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Relocation of the tectonic boundary between the Raukumara and Wairoa Domains (East Coast, North Island, New Zealand): implications for the rotation history of the Hikurangi margin

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Abstract Paleomagnetic studies of Neogene marine sediments have documented large clockwise rotations of the Hikurangi margin (East Coast, North Island) during the Neogene, with the exception of the Raukumara Peninsula, which is unrotated with respect to the Australian plate. Immediately south of the Raukumara Peninsula, the Wairoa region has been rotated clockwise by 50–60°; the boundary between these domains is associated with a change in regional structural trends. However, a declination of 70 ± 14° reported from Otaian (19–22 Ma) sediments in the Rakauroa area is located to the north of this change. Characterisation of how differential rotations have been accommodated along the Hikurangi margin has been frustrated by this apparent mismatch between paleomagnetic and structural data. Paleomagnetic analysis of two new Rakauroa localities has yielded declinations of 16 ± 7° and 19 ± 9°, consistent with expected values for the Australian plate. This region is therefore not part of the Wairoa Domain. A strong viscous magnetic overprint was observed in many samples, the incomplete removal of which resulted in the misidentification of a large declination anomaly in the previous study. The paleomagnetically defined boundary between the Raukumara and Wairoa Domains now coincides with the area where regional structural trends alter. Reassignment of the Rakauroa area to the Raukumara Domain also results in a revised rotation history for the Wairoa Domain, suggesting rotation rates of 4–5°/m.y. since the late Miocene (5–10 Ma), and potentially no earlier rotation. No reliable record of early and middle Miocene vertical axis rotation on the Hikurangi margin now exists north of Marlborough; further studies are required to properly constrain the rotation history for this time interval.

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INTRODUCTION

At the Hikurangi margin on the east coast of the North Island of New Zealand, westward-directed subduction of the Pacific plate occurs at a rate of c. 40 mm/yr (DeMets et al. 1994) (Fig. 1A). Subduction of the anomalously thick (12–15 km) oceanic crust of the Hikurangi plateau (Davy & Wood 1994) has led to the subaerial exposure of forearc basins throughout eastern New Zealand. Paleomagnetic studies of tectonically uplifted Neogene marine sediments along the entire Hikurangi margin (Walcott et al. 1981; Walcott & Mumme 1982; Mumme & Walcott 1985; Wright & Walcott 1986; Mumme et al. 1989; Roberts 1992, 1995; Vickery & Lamb 1995; Thornley 1996; Little & Roberts 1997) have documented clockwise vertical-axis rotations of up to 90° at a number of sites. These data support plate tectonic reconstructions of the New Zealand region which suggest substantial clockwise rotations of the Pacific-Australian plate boundary as a whole since its propagation into the New Zealand region at 23–20 Ma (Rait et al. 1991; King 2000). The couple resulting from rollback of the subducted Pacific plate in the north and "pinning" of the boundary due to underthrusting of buoyant continental crust (the Chatham Rise) in the south has led to a change in the orientation of the subducted plate (Walcott 1989). However, paleomagnetic data from the Raukumara Peninsula, the northernmost onshore part of the margin, show no rotation with respect to the Australian plate since the early Miocene (Walcott & Mumme 1982; Mumme et al. 1989; Thornley 1996). This, combined with evidence of different rates of rotation in areas farther to the south, has resulted in the hypothesis that the margin is divided into discrete domains with independent tectonic histories (Lamb 1988; Walcott 1989). This interpretation requires crustal-scale basement structures that accommodate differential rotations between adjacent domains. The paleomagnetic data suggest that the boundary between the unrotated "Raukumara Domain" and the northernmost rotated block (the "Wairoa Domain") is located at about the latitude of Gisborne (38.5°S; Fig. 1B), an inference consistent with regional structural patterns.

The initiation of subduction in the early Miocene coincided with the southwestward obduction of a late Early Cretaceous–Paleogene passive margin sequence onto the Raukumara Peninsula (Stoneley 1968; Rait et al. 1991), forming the East Coast Allochthon (ECA), and onto Northland (Ballance & Spörli 1979; Spörli 1982; Rait 2000), forming the Northland Allochthon. At that stage, the margin was therefore oriented northwest–southeast, a determination supported by the parallel northwest–southeast trend of the early Miocene Northland volcanic arc (Herzer 1995). On the Raukumara Peninsula, the faults and folds associated with the emplacement of the ECA still have this trend, which

