Large tectonic rotations since the Early Miocene in a convergent plate-boundary zone, South Island, New Zealand

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Received 31 March 1995; accepted 21 July 1995

Abstract

A palaeomagnetic study in part of the New Zealand plate-boundary zone provides new constraints on the temporal and spatial distribution of Neogene and Quaternary tectonic rotations. Thermal demagnetization of samples from Cretaceous basaltic dykes, Palaeocene–Oligocene micritic limestone, and Miocene and Pliocene siltstones in the Marlborough region, South Island, have defined stable, high-temperature magnetic components, which are interpreted as the primary magnetization. Declination anomalies, after tectonic corrections, are interpreted as rigid body rotations about a vertical axis of sample sites relative to the Pacific plate. All palaeomagnetic data from Marlborough cluster into three main groups. A 60–100° clockwise rotation affected Palaeocene to Middle Miocene sedimentary sequences across Marlborough between N 18 Ma and ~ 8 Ma, coeval with a phase of low-angle thrusting. The absence of this rotation in a Late Cretaceous dyke swarm defines the present western limit of the early rotating zone. A regional ~ 20° clockwise rotation occurred in the last 4 Ma during the development of the Marlborough Fault System in a zone of dextral transpression, although locally clockwise rotations ≤ 40° may have occurred near some of the major dextral strike-slip faults. However, a negligible rotation is observed in the same period in the region to the southeast of the major Kekerengu dextral strike-slip fault, which appears to have acted as a hinge zone, accommodating relative rotation by dextral strike-slip on an arcuate fault, bending, and internal deformation. The observed tectonic rotations record the overall clockwise rotation of the trend of the southern end of the Hikurangi margin from W to NW in the Early Miocene to ~ NE today, determined independently from the long-term relative plate motion data for the Pacific and Australian plates.

1. Introduction

An important problem in geology is the relationship between deformation within plate-boundary zones and the motions of the bounding plates. The latter is usually derived from oceanic magnetic anomalies, while the former is determined from detailed field observations. As yet, there is no plate-boundary zone where a complete quantitative agreement has been demonstrated between the inferred long-term relative plate motions and the observed internal deformation. This may partly be a consequence of the uncertainties in long-term plate reconstructions. However, part of the problem may also lie in the difficulty of detecting tectonic rotations, which may form an important component of the deformation. In this respect, palaeomagnetic studies are particularly important, because palaeomagnetic declination anomalies can be used to determine rigid body rotations about vertical axes.

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The problem discussed above is particularly evident in the New Zealand plate-boundary zone, where the oceanic Pacific plate is being subducted beneath the continental Australian plate along the Hikurangi margin (Fig. 1a). Here, plate reconstructions back to Anomaly 6 (Early Miocene), based on finite rotation poles for New Zealand [1], suggest a clockwise rotation of the whole Hikurangi margin with respect to the Pacific Plate from W-NW to NE-trending today [2]. Such large rotations have important implications for our understanding of the evolution of this region and pose a significant structural problem in the hinge zones at the ends of the rotated segments [3,4].

Numerous palaeomagnetic studies [2,3,5,6] in the New Zealand plate-boundary zone, combined with geodetic studies [7], have demonstrated that the Hikurangi margin is rotating rapidly clockwise about a vertical axis and sections have rotated $\leq 35^\circ$ relative to the Pacific plate in the last 4 Ma. However, the sparse evidence for large, pre-Late Miocene, tectonic rotation has left open the question of whether the on-land structural evolution of the plate-boundary zone is consistent with the inferred long-term relative plate motions. Reconciling these may help to both increase our confidence in the inferred long-term relative motions of the Pacific and Australian plates, and also improve our understanding of the behaviour of continental lithosphere in wide plate-boundary zones. In this paper, we address this question by analysing the Neogene history of tectonic rotation near the hinge zone at the southern end of the Hikurangi margin.

1.1. Study area

The study area is located in a zone of dextral transpression, referred to as the Marlborough Fault System, at the northern end of the South Island (Figs. 1b and 2), where subduction is linked to displacement on the Alpine Fault by five major active dextral strike-slip faults [8]. Geodetic studies [7,11] suggest that the current plate motion is accommodated onshore in the Marlborough Fault System,
which is one of the most tectonically active regions in the world. The instantaneous convergence of the Pacific plate relative to the Australian plate in this region is \( \sim 42 \text{ mm/yr} \) at 255° (NUVEL-1 model in [12]).

Lamb [3] divided the Marlborough Fault System into two domains, based on distinct differences in structure. In the southern domain, the major strike-slip faults trend \( \sim 080° \), and are essentially pure strike-slip faults, nearly parallel to the plate convergence direction [13]. In the northern domain, these faults trend more nearly NE and have a significant component of thrusting, giving rise to the rapidly uplifting Kaikoura ranges. Also, the boundary be-

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**Fig. 2.** Geological map of Marlborough (see Fig. 1b for location), showing major faults and the distribution of Pre-Cenozoic basement, Late Cretaceous to Miocene, and Late Miocene to Pliocene sedimentary sequences (after [8,9]). Also shown are the location and mean site declination for all palaeomagnetic sites in the region, labelled by abbreviations (see Table 1, this study and previous work). * = Sites in this study; all remaining sites are from [1,6,19].
tween the two domains more-or-less coincides with the southern edge of the seismically active subducted Pacific plate, so that only the northern Marlborough domain is underlain by a well defined Benioff zone (Fig. 1b, [13,14]).

