene Amuri Limestone [Morris, 1987]. The sampling procedure was designed to average out paleosecular variation. At each locality, at least 15 cores were drilled (with a portable gasoline-powered drill) over a minimum stratigraphic thickness of 26 m, which is estimated to span several tens of

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**Figure 3.** Landsat 7 image of the central Marlborough region between the Awatere and Clarence faults. Arrows highlight examples of mapped strike ridges.
thousands of years, based on long term sedimentation rates
[Berger, 1974; Turner, 1975].

[20] The structural settings of the localities are well
defined and relatively simple. Locality CLA, in the Hau-
muri Bluff region south of the Hope fault, lies midlengh
along the eastern limb of a regional upright anticline. The
axial trace of this extends for ~30 km and the fold axis is
more or less horizontal [Warren, 1995]. Farther north, fold
structures in the vicinity of locality KAI, on the Kaikoura
Peninsula, have their scales on the hundreds of
meters, with generally subhorizontal plunges. Locality PUH
is situated on the east limb of the kilometer-scale Puhi-Puhi
syncline, north of Kaikoura. The Puhi-Puhi syncline is a
regional doubly plunging fold, however locality PUH lies in
the middle section of this structure, where the fold axis is
more or less horizontal.

[21] The ages of the paleomagnetic localities are based on
Morris [1987], using well-defined biostratigraphic zones and stratigraphic correlations. The limestones at localities
CLA and KAI are near the base of the middle Amuri
limestone, with ages of ~54 Ma (Mangaorapan). Locality
PUH lies directly above a distinct cherty limestone unit,
placing it at the base of the Amuri limestone, with an age of
approximately 66 Ma (upper Haumurian to lower Teurian).

4.2. Demagnetization

[22] Individual samples (cores) were cut into specimens
and the magnetizations were measured at the University of
Oxford with either a 2-G 3-axis cryogenic magnetometer
housed in a magnetically shielded room (rest field <200 nT),
or a CCL 2-axis cryogenic magnetometer. Progressive
thermal and alternating-field (AF) demagnetization was
carried out on 12 pilot samples. AF demagnetization yielded
the clearer demagnetization behavior, which could be used
to define the remanence components. For this reason, the
remainder of the samples were subjected to stepwise AF
demagnetization in 12–24 steps up to a maximum field of
100 mT. Demagnetization components were identified from
least squares analysis on linear segments of the vector
trajectories. Some of the samples (cores) yielded multiple
specimens. In such cases, the magnetizations of the indi-
vidual specimens were averaged and assigned to that
sample. The sample directions were averaged to derive a
locality mean, correcting each sample individually for
bedding (see section 4.3).

[23] For the three localities which gave stable results,
typical natural remanent magnetization (NRM) intensities
lie in the range 0.1 to 0.07 mAm/m. The demagnetization
behavior of the specimens proved to be relatively simple
(Figures 4a–4d). A low-coercivity component, oriented in
situ coordinates subparallel to the present Earth’s field, was
usually removed in fields up to 15–20 mT. After removal of
the low-coercivity component, a higher-coercivity compo-
nent remained. This was then demagnetized with fields up
to 60 mT, suggesting that magnetite is the main magnetic
carrier, in agreement with the results of isothermal remanent
magnetization (IRM) acquisition experiments (Figure 4e).
This higher-coercivity component was detected at all three
localities. Some samples within any particular locality
showed opposite polarities, and locality PUH passes the
McFadden and McElhinny [1990] reversal test with a “C”
classification. Unfortunately, localities KAI and CLA
contained too few samples of opposite polarity to provide
a statistically significant reversal test (yielding an indeter-
ninate classification using the McFadden and McElhinny
[1990] reversal test), although in both cases the “reverse”
directions plot within the 0.95 of the “normal” samples
when inverted. Locality mean directions and statistics for
the characteristic high-coercivity component are tabulated
in Table 2, and illustrated in Figure 5a in both situ and
tilt-corrected coordinates.