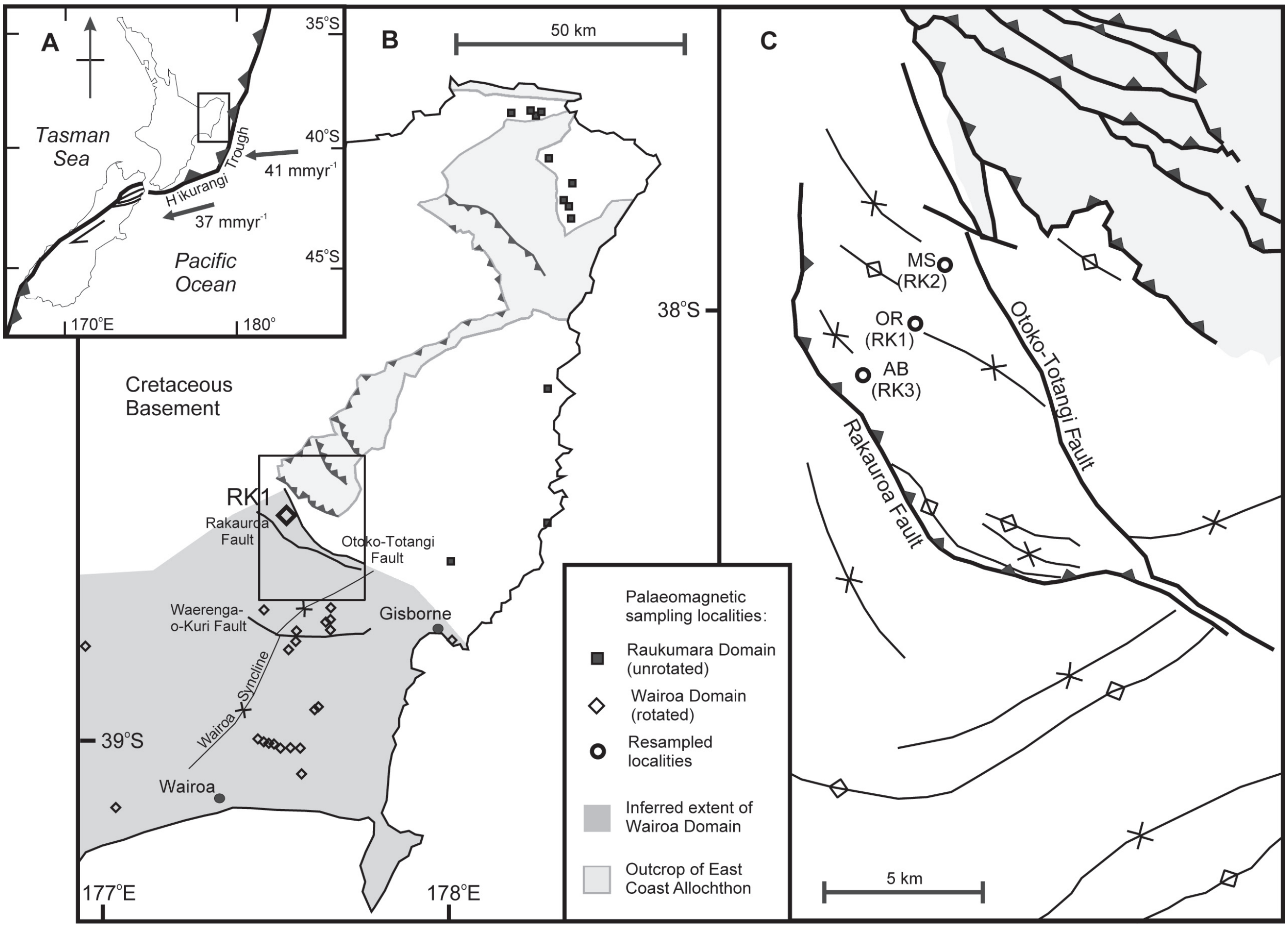


Fig. 1 **A**, Tectonic setting of the New Zealand region, showing the boundary between the Pacific and Australian plates. Local plate motion vectors are from DeMets et al. (1994). **B**, Detail of northeastern North Island, including the locations of sites from which paleomagnetic data have been reported. The boundaries of the Wairoa Domain are inferred from sites where large declination anomalies have been measured. The RK1 locality of Mumme & Walcott (1985) (large diamond) is the northernmost of these. **C**, Tectonic map of the study area, showing the principal structures and the location of the localities sampled by Mumme & Walcott (1985) that were resampled in this study. Adapted from Mazengarb & Speden (2000).

implies that substantial vertical-axis rotations have not occurred in this region during the Neogene, consistent with the aforementioned paleomagnetic studies. In contrast, the rotated "Wairoa Domain" to the southwest of Gisborne is dominated by structures that have the southwest–northeast orientation of the present day margin.