Lamb and Bibby [4] proposed a two-phase model for the Neogene and Quaternary history of tectonic rotation in the Marlborough region, with large clockwise rotations during a phase of Early Miocene thrusting (D₁, [4,15–17]) and subsequent clockwise rotation of 20–40° [6,18] during Plio–Pleistocene strike-slip deformation (D₂). Although this model was consistent with plate reconstructions [2], palaeomagnetic evidence for regional tectonic rotation during the D₁ phase of deformation was lacking. For instance, Rait et al. [16], using a different structural interpretation, have proposed that there was no tectonic rotation of the New Zealand plate margin in the Marlborough region prior to the Pliocene.

We combine new palaeomagnetic data for Marlborough with new structural interpretations [17] and previous palaeomagnetic work, to constrain the spatial and temporal distribution of rotational strain and its accommodating structures in Marlborough since the Early Miocene.

1.2. Palaeomagnetic sampling

Previous palaeomagnetic studies in the Marlborough region have only obtained, with one exception, successful results from Late Miocene to Pliocene siltstone units [6,18,19]. Thus, many gaps exist in both the temporal and spatial coverage of rotational strain (Fig. 2). In this study, a total of 16 new sites were drilled in Palaeocene to Pliocene sedimentary rocks, and a Late Cretaceous dyke swarm, in an attempt to fill sampling gaps, both in time and space (Fig. 2). Fig. 2 shows the location of the drilled sites from this study, together with all existing palaeomagnetic sites from the Marlborough region.

A minimum of 6 unweathered cores, spanning a stratigraphic thickness large enough to average out the effects of secular variation (> 10,000 yr), were taken from each site using a portable petrol-engined drill with a brass, diamond-tipped barrel (internal diameter 25 mm). All sites contained clear evidence of bedding and way-up, and a lack of internal deformation. Siltstone cores were collected from water-saturated outcrops close to stream level and wrapped in cling film in order to prevent drying out, which had previously been shown to produce a strong viscous remanence [19].

2. Palaeomagnetic results

The magnetization from unaltered specimens was measured on CCL cryogenic and Molspin magnetometers at the Department of Earth Sciences at Oxford. All samples were subjected to stepwise thermal demagnetization until no measurable signal remained (typically <1% of the initial intensity). Also, bulk susceptibility was measured after each step to monitor the growth of magnetic minerals during heating. The magnetic mineralogy of selected samples from each site was investigated using alternating field demagnetization and Isothermal Remanent Magnetization (IRM) acquisition. Components of the sample magnetic field were analyzed with orthogonal Zijderveld plots (Z-plots), using the LINEFIND algorithm [20], to determine best-fitting magnetic vectors.

A description of each locality and demagnetization data are summarised below. Palaeomagnetic results, including previous studies, are shown in Table 1.

2.1. Late Cretaceous dykes

2.1.1. Geological setting

The Awatere and Clarence faults enclose a block of pre-Cretaceous and intensely deformed greywacke sequences, which are overlain by the well bedded and gently dipping Cretaceous Gladstone and Winterton formations, including Late Cretaceous Lookout Formation lavas (Fig. 2, [21]). Southeast of the Awatere fault, in the middle Awatere valley, a dyke swarm of more than 500 dykes with a clear alkaline affinity [22] intrudes Cretaceous sedimentary rocks and older basement. The dykes generally have a consistent orientation, striking at ∼100°.

The Late Cretaceous sedimentary sequences, lavas and dykes in the middle Awatere valley are folded into a broad syncline and anticline, trending 040° and plunging at 5–7° to the southwest. The folds are cut by splays off the main Awatere fault and by a
number of normal faults. The dykes themselves are not internally folded or faulted. The sample sites in Gladstone Stream (GS1) and Winterton River (WS1) are structurally separated by a low-angle fault, which the dykes intrude and post-date. Gladstone Stream is not internally folded or faulted. The sample sites in period 100-60 Ma. Grapes et al. [22] found no dates for the Awatere dyke swarm [22] span the feeders to the Late Cretaceous Lookout lavas. K/Ar are structurally separated by a low-angle fault, which Gladstone Stream (GS1) and Winterton River (WS1) are shown in Figs. 3 and 4c.

Challis reported that a couple of the dykes were feeders to the Late Cretaceous Lookout lavas. K/Ar ages are emplacement ages. Even if this apparent age range is the result of argon loss, it does not affect our evidence for alteration and concluded that the K/Ar ages are emplacement ages. Even if this apparent age range is the result of argon loss, it does not affect our conclusions.

2.1.2. Demagnetization (Figs. 3a and 4c)

Demagnetization of cores from the Gladstone Stream site (GS1) removed an unstable low-temperature component between 0° and 270/325°C, and a stable, linear, high temperature component between 270/325° and 585°C. Demagnetization of cores from the Winterton River site (WS1) removed similar components up to 585°C, although most displayed curved sections between components. In such cases, the high temperature components were calculated using great circle analysis. A typical demagnetization plot and a stereogram of magnetic vectors for site GS1 are shown in Figs. 3 and 4c.