4.3. Field Tests and the Age of Magnetization

[24] We regard the low-coercivity component, present in
virtually all specimens for fields up to 20 mT, as a
secondary viscous-remanent magnetization, probably of
Recent origin. We consider the higher coercivity component
to be a primary magnetization, acquired not long after the
limestone was deposited. This conclusion is supported by
the observations that magnetite appears to be the main
magnetic carrier and subparallel normal and reversed com-
ponents were found at the same locality.

[25] The tectonic correction for primary magnetizations,
in all cases, was a simple tilt correction. We felt justified
in this because no localities were situated within signifi-
cantly plunging parts of fold structures. Tilt correction
resulted in a small improvement to the statistical param-
eters for one site (KAI) and a small increase in the scatter
in the other two, though the changes in the statistical
parameters within each locality are not statistically signif-
cant using the McElhinny [1964] fold test. This is likely
because within-locality bedding orientations only varied
very slightly. When the locality-mean directions are com-
pared with each other, there is a noticeable improvement
in clustering after a tilt correction is applied. Given that we
suspected the presence of tectonic rotations, we examined
the improvement in the clustering of the inclinations using
the McFadden and Reid [1982] inclination-only fold test.
This test was positive at the 95% confidence level, further
supporting our conclusion that the higher coercivity com-
ponent pre-dates deformation and represents a primary
magnetization (Figure 5b).

4.4. Declination and Inclination Anomalies

[26] Declination and inclination anomalies were calculated
for the paleomagnetic localities by comparing our results
with a reference apparent polar wander (APW) path for the
Pacific plate. There are insufficient available paleomagnetic
measurements from the Pacific plate itself to construct
such a path directly. Therefore, in line with previous authors
[Walcott, 1998], we took the APW path of DiVenere and
Kent [1994] for West Antarctica and rotated it into a New
Zealand frame of reference (Pacific plate) using the finite
rotation poles of Cande et al. [1995]. Relative motion
between East and West Antarctica will introduce an error
into this procedure [Cande et al., 2000], but as this is only
likely to make ~2° difference in the location of the
transferred VGPs, it is not a significant source of error.
We calculated from the APW path an expected declination and inclination for the paleomagnetic localities. In all cases, the observed tilt-corrected inclination falls within error of the expected inclination, considering the age and position of each locality (Table 2). There are, however, discrepancies between the observed and calculated declinations, with all localities having mean declinations (quoted at the 95% confidence level) that lie clockwise of the expected declination: CLA: 9.8° ± 17°, KAI: 40.5° ± 17°, PUH: 84.3° ± 18.6° (Table 2 and Figure 6). Locality CLA lies within error of the expected declination. However, the other two show significant declination anomalies. We

Figure 4. Alternating-field demagnetization Zijderveld plots showing tectonically corrected data for typical specimens from each location sampled. (a) Claverley site (CLA), normal component. (b) Kaikoura Peninsula (KAI), reverse component. (c and d) Puhi Puhi syncline (PUH), normal and reverse components, respectively. Open points, inclination; solid points, declination. (e) Results of the isothermal remanent magnetization (IRM) acquisition experiments for each locality. All suggest magnetite is the main magnetic carrier.

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interpret the declination anomalies in terms of rigid-body, vertical axis rotations of the crustal blocks in which the paleomagnetic localities lie. The dimensions and geometry of the blocks are discussed further on in section 6.

5. Timing of Deformation

[28] We can constrain the maximum age of the paleomagnetic rotations simply from the age of the rocks in the paleomagnetic localities. We can now use this to constrain the timing of the vertical axis rotation of the Torlesse terrane structural grain across the plate boundary zone, by comparing the paleomagnetic and structural data. The age of the paleomagnetic sites used in this comparison is important, as the younger sites are less likely to record the full deformational history. For this reason the data is analyzed in two different subsets: rocks older than ~17 Ma, which will pre-date most of deformation associated with the formation of the Hikurangi margin [Lamb and Bibby, 1989], and those younger than 8 Ma (see Tables 1 and 2 for sample site ages). The comparison between the paleomagnetic and structural data is done in two different ways. First, both the paleomagnetic vertical axis rotations and the mean change in Torlesse bedding orientation with respect to the undeformed Pacific plate are plotted against their mean change in Torlesse bedding orientation with respect to the undeformed Pacific plate are plotted against their mean change in Torlesse bedding orientation with respect to the undeformed Pacific plate are plotted against their mean change in Torlesse bedding orientation with respect to the undeformed Pacific plate are plotted against their mean change in Torlesse bedding orientation with respect to the undeformed Pacific plate are plotted against their mean change in Torlesse bedding orientation with respect to the undeformed Pacific plate. The rotation [R] and flattening [F] parameters and their associated errors at the 95% confidence level (DR and DF) have been calculated using the method of Beck [1980] and DeMarest [1983].