The structural change between the Raukumara and Wairoa Domains coincides with major changes in both the topography of the subduction margin (Collot et al. 1996) and the crustal structure of the overlying plate (Reyners et al. 1999); however, basement structures that have accommodated large differential rotations have proved difficult to identify. Attempts to use paleomagnetic methods to further constrain the location of the rotation boundary in the critical region between Gisborne and Opotiki have been frustrated by the paucity of stably magnetised rocks (Mumme et al. 1989; Thornley 1996). However, Mumme & Walcott (1985) reported a mean declination of 70 ± 14° from early Miocene (Otaian; Colin Mazengarb, GNS, pers. comm. 2002) rocks in the Rakauroa area (referred to in later literature as the "RK1" locality; Fig. 1B). The implied clockwise rotation of c. 50° relative to the Australian plate makes this the northernmost locality reported to belong to the rotated Wairoa Domain, and provides an important constraint on the location of any structural boundary. Its age confers additional significance: most rotated sites on the east coast of the North Island are dated as mid–late Miocene, making RK1 a primary support for the hypothesis that the rate of rotation of the Hikurangi margin with respect to the Australian plate has steadily increased over time, from 2–3°/m.y. in the early Miocene to 7–8°/m.y. from the Pliocene onwards (Wright & Walcott 1986; Walcott 1989).

The large clockwise rotations reported from Rakauroa become somewhat problematic when regional geology is considered. The RK1 declination anomaly is based on data compiled from three sampling localities, distributed across a syncline located just to the south of the frontal thrust of the ECA (RK1-3, Fig. 1C). This fold has a northwest–southeast trend, as do other nearby folds (Mazengarb & Speden 2000), and is clearly associated with emplacement of the allochthon. Thus, from a geological perspective, one would expect this area to be unrotated with respect to the Australian plate.

Good paleomagnetic data are needed from the Rakauroa area to properly constrain the Neogene tectonic evolution of the Hikurangi margin. We present the results from new sampling, undertaken as close as possible to the original localities described by Mumme & Walcott (1985), in an effort to reconcile the paleomagnetic data with the regional geology. The data published by Mumme & Walcott (1985) are also reassessed in the light of more recent insights into the magnetisation of New Zealand Cenozoic sediments.

GEOLOGICAL BACKGROUND

The area investigated in this study is bounded by the Otoko-Totangi and Rakauroa Faults, to the north and south, respectively (Fig. 1C). Thickness variations in Early Cretaceous and Paleogene sediments revealed by seismic data (Field et al. 1997) demonstrate that both faults predate the current tectonic regime. The Otaian units sampled were deposited in a flexural basin associated with obduction of the ECA, and were folded soon after deposition; Altonian strata were unconformably deposited on the anticline directly northwest of the Rakauroa Fault. The trend of the folds suggests southwestward-directed shortening, supporting the inference that they formed contemporaneously with emplacement of the allochthon.

The folds have subsequently been disrupted by probable post-early Miocene dextral strike-slip on the reactivated Otoko-Totangi Fault, but the overall structural grain is still oriented northwest–southeast, which precludes any significant vertical-axis rotations in the Neogene. Evidence for any recent tectonism is equivocal, although observations of tilted Pleistocene beds along strike from the Otoko-Totangi Fault are reported by Field et al. (1997).

SAMPLING AND METHODS

Paleomagnetic sampling was carried out by drilling 25 mm diameter cores from three localities with good exposure and clear, measurable bedding structures, as close as possible to the original RK sites studied by Mumme & Walcott (1985).

OR—Oliver Road (NZMS 260 grid ref. X17/118988). A roadcut/verge outcrop of moderately weathered, shallowly dipping grey and brown sandy mudstones and siltstones was sampled, at the highest point on Oliver Road before it descends to Matawai Station. This is a direct resampling of the RK1 locality described by Mumme & Walcott (1985). Seventy cores were collected across a total stratigraphic thickness of 27.1 m.

MS—Matawai Station (grid ref. X17/128009). A fairly continuous exposure of light blue-grey calcareous mudstones with massive sandstone interbeds was sampled in the bed of the Waikohu River, 100–200 m west and upstream of where it is bridged by Oliver Road north of Matawai Station. The RK2 locality described by Mumme & Walcott (1985) is just downstream from this bridge; it was not directly resampled due to a lack of clear bedding structures. A total stratigraphic thickness of 58.5 m was sampled (63 cores).