The maximum unblocking temperature of these cores (585°C) is close to the maximum Curie temperature of magnetite grains. Alternating field demagnetization and IRM acquisition, showing satura-

Table 1

Palaeomagnetic data from Marlborough, South Island, New Zealand, including both this study and previous work

<table>
<thead>
<tr>
<th>Site</th>
<th>In Situ Df (°)</th>
<th>Correction 1 (1) Df (°)</th>
<th>Correction 2 (2) Df (°)</th>
<th>Plunge (3)</th>
<th>Tilt (4)</th>
<th>αφ (5)</th>
<th>N</th>
<th>K</th>
<th>Δ±δ (°)</th>
<th>Age (Ma)</th>
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<td></td>
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<td>307/-74</td>
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<td>237/-35</td>
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<td>65</td>
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<td>67</td>
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<td>301/-71</td>
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<td>22</td>
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<td>122±12°*</td>
<td>084/-10</td>
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<td>11</td>
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Previous Studies:

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See Fig. 2 for location of sites. Preferred declination anomalies, used in this study, are marked with *; (1) simple tilt correction; (2) correction taking into account polyphase folding; (3) expected inclination for site, given its age and latitude and assuming that it has remained part of the Pacific plate; (4) 95% cone of confidence about the mean direction; (5) number of specimens; (6) Fisher precision parameter; (7) declination anomalies with respect to the Pacific plate: positive = clockwise, negative = anticlockwise.
tion at ca. 100 mT, also indicated that magnetite was the remanence carrier.

2.2. Palaeocene–Oligocene limestone

2.2.1. Geological setting

These sites are found in various structural positions within a unit of white to pale pink, micritic marine limestone, referred to as the Amuri Limestone (Fig. 2, [23,24]). This is up to several hundred metres thick, outcropping mainly in the region to the southeast of the Clarence fault. Sites WC1 and WC2 are located within a D1 thrust pile [4,15,17], which has been folded into an anticlinal structure (Benmore Anticline), which plunges ~10° NE between the Clarence and Kekerengu faults (Fig. 2). The eastern limb of this anticline is truncated by the Kekerengu fault and the western limb is adjacent and parallel to the Clarence fault. The sites are part of a unit which youngs and dips at ~50° to the NNE between NNW-trending tilted D1 thrust surfaces, which dip steeply at 70–80° to the ENE.

Sites BB1 and 2 come from a prominent subvertical limestone ridge between Cape Campbell and

Fig. 3. Diagrams showing thermal demagnetization Zijderveld plots for typical specimens from various palaeomagnetic sample sites. □ = declination data; ■ = inclination data. (a) Basaltic dyke at Gladstone stream site (GS1). (b) Micritic pinkish limestone at Woodside Creek site (WC1). (c) Marine siltstone at Heavers Creek site (HC3). (d) Marine siltstone at Washdyke stream site (WD1).
Ward (Fig. 2). This ridge is within a NNE-trending fault zone cutting Late Miocene to Pliocene siltstones and turbidites [8]. The Ward and Cape Campbell synclines fold the siltstone sequences, trending NNE and plunging less than 10° to the north. The limestone is also folded on an outcrop (metres-decametres) scale. Cores were taken from different bedding orientations. The bedding defines a fold axis plunging 26° at 023°.

The pinkish limestone in Woodside Creek at site WC1 lies ca. 35 m stratigraphically above the K/T boundary, defined by Strong [25]. Assuming an average sedimentation rate between 0.3 and 2 cm/ka [26], the age of these sites ranges between ~ 63 Ma and ~ 54 Ma. The limestone has been palaeontologically dated at the New Zealand stages Teuriun to Waipawan (54–66 Ma) [24]. Thus, we assume an age of 59 ± 5 Ma for the sample locality WC1. Site WC2 is from a similar stratigraphic position, although the age is less well constrained due to its more isolated location. The limestone ridge between Cape Campbell and Ward (Fig. 2), which outcrops in Boo Boo Stream, has been dated using foraminifera as part of the New Zealand Landon Series [23] with an Oligocene age (~ 25 to ~ 35 Ma).

2.2.2. Demagnetization (Figs. 3b and 4c)

Demagnetization of cores from the two sites along Woodside Creek (WC1 and WC2), and also Boo Boo Stream (BB1 and 2), removed an unstable, low temperature component up to 220°C followed by a stable, high temperature component between 220°C and 640°C (Fig. 3b). The maximum unblocking temperature exceeds the maximum Curie temperature of magnetite, indicating the presence of haematite grains (suggested also by the pinkish colour of the limestone). IRM acquisition showed the presence of magnetites and haematite (± geothite) within the samples.

2.3. Miocene siltstone

2.3.1. Geological setting

These sites all come from the deformed region to the southeast of the Kekerengu fault (Fig. 2). This region has undergone a complex sequence of deformation [4,17]. Early D1 thrusting and folding was followed by a later D2 episode of folding and strike-slip deformation. Beds generally dip greater than 50°. Sites HC1–3 are from a sequence of folds in siltstones and sandstones which plunge variably less than 30° near the Kekerengu and Heavers Creek strike-slip faults. Sites SS1 and 2 are in a homoclinal, eastward-younging and conformable sequence of Amuri Limestone to Miocene conglomerates, which are slightly overturned and dip at ~ 70° to the west. The tilted beds are cut by five dextral strike-slip faults with individual offsets of a few hundred metres. Sites WB1–3 are in siltstones near the axis of a kilometre-scale syncline, defined mainly by units of Amuri Limestone, which plunges steeply to the north.