[30] In marked contrast to the large rotations observed in Paleocene to middle Miocene rocks, there appears to be either no clockwise rotation, or even a small amount of anticlockwise rotation, for localities younger than 8 Ma. Thus, virtually all of the clockwise vertical axis rotation must have occurred between 25 and 8 Ma, with a majority of this between 17 and 8 Ma.

5.2. NE Marlborough

[31] Paleomagnetic studies [Vickery and Lamb, 1995] show that the largest clockwise rotations in NE Marlborough are generally ~35° greater than those for the region farther southwest in central Marlborough (Figures 7a and 7b). An average clockwise rotation of ~35° is also observed in this region for the late Miocene and younger rocks (Figure 7b). The simplest explanation for this is that both central and NE Marlborough have had a similar rotation history until ~8 Ma, but that subsequently NE Marlborough underwent an extra phase of rotation. Unfortunately, the distribution of paleomagnetic localities is still too sparse to determine the exact extent of the boundaries.
between rotational domains in central and NE Marlborough, though it may coincide with the kink in the structural grain identified by Little and Roberts [1997].

6. Kinematics Models of Vertical Axis Block Rotation

6.1. Theoretical Framework

The previous analysis suggests that the pattern of clockwise vertical axis rotation documented in both our structural and paleomagnetic data for central Marlborough is the result of distributed finite strain around the plate boundary zone since the early-middle Miocene. However, the precise mechanism of block rotation will determine the magnitude of finite displacements that we might deduce from the rotations. Although on a large scale (equivalent to the width of the plate boundary zone) the deformation may appear more distributed, our fundamental assumption is that paleomagnetism records the rotation of rigid crustal blocks [Lamb, 1987]. This is because upper crust must deform in a brittle manner, and there is no evidence for significant faulting or shearing within the palaeomagnetic localities.

One model of block rotation, referred to as the floating block model, assumes that the blocks are effectively “floating” on a fluid-like underlying part of the lithosphere, and that their motion is principally driven by the underlying flow (Figure 8) [McKenzie and Jackson, 1983; Lamb, 1987, 1994]. Lamb [1994] showed that, even if the blocks are driven by forces at their edges rather than at their base, they would be expected to rotate in a similar fashion to that predicted by the floating block model. In fact, simple considerations of the symmetry of both the block shape and finite strain suggest that the basic features of block rotation will be shared by almost all models of block rotation [Lamb, 2001]. For this reason, we believe that the floating block model is a useful guide to the rotational behavior of rigid blocks, regardless of the true rheological model, and has the added advantage of being mathematically tractable.

In the following analysis, we attempt to account for the first-order pattern of rotation and bending observed in the Marlborough region, using the floating block model. To this end, we assume that the large-scale mode of deformation in the region is essentially simple shear in a zone parallel to the Wairau fault, consistent with the overall pattern of both Quaternary and earthquake faulting, and geodetic studies. In other words, the velocity or displacement vectors are constant and aligned parallel to the trend of the zone, although their magnitudes will vary across its width. The floating block model predicts that the vertical axis rotation rates of the blocks will be a function of both their plan view aspect ratio ($k$) and orientation, except in the special case when blocks are equidimensional. Given an underlying simple shear flow, there are two end-member situations, which can be represented by equidimensional blocks (aspect ratio = 1) and elongate blocks (aspect ratio $\ll 1$). The amount of rotation $R$ expected for these different situations, assuming small blocks, is given by the following formula [Lamb, 1987]:

\[
\begin{align*}
\text{Equidimensional block (} k = 1 \text{): } R &= -0.5 \frac{dU}{dx} , \\
\text{Elongate block (} k \ll 1 \text{): } R &= \tan^{-1} \left( \frac{dU}{dx} - \phi \right). 
\end{align*}
\]

where axes $x$ and $y$ are orientated parallel and perpendicular to the zone (Figure 8), $U$ is the displacement in the $x$
direction, $\phi$ is the initial orientation of the block relative to the shear zone, and $k$ is block aspect ratio.

[35] If we are to apply these models to the observed rotational data, we also need a displacement field for the shear zone. We add to the assumption of simple shear an exponential increase in displacement away from the plate boundary (or a reduction away from the Wairau fault). Such an exponential form is sufficiently general, with two degrees of freedom (see below), to have no specific dynamical implications, but is, in fact, the form of analytical solutions to flow of a thin viscous lithosphere [England et al., 1985; Sonder et al., 1986]. In addition, this approximation fits well with the geodetic velocity field southeast of the Alpine-Wairau fault zone [Moore et al., 2002]. Assuming no variation in strike-parallel displacement ($du/dy = 0$), the exponential decay of displacement across the shear zone is defined by the following relation, where the origin $x = 0$ is defined to be at the Wairau fault:

$$U = U_0 e^{(-x)/\lambda},$$

$$\frac{dU}{dx} = \frac{U_0}{\lambda} e^{(-x)/\lambda},$$

where $U_0$ is the displacement relative to the Pacific plate at the Wairau fault and $\lambda$ is a constant associated with length scale of deformation.

[36] By combining equations (1)–(4), theoretical curves of rotation against distance can be calculated for both the equidimensional and elongate block models. The behavior of these blocks can then be compared with the observed

\[Figure 6.\] Geological map showing the observed tectonic rotation of all paleomagnetic locations in the Marlborough region, labeled by abbreviations (see Tables 1 and 2). Shading indicates age of rock: solid: >17 Ma; open <8 Ma. Short-dashed line represents line of section in Figure 7. Long-dashed line represents average trend of the structural data, from Figure 2.\]
rotational data to find a best fit solution, searching for values of $U_o$ and $\lambda$ that minimize the root-mean-squared (RMS) misfit between the model and the observations. Uncertainties in this fit can be investigated more fully by conducting a Monte Carlo simulation of the observations, given their observational uncertainties. For the elongate block model, the rotation depends critically on the initial orientation. We assume that the long axes of the blocks were initially everywhere parallel to the strike of the structural grain ($\sim 110^\circ$) at the edge of the Pacific plate (Figure 6).

**6.2. Results**

[37] The best fit solutions for the floating block model, given the two end-member block shapes, are shown in Figure 9. These are presented in terms of both the predicted vertical axis rotation (Figure 9a) and the predicted finite displacement (Figure 9b). Table 3 shows the relevant parameters for each best fit solution.

[38] It is clear that the elongate block model has a better fit to the data. The RMS misfit and the error bands (for the Monte Carlo analysis) are smaller for elongate blocks than equidimensional blocks, and the rotation of elongate blocks reproduces the pattern of deformation much more successfully at large distances from the deformation origin. The equidimensional block model requires a greater length scale of deformation ($l$) than that suggested by the width of the plate boundary zone.

[39] It is important to emphasize that our analysis so far incorporates no information about observed displacements, only strike measurements of the strata without any reference
to faulting or continuity of particular rock units. Therefore a comparison with an estimate of the actual displacement field should distinguish between the two end-member block shapes, or perhaps some intermediate shape. The only feature in the Marlborough region that potentially could be used to estimate the actual displacement field is the Esk Head subterrane. Unfortunately, this is both poorly exposed and defined. Therefore we compare the model results with the displacement field determined from the much better defined geometry of the Junction Magnetic Anomaly of the Maitai terrain in the southern part of South Island (Figure 1). On a large scale, this is an essentially continuous band, so forms a passive marker line in the finite strain. If the Junction Magnetic Anomaly’s geometry SE of the Alpine fault had formed in a zone of simple shear, as used in our model, a total displacement of $\sim 170$ km across a width of $\sim 175$ km (equivalent to a bulk shear strain $\gamma \sim 0.91$) would be required to produce the observed outcrop pattern [Molnar et al., 1975; Norris, 1979; Sutherland, 1999].