AB—Anzac Bridge (grid ref. X17/096972). Outcrops of fractured, massive blue-grey mudstones, with rare massive sandstone beds, were sampled from the banks of the Waihuka River, where a tributary joins it 200 m east and downstream of where it is crossed by State Highway 2 (Anzac Bridge), 2–3 km southeast of the Oliver Road turn-off. The RK3 locality described by Mumme & Walcott (1985) was identified just downstream from the bridge, but was not resampled due to a lack of clearly identifiable bedding structures. It is possible that Mumme & Walcott (1985) measured joint surfaces rather than bedding, since their reported variable bedding measurements are not consistent with the clear regional structural trend. A total stratigraphic thickness of 52.6 m was sampled (41 cores).

Weathered surficial material was removed from each outcrop before sampling. Cores were stored and transported to the laboratory in a mu-metal shield and were cut into samples of 21 mm length. Stepwise demagnetisation of the samples was undertaken using a 2G-Enterprises cryogenic magnetometer at the Southampton Oceanography Centre (SOC). The instrument is situated in a magnetically shielded room, which reduces the level of the ambient magnetic field to <300 nT, which is further reduced to c. 1–2 nT in the measurement region of the magnetometer. This enables measurement of magnetisation with a sensitivity of better than 10^{-5} Am^{-1}.

Thermal demagnetisation has frequently proven to be more effective than alternating field (AF) demagnetisation at isolating primary remanence directions in weakly magnetised New Zealand Cenozoic sediments (Pillans et al. 1994; Turner 2001). A pilot study involving detailed stepwise AF (5 mT steps to 60 mT) and thermal (steps of 20°, 80°, 120°, 160°, 200°, 240°, 280°, 320°, 360°, 380° and 400°C) demagnetisations of individual samples from each stratigraphic level confirmed that thermal methods yielded more stable demagnetisation paths; all subsequent samples were therefore thermally treated. Low-field bulk magnetic susceptibility was measured after each heating step to monitor for thermal alteration effects. Vector-component diagrams were used to identify samples where characteristic remanent magnetisation (ChRM) directions could be isolated and analysed using principal component analysis (Kirschvink 1980). Fisher (1953) statistics were used to calculate mean paleomagnetic directions; declination errors were calculated according to Demarest (1983). The stepwise demagnetisation data for many samples follow great circle paths, which can be combined with ChRM directions using the method of McFadden & McElhinny (1988). Great circle analysis has been utilised for magnetostratigraphic studies of New Zealand Cenozoic mudstones (Pillans et al. 1994; Roberts et al. 1994), but not for tectonic studies, where a precise direction, rather than simply a polarity determination, is required. However, this technique is certainly adequate to fulfil the minimum requirement of this study: that is, to distinguish between substantial clockwise rotations (a declination of 70°) and no net rotation with respect to the Australian plate (a declination of 20°).

RESULTS

Stepwise demagnetisation

The NRM intensities of all samples from the three study sites are weak, ranging from 1×10^{-4} to 8×10^{-3} Am^{-1}. In a large proportion of the samples, the low temperature remanence component has an orientation close to that of the present-day field in geographic co-ordinates (Declination (D) = 20.5°, Inclination (I) = –63.7°) and is therefore interpreted as a viscous overprint. This component unblocked at temperatures of 200–240°C. No meaningful data were collected above temperatures of 360–380°C, due either to the magnetic intensity falling below the noise level of the magnetometer,