Dating is based on biostratigraphical correlations using foraminifera [8,17,27–29] to the New Zealand stages Lillburnian–Otaian (15–24 Ma).

2.3.2. Demagnetization (Fig. 3c)

Cores had relatively weak initial intensities (generally < 0.5 mA/m). Demagnetization in many cores displayed overlapping blocking temperature spectra, although one or two cores from each site reached a stable end-point. Thus, great circle analysis was used in many cases to calculate the higher temperature component direction. Demagnetization of the remaining cores removed an unstable, low temperature component between 0° and 100°C, and a stable, high temperature component between 100°C and 450°C (Fig. 3c), although many cores became unstable above 400°C.

The maximum unblocking temperature and IRM acquisition were both indicative of titanomagnetite ± pyrrhotite.

2.4. Pliocene siltstone

2.4.1. Geological setting

Sites WD1 and WD2 are in massive and turbiditic siltstones, exposed in the coastal regions southeast of the Kekerengu fault (Fig. 2). In the south, these siltstones are in sedimentary contact with, and lie directly above, older Miocene conglomerates. However, there is a marked age difference across this contact which suggests an unconformity (see below). The siltstone beds, themselves, strike NNW and dip
mostly at 50–86° to the east. Eastward younging evidence was found in the south, close to the lower contact with the conglomerate.

Dating is based on biostratigraphical correlations, using foraminifera, to the New Zealand stages Nukamaruan–Opoitian (2–5 Ma) [17,28,29].
Table 2
Fold tests [30] on palaeomagnetic data in Marlborough, South Island, New Zealand, using data from this study and previous work.

<table>
<thead>
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<th>Sites</th>
<th>(1) N</th>
<th>(2) k₁</th>
<th>(3) k₂</th>
<th>k₂/k₁</th>
<th>Significance of fold test</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sites in this study</td>
<td>10</td>
<td>2.5</td>
<td>9.4</td>
<td>3.76</td>
<td>Yes at 99% level</td>
</tr>
<tr>
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<td>11.4</td>
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<td>Yes at 99% level</td>
</tr>
<tr>
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<td>204.2</td>
<td>9.0</td>
<td>Yes at 99% level</td>
</tr>
<tr>
<td>Group 2</td>
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<td>17.1</td>
<td>162.2</td>
<td>13.4</td>
<td>Yes at 99% level</td>
</tr>
<tr>
<td>Group 3</td>
<td>8</td>
<td>2.6</td>
<td>46.3</td>
<td>17.81</td>
<td>Yes at 99% level</td>
</tr>
</tbody>
</table>

(1) Number of sites in test; (2) Fisher precision parameter for uncorrected sites; (3) Fisher precision parameter for corrected sites.

2.4.2. Demagnetization (Figs. 3d and 4c)

Cores from WD1 and WD2 had relatively strong initial intensities (l₀ max: 36 mA/m) in comparison to cores from sites in Miocene siltstone. Demagnetization removed two clear components: a low temperature component between 0° and 100°C, and a stable, linear, higher temperature component between 100° and 350°C (Fig. 3d).

IRM acquisition and demagnetization characteristics suggest the presence of both magnetite and pyrrhotite grains.

3. Tectonic correction

If the high temperature components represent the primary magnetization, acquired soon after deposition or emplacement, they should be corrected for subsequent folding. Two corrections were applied: a simple rotation about the in situ strike of the beds (correction 1), and a plunge and tilt correction (correction 2). For sites in the Awatere valley (sites GS1 and WS1) and those between Cape Campbell and Ward (BB1 and BB2), correction 2 was a simple plunge and tilt correction. For all other sites, correction 2 takes into account the possibility of polyphase folding [17]. For these sites, plunge was removed by rotating bedding and the mean component about the second phase fold axis (321°/00°) by the amount required to restore the site's relevant fold axis back to the horizontal. This was followed by a straightforward tilt correction of the plunge-corrected magnetization, restoring bedding back to the horizontal. The uncorrected magnetization at sites WB1-3 is parallel to the present day field and is not discussed further (Table 1).

The corrected magnetization directions, expressed as declination and inclination, for palaeomagnetic sites obtained during this study, are shown in Table 1. Table 1 also includes data from previous studies. The magnetization directions for each site can be expressed in terms of a declination anomaly. This is the difference between the tectonically corrected magnetization direction and the expected direction for the site latitude and longitude (see later), given the site age and assuming that it has remained part of the Pacific Plate. It is clear that many sites have large declination anomalies.