Figure 8. Schematic diagram of rotating crustal block. The diagram represents a rigid block lying over a continuously deforming shear zone. The aspect ratio of the block is given by $a/b$. The underlying velocity field is parallel to the strike of the shear zone, with $U_o$, representing the velocity at the fault zone.

There are, however, some significant discrepancies that should be noted. The displacement implied by the Junction Magnetic Anomaly is significantly less than our elongate block model predictions, at the 1 sigma error, for distances less than about 10 km from the Alpine-Wairau fault, and overall, the terrane shows systematically slightly less displacement than predicted. This misfit cannot be accounted for by adopting a less elongate block shape, as such a shape would only make the misfit worse. The explanation may simply be that the model and the observations are from different regions and the distribution and amount of distributed deformation may also differ slightly.

It is more likely that our model displacement is too high. From the overall pattern of bending either side of the Alpine-Wairau fault zone, defined by features such as the Junction Magnetic Anomaly [e.g., Hunt, 1978], an actual distributed shear displacement is expected of nearer $170$ km [Molnar et al., 1975; Norris, 1979; Sutherland, 1999]. The problem may lie in the details of the exponential displac-

Figure 9. Kinematic modeling results. (a) Minimum misfit curves for both equidimensional (thin dashed line) and elongate block models (continuous line) to the mean structural rotation data (circles with 1 sigma error bars). Model errors calculated using Monte Carlo analysis. (b) Displacement curves for each minimum misfit model. The approximate displacement curve of the Junction Magnetic Anomaly is added for reference (thick dashed line).
ment field used in our model. A significant amount of this displacement occurs within a few tens of kilometers of the Wairau fault ($x = 0$), and cannot really be resolved with our analysis. But these are really secondary effects, and our aim has been to account for the general geometry and length scale of deformation, and hence distinguish between the two end member styles of block rotation.

The paleomagnetic data for NE Marlborough shows clockwise rotations up to $140^\circ$ in middle Miocene and older rocks, however equation (2) will not allow a rotation of an elongate block of more than $120^\circ$, given our assumed initial orientation. In this case, the elongate block model cannot entirely explain the paleomagnetic observations in NE Marlborough. However, a comparison with the rotations in central Marlborough suggests that all of Marlborough rotated in a similar fashion until $8$ Ma, after which an extra $35^\circ$ of clockwise rotation occurred in NE Marlborough. This additional rotation could be explained if blocks in NE Marlborough during the last $8$ Ma were more equidimensional. In this case, it is clear from equation (1) that rotation can continue beyond $120^\circ$.

7. Geological History

7.1. Central Marlborough Bending

The good correlation between the structural and pre-17 Ma paleomagnetic data places the majority of the basement terrane deformation to within the Neogene, contemporaneous with the main phase of strike-slip deformation in the South Island. In other words, the large-scale bend of the basement has been produced by Cenozoic distributed deformation across the plate boundary zone (Figure 10). This fits in well with Little and Mortimer’s [2001] conclusion that Neogene reverse faults and folds on both sides of the Alpine fault have been involved in significant degrees of vertical axis rotation.

The predominantly Miocene age of the vertical axis rotation correlates with a major increase in sedimentation rates at this time, marking the beginning of significant tectonic activity in the region [Lamb and Bibby, 1989; Rait

<table>
<thead>
<tr>
<th>Model</th>
<th>$U_0$, km</th>
<th>$l$, km</th>
<th>RMS, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equidimensional blocks</td>
<td>511 ± 79</td>
<td>126 ± 26</td>
<td>14</td>
</tr>
<tr>
<td>Elongate blocks</td>
<td>273 ± 52</td>
<td>56 ± 16</td>
<td>11</td>
</tr>
</tbody>
</table>

$^{a}U_0$ is the total displacement across the deforming zone, $l$ is a measure of the length scale over which the deformation decays away from the Wairau fault, and RMS is the root-mean-squared misfit of the observations to the model.