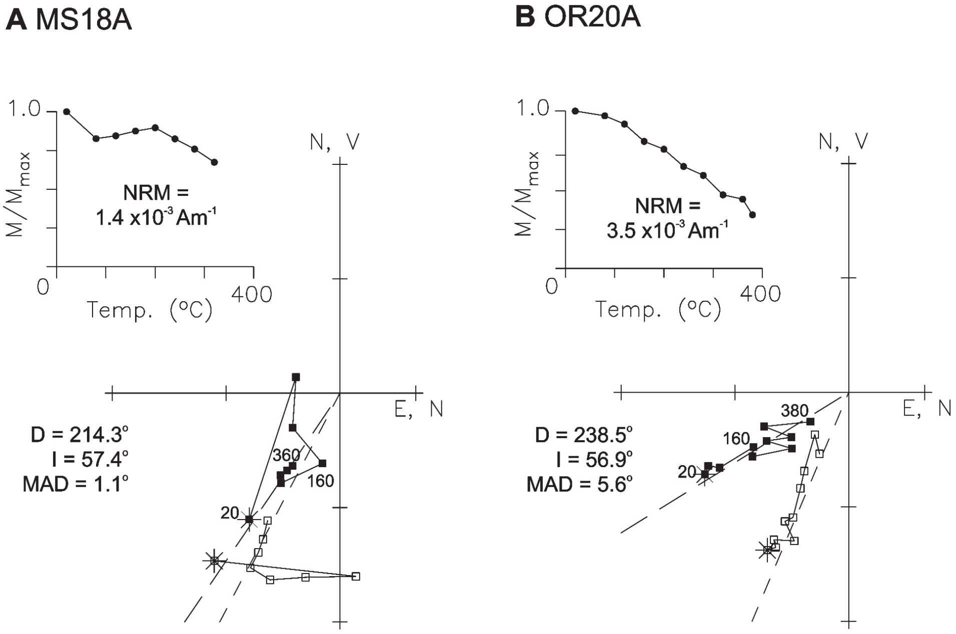


Fig. 2 Vector-component plots of thermal demagnetisation data showing anchored best fit ChRM determinations, from: (**A**) Matawai Station, following removal of a secondary overprint that unblocks at 200°C, and (**B**) Oliver Road, where no overprint is observed. Labelled points indicate the demagnetisation step in °C. Solid symbols denote projections onto the horizontal plane (declinations); open symbols denote projections onto the vertical plane (inclinations).

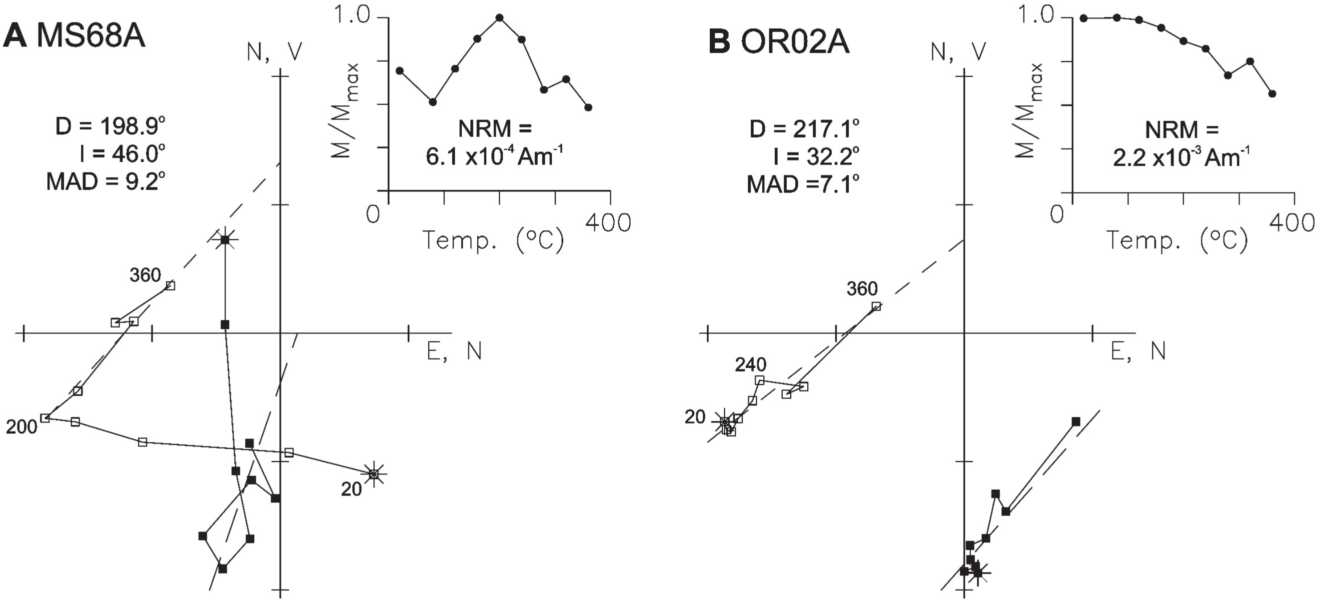


Fig. 3 Vector-component plots of thermal demagnetisation data from: (**A**) Matawai Station, and (**B**) Oliver Road, which exhibit an unanchored ChRM fit due to the presence of a higher T_b diagenetic component that is interpreted to result from weathering. The trends of these intermediate components are similar to those of samples without higher T_b components (Fig. 2). Symbols are as in Fig. 2.

or to thermal alteration (indicated by large increases in low-field bulk magnetic susceptibility) producing new magnetic minerals that obscured the primary paleomagnetic signal. There was therefore only a small range over which ancient higher temperature components could potentially be observed. Samples from Anzac Bridge do not exhibit systematic behaviour within this range, which indicates that any primary magnetisation has been completely obscured by overprinting (NRMs from this locality are particularly strongly clustered around the present-day field direction); data from this locality are therefore excluded from further analysis.