Fig. 4. Equal area stereograms illustrating mean magnetic directions for sample sites throughout Marlborough, from this study and previous work (recalculated in all cases for upper hemisphere stereoplots, see Table 1). (a) Uncorrected (in situ) and corrected (tectonic correction) site palaeomagnetic directions are compared. There is a marked improvement in clustering after tectonic correction (Table 2), suggesting that magnetization was acquired prior to folding and is primary. (b) In detail, after tectonic correction, three groups of sites can be recognised. Group 1 sites show negligible declination anomalies (relative to the Pacific plate) in Pliocene sites, with a mean of 355°/−57°. Group 2 sites show moderate clockwise declination anomalies in Late Miocene and Pliocene sites and Late Cretaceous dykes, with a mean direction of 027°/−63°. Group 3 sites show large clockwise declination anomalies in Palaeocene and Early Miocene sites, with a mean of 123°/−63°. In detail, Groups 2 and 3 can be further subdivided (see text). (c) Equal area plots (after tectonic correction) of individual high temperature magnetic components defined from Zijderveld plots of thermal demagnetization (flipped to upper hemisphere for reversed magnetisation) for basaltic dykes from Gladstone Stream site (N = 15, site GS1); micritic pinkish limestone from Woodside Creek (N = 30, site WC1); siltstone from Washdyke Creek (N = 15, site WD1). See Table 1 for site details.
3.1. Fold tests

The validity of applying a tectonic correction to the high temperature magnetic components can be checked by applying a fold test (Table 2). We used the McElhinny fold test [30], assuming that the palaeomagnetic data represent a relatively simple pattern of declination anomalies. We can compare the scatter of all sites without any tectonic correction with that for these sites with a tectonic correction. We would expect the tilt correction to reduce the scatter. In this case, the sample sites in this study pass the McElhinny Fold Test at the 99% confidence level. We extended this test by applying it to all the available palaeomagnetic data for Marlborough. These also pass the fold test at the 99% confidence level (Fig. 4a).

It is clear, from inspection of the palaeomagnetic data, including that from previous studies, that they do not form a single simple cluster. We believe that, in detail, we can recognise three distinct groups, labelled Groups 1, 2, and 3 (Fig. 4b). If we perform the fold test individually for each of these groups, we find a very marked improvement in clustering and they all pass the fold test with the 99% confidence level. All this suggests that the tilt corrections are valid.

3.2. Declination and inclination anomalies

The Alpine Fault and its extension, which has accommodated a large proportion of the relative plate motion in the New Zealand region, lies to the north and west of the Marlborough region (Fig. 1b). Therefore, it seems appropriate to consider the Marlborough region as contiguous with the Pacific plate and quote all declination anomalies with respect to this plate. During the last ~20 Ma, the Pacific plate has undergone negligible rotation relative to true north, although there has been some latitudinal drift [31]. Therefore, for rocks younger than 20 Ma, the declination anomaly will merely be the mean palaeomagnetic declination (assuming normal magnetization). Palaeolatitudes from Lawver et al. [31] were used to compare the observed and expected inclinations for each site (Table 1). For rocks older than 20 Ma, there have been substantial changes in the longitude, as well as latitude, of the Pacific plate. For this reason, the expected declination and inclination of the primary component at these sites was calculated from the polar wander path for Australia and finite rotation poles for the New Zealand region relative to Australia ([17], Table 1).

In all cases (excluding sites WB1–3, which gave a present day field direction without a tilt correction), the tectonically corrected inclinations fell within error of the expected inclinations, considering the site age and coordinates. This supports the conclusion that all these directions represent primary magnetizations acquired at or near to the time of formation of the lithological units.

4. Interpretation

Since there is no evidence for pervasive and penetrative shear fabrics in any of the sample sites, the declination anomalies can be interpreted in terms of rigid body rotation about a vertical axis of the samples relative to the Pacific plate (positive clockwise, negative anticlockwise, Table 1 and Fig. 2). Structural analysis [4, 17] shows that these rotations apply to blocks from decametres to several kilometres across.

In general, there is not a great difference between the declination anomaly derived for sites using either correction 1 or correction 2. However, there are a few notable exceptions. The declination anomaly for SS1 and 2 is greater than 67°, at the 95% confidence level, using either correction. However, the validity of the more complex correction 2 is uncertain here and we prefer the higher tectonic rotation (N 122°) implied by correction 1.

For sites WD1 and WD2, a simple tilt correction (correction 1) results in declination anomalies of −11 ± 4.7° and −4 ± 8.0°, respectively, but using correction 2 these are −38 ± 4.7° and −47 ± 8.0°. This region lies between northward-plunging structures to the north, and southward-plunging structures further south. Correction 2 assumed that WD1 and WD2 were part of the steeply plunging northward structure, although this could not be confirmed by structural measurements. We believe that the fold plunge could be more nearly horizontal in the crest between doubling plunging structures. In this case, the simple tilt correction used in correction 1 is more appropriate, suggesting negligible or a very small anticlockwise rotation of these sites. These results
are consistent with those of Roberts [6] for a site in rocks of the same age outcropping a few kilometres further south in Camp stream (Table 1).

Sites GS1 and WS1 in Late Cretaceous dykes from the Awatere valley yield clockwise declination anomalies of $25^\circ \pm 15^\circ$ and $106^\circ \pm 63^\circ$, respectively. The large error for WS1, which is both a consequence of the steep inclination and the great circle analysis used to isolate the high temperature components, makes interpretation of the declination anomaly difficult. There is no evidence for significant deformation between such closely spaced sites, which could accommodate relative rotation. We prefer to place more weight on the result from GS1, and leave the question of the interpretation of WS1 open.

Finally, the steep inclination for the corrected magnetization at site HC1 (Table 1) results in an error larger than the declination anomaly. The declination anomaly at this site is essentially unquantifiable.