Figure 10. Cartoon to summarize the Neogene evolution of the Marlborough region. (a) Before formation of the plate boundary zone in the Eocene, the Junction Magnetic Anomaly formed a straight line across the region. (b) From the late Oligocene to late Miocene the relative plate motion was almost pure strike slip. The strain was partitioned between discrete motion on the Alpine fault and more distributed deformation, which gave rise to the vertical axis rotation of the South Island basement terranes. (c) After the introduction of a significant component of convergence to the plate motion in the late Miocene, distributed deformation probably ceased in the central Marlborough region, with all relative plate motion now taken up on the discrete strike-slip faults. Distributed deformation, however, is still ongoing in the central Alpine regions.
Plate reconstructions show that strike-slip deformation along the plate boundary began much earlier, in the early Oligocene (~35 Ma), however at this time, the relative pole of rotation of the Australian relative to the Pacific plate was very close to the plate boundary zone, so that the rate and amount of motion would have been small. Between the late Oligocene and early Miocene, the relative rotation pole rapidly moved away from the plate boundary and the rate of relative plate motion accelerated [Sutherland, 1995; Walcott, 1998], possibly leading to the initiation of the Alpine fault [Norris and Turnbull, 1993]. Therefore it is likely that the majority of relative plate motion has been accommodated since this time, consistent with the predominantly Miocene age of the vertical axis rotation. Indeed, late Quaternary slip rates on the Alpine fault suggest that in the central part of South Island, distributed deformation may still be ongoing, potentially accounting for 30% of current plate motion [Norris and Cooper, 2000].

Our simple kinematic model illustrates a plausible mechanism of deformation consisting of rigid elongate crustal blocks within a shear zone, riding and rotating on a continuously deforming lithosphere. The shear across the Marlborough fault decays significantly over ~150 km, on the same length scales as the geodetically determined velocity field [Bourne et al., 1998]. This is also comparable with the length scales of deformation at the southern end of the plate boundary zone, inferred from the geometry of the Junction Magnetic Anomaly. Although geodetic data and surface geology show the width of deformation may be slightly narrower in the central Alpine fault zone [Walcott, 1998; Beavan et al., 1999], overall there appears to be a surprisingly uniform zone of shear along the whole length of the plate boundary zone, possibly because the distributed deformation has occurred by similar deformational mechanisms. The total displacement of 273 ± 52 km predicted by the kinematic model is plausible (though possibly a few tens of kilometers too high), despite the simplicity of the model’s underlying assumptions.

Rotation of elongate blocks in the brittle upper crust must occur by faulting, yet there is no evidence of large-scale faults, with offsets greater than a few kilometers, which could accommodate this rotation. For example, the Esk Head subterrane appears to be essentially continuous, except for relatively minor (<20 km) offsets across the Marlborough faults. Given the Quaternary slip rates on the Marlborough faults, these offsets could have been achieved in much less than 5 Myr and so are likely to have occurred relatively late in the geological evolution of the region. In the south, the Maitai terrane and the Junction Magnetic Anomaly within it, have a very similar geometry, with virtually no offsets. The mechanism of continuous deformation must therefore be a more pervasive shear, which is accommodated by motion on many smaller-scale faults.