In 21% of the samples from Matawai Station, a stable component (defined by three or more collinear points, with maximum angular deviation (MAD) values of <15°) with reversed polarity is observed at temperatures of 200–380°C (Fig. 2A, 3A). A component with a similar trend can also be isolated from 11% of the Oliver Road samples, but in most cases only where there is no obvious viscous overprint (Fig. 2B, 3B). This component can generally be anchored to the origin of the vector-component plot (Fig. 2), but in some samples it misses the origin (Fig. 3), which may indicate the presence of a further component with unblocking temperatures >400°C. Samples exhibiting both types of behaviour can be identified from the same stratigraphic level at both localities.

In a further 50% of the samples, the blocking temperature (T_b) spectra of the viscous and intermediate components overlap to the extent that the latter cannot be isolated. Nevertheless, there is a consistent trend toward a reversed polarity direction

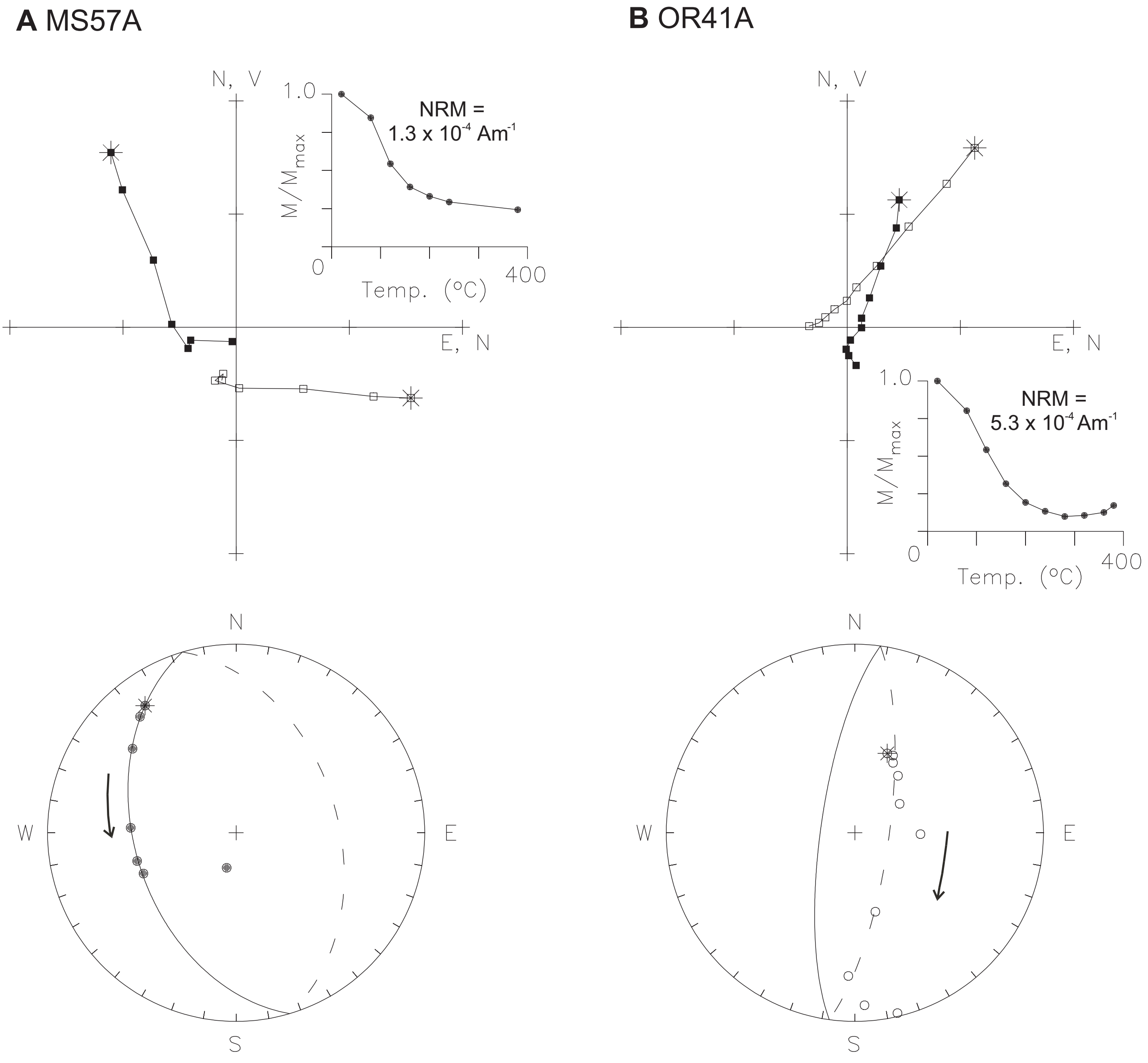


Fig. 4 Vector-component and equal area stereographic plots of thermal demagnetisation data from: (**A**) Matawai Station, and (**B**) Oliver Road, demonstrating removal of secondary overprints along a great circle path. Symbols for vector-component plots are as in Fig. 2. Solid (open) circles on the stereoplots represent projections onto the lower (upper) hemisphere.