In view of the above discussion, and taking all the available palaeomagnetic data in the Marlborough region into consideration, we can define three main groups of sites (Table 1):

Group 1. Negligible or a very small anticlockwise rotation (sites: SW, CS [6]; WD1, WD2 [this paper]).

Group 2. $\sim 20^\circ$ to $\sim 40^\circ$ clockwise rotation (sites: WV, WH, UB, BS, SV, RB, BR, NC [6]; CC [18]; GS1 [this paper]).

Group 3. $\sim 100^\circ$ to $\sim 140^\circ$ clockwise rotation (sites: DS [19]; HC2, HC3, SS1 and 2, WC1, WC2, BB1 and 2 [this paper]).

4.1. Timing of rotation

A plot of observed tectonic rotation against the stratigraphic age of the sample site can be used to deduce the history of tectonic rotation in Marlborough (Fig. 5). Interpretation is complicated by the geographical distribution of sites, because closely spaced sites do not vary widely in age.

4.1.1. Early–Middle Miocene

In view of the above discussion, and taking all the available palaeomagnetic data in the Marlborough region into consideration, we can define three main groups of sites (Table 1):

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4.1.1. Early–Middle Miocene

It is clear that Group 3 rotations affect all sample sites older than $17 \pm 1$ Ma. However, none of the sample localities younger than $8 \pm 1$ show these large rotations. The exact magnitude of tectonic rotations that occurred prior to $\sim 8$ Ma depends on an interpretation of the structure.

The Amuri Limestone forms a subvertical ridge between Cape Campbell and Ward. Sites BB1 and 2 are situated approximately halfway along this ridge,
where there is a marked kink in the trend of the ridge in a ~2 km long segment. The kink is approximately along-strike from the on-land northern termination of the Clarence fault, and may reflect more distributed Plio–Pleistocene dextral shear associated with the northward propagation of this fault [17], contributing ~40° to the observed tectonic rotation. The regional rotation of ~20° to ~40° (Group 2), observed in Late Miocene sediments either side of the limestone ridge, may also have contributed to the observed tectonic rotation at BBl and 2. Thus, the tectonic rotation here, prior to the Late Miocene is likely to be 40–80° less than the total observed tectonic rotation at this site, or 60–100° clockwise.

The remaining Group 3 sites are located in a zone of intense Plio–Pleistocene deformation adjacent to the Kekerengu fault [4,17]. This raises the possibility of substantial local Plio–Pleistocene tectonic rotations of these sites [4,15,17]. Group 3 sites southeast of the Kekerengu fault (HC1–3, SS1 and 2, Deadman Stream [19]) seem to record rotations which are marginally lower (20–40° less) than those for other Group 3 sites. One possibility is that regional Plio–Pleistocene Group 2 rotations do not apply to this region. This is also suggested by the negligible rotations recorded in Pliocene sites in this region (sites WD1 and WD2, Camp Stream [6]).

Thus, tectonic rotations in Group 3 sites throughout Marlborough prior to the Late Miocene may all be in the range 60–100°. This rotation occurred in a period of ~10 Ma between the Early and Late Miocene at average rates of 6–10°/Ma, coinciding with D3 deformation in the northern Marlborough domain.

Fig. 6. Diagrams showing the spatial distribution of tectonic rotations of various magnitudes, inferred from the palaeomagnetic data. (a) Regions that may have experienced Group 3 rotations are principally to the southeast of the Clarence fault. The boundaries to this region are inferred to be just north of Kaikoura and west of the Clarence fault and west of the Awatere fault in the north. An analysis of the deformation history suggests that these regions rotated between 60° and 100° clockwise in the Early-Middle Miocene, between ~18 Ma and ~8 Ma. (b) Regions that have experienced Group 2 regional rotations of ~20° clockwise in the last 4 Ma. A block ~30 km across at the northern end of the Clarence fault has experienced a slightly greater clockwise rotation of ~35° in the same period [4,6]. In addition, localised small block rotations ≤40° clockwise, related to dextral shear on the Clarence and Kekerengu faults, may also have occurred. The southern boundaries to the rotating zones are defined by Group 1 sites as being southeast of the Kekerengu fault. Also, the southwestern boundary may coincide with the boundary between the two Marlborough domains (Fig. 1b), where the major strike-slip faults change trend.
4.1.2. Late Miocene to recent

Group 2 sites record \( \sim 20^\circ \) to \( \sim 40^\circ \) clockwise rotation in sites as young as \( 3.9 \pm 0.8 \) Ma [6]. These block rotations coincide with the younger \( D_2 \) dextral strike-slip deformation in Marlborough [4,17]. A similar rotation is observed at site GS1 in the Late Cretaceous Awatere basement dyke swarm. Studies of the active kinematics of the northern Marlborough domain, using geodetic and fault slip data, suggest that the blocks between the major faults in this region are actively rotating at \( \sim 5^\circ/\text{Ma} \) [3,32], consistent with the average regional rotation rate sug-