The large-scale distributed pattern of Neogene finite strain in the upper crust still needs to be reconciled with the fact that the paleomagnetic rotations must be those of rigid blocks. The rotation of numerous small and very thin elongate blocks, parallel to the main structural fabric, with small amounts of slip occurring between the blocks, seems to be the only way of fitting both these requirements. This is in contrast to the behavior of equidimensional blocks, which would require much larger discrete faults between the blocks because their rotation will accommodate only about half of the overall shear (equation (1)). The elongate block model is compatible with the style of the most recent phase of deformation of the Torlesse terrane. This is at least partially Cenozoic in age and has involved pervasive faulting, bedding plane shear and brecciation on a variety of scales [Little and Roberts, 1997]. This indicates that, on a regional scale, deformation has occurred in a relatively distributed fashion at shallow depth. However, on a smaller scale, any more rigid units present within the terrane would have remained as coherent elongate blocks, running parallel to the strike. Both extensional basins and thrust faulting would be expected to accompany such block rotation. These are hard to distinguish within the Torlesse basement as these features would only have small-scale offsets and there are no well-defined marker beds within the study region. There are, however, numerous Neogene basins and thrust faults present in the NE Marlborough region, which run subparallel to the structural grain [Little and Roberts, 1997; Audru and Delteil, 1998]. Furthermore, Little and Mortimer [2001] attribute Oligocene-Miocene faults and folds observed elsewhere along the South Island plate boundary zone to a similar mechanism of distributed deformation.

The models explored in this paper, strictly speaking, assume that the surface deformation is a direct result of distributed deformation in the lithospheric mantle beneath. As the patterns of surface deformation implied by the model correlate with both the observed surface marker terranes and the geometry of distributed deformation in the underlying mantle [Molnar et al., 1999], it is reasonable to suggest that the finite strain in the lithospheric mantle has occurred within the same time frame.

Despite the poor spatial resolution of the paleomagnetic data, the simplest interpretation is that the central Marlborough region has undergone little rotation (<10°) in the last 8 Ma. Compilations of current fault slip rates indicate that Quaternary motion on the individual Marlborough faults accounts, within error, for the current relative plate motion and the geodetically determined instantaneous velocities [Holt and Haines, 1995; Bourne et al., 1998], though the uncertainties involved in this comparison are of the order of 30%. Thus, it is plausible that since the late Miocene, block rotation played a minor role in the accommodation of relative plate motion in the central Marlborough region. If the Marlborough faults initiated around 6.4 Ma, coincident with the onset of significant convergence [Walcott, 1998], then it seems likely that these faults accommodate the strain previously taken up by distributed shear. Even if there were still some distributed deformation between the faults, this rotation would be expected to be very slow because of the unfavorable orientation of the elongate blocks (see equation (2)).

7.2 NE Marlborough

The situation in NE Marlborough appears to be very different from that in central Marlborough, with continued
rapid block rotation between the faults since 8 Ma. Our kinematic model suggests that the rotation of equidimensional blocks, rather than elongate blocks, would be a better description for this area. Such blocks must be defined by both the main Marlborough faults and additional cross faults [Lamb, 1994]. This style of deformation may be a consequence of the kinematic requirements of fault termination in the MFZ at the subduction zone.

8. Conclusions

[52] The structural and paleomagnetic data presented here indicate that approximately 100° of clockwise rotation of the crust has occurred across the Marlborough region during the Neogene. Most of this took place between the early and late Miocene (circa 25–8 Ma), indicating that the curved geometry of the basement terranes has formed contemporaneously with the majority of motion on the Alpine-Wairau fault, and is due to more distributed shear across the plate boundary zone. Overall, Neogene finite strain has been partitioned between distributed shearing and discrete deformation on the Alpine fault. A simple kinematic model suggests that this distributed deformation has been accommodated by the rotation of small elongate blocks parallel to the main fabric, in response to continuous deformation in the underlying lithospheric mantle beneath.

[53] The introduction of a significant convergent component to the plate motion in the late Miocene, and possibly the subsequent formation of the MFZ in its current configuration, may have resulted in a major change in deformational regime in the Marlborough region. In the southeastern part of the MFZ (central Marlborough), distributed deformation may have ceased to play such a significant role, and the motion became concentrated on the Marlborough faults themselves. The northeastern part of Marlborough (NE Marlborough) appears to have a different deformational history from the late Miocene to the present, with an extra clockwise rotation of ~35° that might be explained by the reorganization of the crust into more equidimensional blocks where they terminate against the Hikurangi margin.

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