along a great circle demagnetisation path (Fig. 4). Despite the possible presence of a higher T_b component in some samples, the reversed polarity, intermediate T_b component is interpreted here as a primary ChRM. Its presence is discernible in all samples with stable demagnetisation behaviour; the combined data from the two sites also pass a fold test (Fig. 5), implying that the magnetisation predates the early Miocene tilting of the sampled units. The magnetic behaviour of these samples is therefore comparable to that of Pliocene sediments from the Wanganui Basin described by Turner (2001), where an intermediate T_b (150–250°C) component was found to carry the primary remanence. A higher T_b (>250°C) component, carried by a distinct higher coercivity population of magnetic grains, was considered to be diagenetic in origin, probably related to weathering.

Paleomagnetic directions

Combining the isolated ChRM directions from each site, after correction for bedding tilt, yielded a mean direction of $D = 197.8°$, $I = 48.8°$, $\alpha_{95} = 9.4°$ for Matawai Station (Fig. 6A), and $D = 212.4°$, $I = 51.1°$, $\alpha_{95} = 14.9°$ for Oliver Road (Fig. 6B). These directions are indistinguishable at the 95% confidence level (Fig. 7A); however, the small number of samples may not adequately average out secular variation and random measurement errors (Van der Voo 1993).

To further constrain the mean direction, the stable endpoints were combined with great circle arcs, according to the method of McFadden & McElhinny (1988). Although the T_b spectrum of the high-temperature component does not overlap with the ChRM below 400°C (Fig. 3), the demagnetisation paths of samples in which this third component is present will not

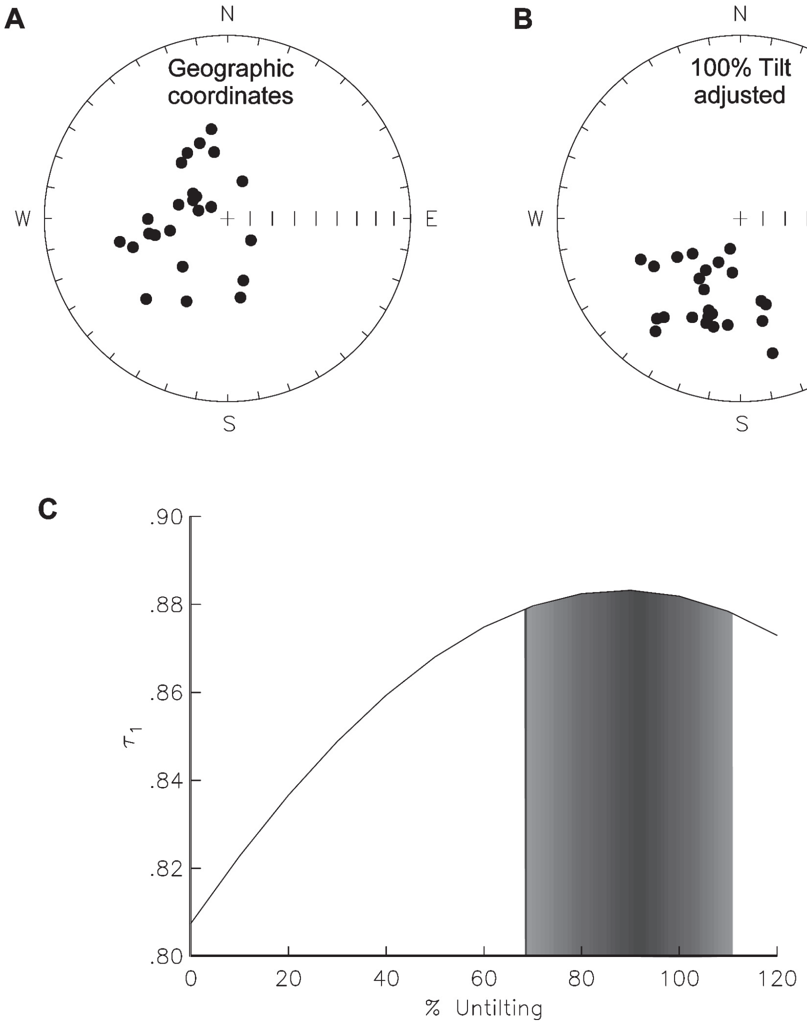
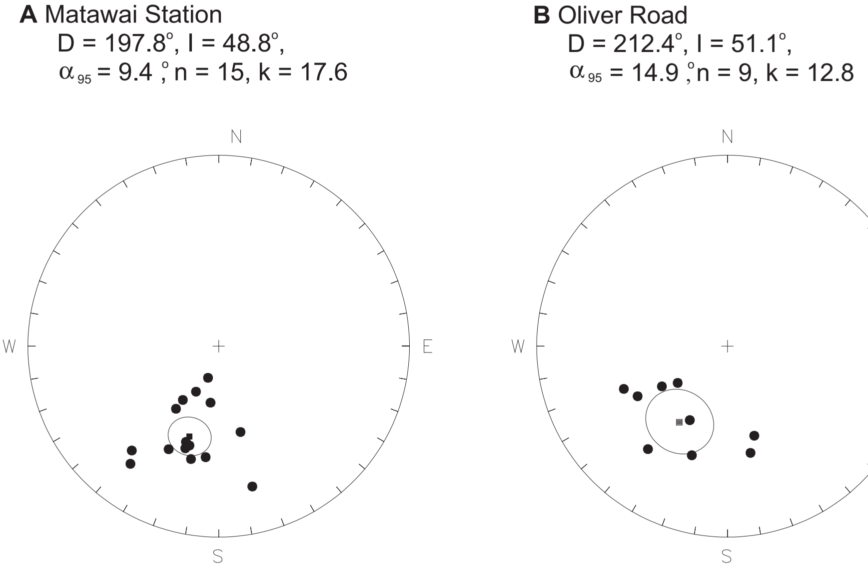