Fig. 7. Kinematic models of tectonic rotations in Marlborough, South Island, New Zealand. (a) Tectonic rotations in the Early–Middle Miocene (\( \sim 18 \) to \( \sim 8 \) Ma) are coeval with the development of a low angle thrust complex \( (D_1) \). Rotation may have occurred by motion on thrusts, pinned at their southern ends against a structural high. In this case, displacement on the thrusts would have increased progressively to the north, overall accommodating \( 60^\circ-100^\circ \) of clockwise tectonic rotation (see text). (b) Since the Early Pliocene (last 4 Ma), the northern part of the Marlborough Fault System has rotated regionally \( \sim 20^\circ \) clockwise \( (D_2) \) deformation. This appears to have been hinged southeast of the Kekerengu fault and at the boundary between the northern and southern Marlborough domains (Fig. 1b), where the major strike-slip faults change trend. Thus, \( \sim ENE \) dextral shear in the southern Marlborough domain is partly taken up by regional block rotation in the northern domain. An additional \( \sim 15^\circ \) of clockwise rotation of a block to the north of the Clarence fault has taken up some of the dextral displacement associated with this fault. Folding and sinistral strike-slip southeast of the Kekerengu fault have also helped to accommodate the regional clockwise rotations.
Fig. 8. Reconstructions of the New Zealand plate-boundary zone, based on finite plate motions [1] and palaeomagnetic data. Shaded areas represent continental lithosphere, oblique ruling indicates oceanic lithosphere. These show the progressive swing of the Hikurangi margin, from W to NW-trending in the Early Miocene to ~ NE-trending today. The study area forms the southern end of the Hikurangi margin and effectively acted as a type of hinge zone. Arrows show the relative plate convergence vector at particular periods [33]. (a) Rotation in the Early Miocene coincided with the deposition of the chaotic submarine fan deposits of the Great Marlborough Conglomerate (stippled pattern labelled GMC), and an early phase of seaward-directed thrusting (D1) in Marlborough. Rotation may have been accommodated by pinning at the southeastern ends of thrusts against a structural high on the Chatham Rise, with progressive increase in displacement towards the NW. Relative plate convergence at this time was essentially orthogonal to the Hikurangi margin [33]. (b) In the early Pliocene, the Hikurangi margin trended ~ N in the study area. A change in the relative plate convergence vector and the overall swing in trend of the plate margin resulted in the development of the Marlborough Fault System and predominantly dextral shear in the northeastern part of the South Island (D2 deformation). At this time the Southern Alps began to develop. (c) Today the Hikurangi margin trends ~ NE, with a ~ 45° change in trend since the Early Pliocene. The general plate convergence is ~ 46 mm/yr.
gested by Group 2 sites. The available data suggests that there was no regional tectonic rotation of crustal blocks in Marlborough between \( \sim 8 \) Ma and \( \sim 4 \) Ma.

4.2. Spatial distribution of tectonic rotation

The spatial distribution of tectonic rotations since the Late Miocene is suggested by the following:

1. in detail, Group 2 rotations can be subdivided into those of \( \sim 35^\circ \), which apply only to the region at the northern end of the Clarence fault (Fig. 6b, [6]), and affect rocks as young as \( 3.9 \pm 0.8 \) Ma,
2. the remaining Group 2 sites, located northwest of the Kekerengu fault, suggest rotations of \( \sim 20^\circ \) since the Late Miocene (Fig. 6b);
3. a \( \sim 25^\circ \) rotation is observed in Late Cretaceous basement rocks in the Awatere Valley.

All this suggests that a \( \sim 20^\circ \) clockwise rotation affected most of the northern Marlborough domain in the last \( 3.9 \pm 0.8 \) Ma (Fig. 6b). However, a block \( \sim 30 \) km across at the northern end of the Clarence fault rotated an additional \( \sim 15^\circ \) in the same period. Lamb and Bibby [4] and Roberts [6] have suggested similar models for this additional rotation, which appears to take up most of the dextral strike-slip motion on the Clarence fault, which terminates onshore (Figs. 6b and 7b). Negligible rotations in Pliocene sites on the southeastern side of the Kekerengu fault (Fig. 6b) suggest that the Kekerengu fault and an associated zone of intense Plio–Pleistocene deformation form the southern boundary to the rotated zone since the Late Miocene.

Large pre-Late Miocene tectonic rotations are only found in sites southeast of the Clarence fault (Fig. 6a), and further north in the Cape Campbell-Ward area, in regions affected by the Early–Late Miocene \( D_1 \) phase of thrust tectonics.

4.2.1. Hinge zone

The margins of the rotating zones can be considered as a type of hinge. The distribution of \( D_1 \) structures, which developed during the Early–Middle Miocene phase of tectonic rotation, suggest that the southern limit of this phase of deformation and rotation was just west of Kaikoura, near a major NE-trending syncline, which is most likely a \( D_1 \) structure [4,17]. The western margin of the rotating zone appears to be east of the Late Cretaceous dyke swarm in the Awatere valley. We suggest that rotation occurred in an evolving thrust stack in the Miocene, with pinning of the southern ends of thrusts (in their present orientation) near Kaikoura (Fig. 6 and Fig. 7a). This requires the displacement on these thrusts to increase progressively to the north, although, as yet, there is no independent evidence for this (Figs. 7a). A high-level detachment zone may have decoupled the back of the rotating thrust stack from the greywacke basement, which is presently further west.

Since the Late Miocene, the region southeast of the Kekerengu fault appears to have acted as a hinge zone. Dextral strike-slip on the curved Kekerengu fault trace allows the regions to the north to rotate clockwise relative to the regions further south (Fig. 7b, [17]). Also, relative rotation may have caused the observed refolding of the earlier fold axes and a ‘bending’ of the two halves of the area immediately southeast of the Kekerengu fault, accommodated by an E-trending, kilometre scale, sinistral strike-slip fault (Fig. 7b). On a more regional scale, Lamb [3] suggested that dextral strike-slip on the major ENE-trending faults in the southern Marlborough domain may be taken up partly by block rotation of the whole northern Marlborough domain (Fig. 7b).

5. The evolving Hikurangi plate margin

Plate reconstructions based on finite rotation poles [2] suggest a clockwise swing in the trend of the Hikurangi margin, from W to NW in the Early Miocene to NE today. The trend of the relative plate motion vector at any instant has also changed, swinging from \( \sim NE-SW \), in the Early Miocene, to nearly E–W today [33]. All this suggests profound changes in the geological evolution of the Hikurangi margin. The Marlborough region, at the southern end of the Hikurangi margin, appears to have behaved as an hinge zone separating the rotating margin from the Pacific plate. This study, combined with structural studies [4,17], suggests that the hinge zone evolved in two distinct phases.

5.1. Early–Middle Miocene

The transition from Palaeogene deep-water micritic limestones to a thick sequence of Early Miocene
chaotic submarine fan deposits in Marlborough marks the onset of subduction at the southern end of the Hikurangi plate margin (Fig. 8a, [4,17]). Low-angle thrusting of Palaeogene and early Neogene sequences is syn-sedimentary with respect to the deposition of the submarine fan deposits, referred to as the Great Marlborough Conglomerate [4,17]. This deformation is also associated with large tectonic rotations of 60–100°, presumably driven by the overall swing in the Hikurangi margin as a consequence of the relative plate motions [2].

Thrust sheets may have been pinned against a structural high on the Chatham Rise (Fig. 7a). After removal of the effects of later Plio-Pleistocene deformation (D₂) and unrotating the D₁ thrusts [4,15,17], the thrusts are restored to a W to NW-trending and seaward-directed orientation (Fig. 8a). When viewed in conjunction with plate reconstructions in the Early Miocene, this orientation approximately parallels the orientation of the plate margin in the Marlborough region and the seaward thrusting along the east coast of the North Island (Fig. 8a). Sediment transport directions from the Great Marlborough Conglomerate [27] indicate sedimentary flow from the WNW, which restores to a N-directed flow. This may partly reflect flow along the trench from a structural high in the south, forming part of the Chatham Rise (Fig. 8a).

5.2. Late Miocene to recent

By the Late Miocene the trend of the Hikurangi margin had rotated clockwise to a N-trending orientation (Fig. 8b). The Late Miocene is marked in Marlborough by the cessation of D₁ thrusting and the development of a regional unconformity surface. It appears that, in the period ~8 Ma to ~4 Ma, there was no regional tectonic rotation of crustal blocks and this period may mark a relative reduction in tectonic activity in the Marlborough region.

In the Early Pliocene there was a marked change in trend of the relative plate convergence vector (Fig. 8b, c, [1,12,33]), resulting in the uplift of the Southern Alps and the development of the Marlborough Fault System [4]. The Marlborough Fault System accommodated oblique convergence by transpressive dextral strike-slip faulting, folding and tectonic rotation. The effect of this deformation in the last 4 Ma has been to allow the plate-boundary zone here to rotate overall an additional ~45° into its present NE-trending orientation (Fig. 8c).

6. Conclusions

This study has documented the Neogene and Quaternary history of rotation in the Marlborough region of South Island, New Zealand. This rotation records the overall rotation of the Hikurangi plate margin, suggested by plate reconstructions, from W to NW in the Early Miocene (Fig. 8a) to ~NE today (Fig. 8c), suggesting an overall agreement between the inferred long-term relative plate motions and the internal deformation in the plate-boundary zone (Fig. 8, [2]).

A regional clockwise tectonic rotation of 100–140° is observed in Palaeogene to Middle Miocene sedimentary rocks throughout Marlborough. Rotations between 60° and 100° are interpreted to be a consequence of displacement on large-scale pinned thrusts in an evolving low-angle thrust belt between ~18 Ma and ~8 Ma. This early deformation (D₁) marks the early stages of the development of the subducting Hikurangi margin in this region. These rotations do not affect Late Cretaceous dykes in the Awatere valley in the western part of Marlborough.

A subsequent regional and clockwise tectonic rotation of ~20° affected all of Marlborough north of the Kekerengu fault in the last 4 Ma. An additional rotation of ~15° affected a large block to the north of the Clarence fault. Also, it is inferred that local rotations ≤40° clockwise affected regions adjacent to the Kekerengu fault and the projected northeastern extension of the Clarence fault.

The region immediately to the southeast of the Kekerengu fault appears to have formed a type of hinge zone in the last 4 Ma, decoupling the rotating Hikurangi margin to the north from the unrotating regions further south.

Acknowledgements

This work was carried out during the tenureship of a NERC studentship, held by Sara Vickery at the Department of Earth Sciences, Oxford. We are grateful to Jim Briden, Brian Daniels, John Dewey, Buffy McClelland and Rick Thomas for all their help and
advice during the preparation of this work. Simon Lamb has a Royal Society University Research Fellowship. The manuscript benefitted from reviews by Richard Norris and an anonymous reviewer.

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