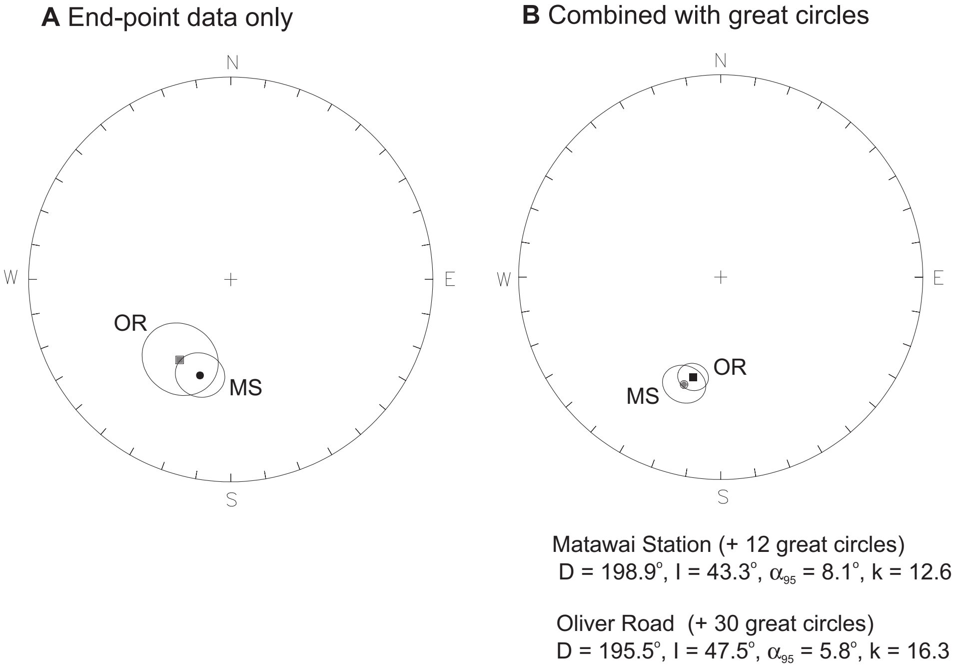
Fig. 5 Combined ChRM data for both Oliver Road and Matawai Station, in: (**A**) geographic, and (**B**) tilt-corrected, co-ordinates. **C**, Fold test of Tauxe & Watson (1994). The 95% confidence interval of the maximum value of the principal eigenvector τ_1 (shaded) encompasses 100% unfolding, consistent with remanence acquisition before tilting of the beds.


A Matawai Station
D = 197.8°, I = 48.8°,
α_{95} = 9.4°, n = 15, k = 17.6

B Oliver Road
D = 212.4°, I = 51.1°,
α_{95} = 14.9°, n = 9, k = 12.8

Fig. 6 Equal area stereographic plot of ChRM directions (solid circles) obtained for: (**A**) Matawai Station, and (**B**) Oliver Road, with calculated mean directions (solid squares) and α_{95} confidence ellipses.

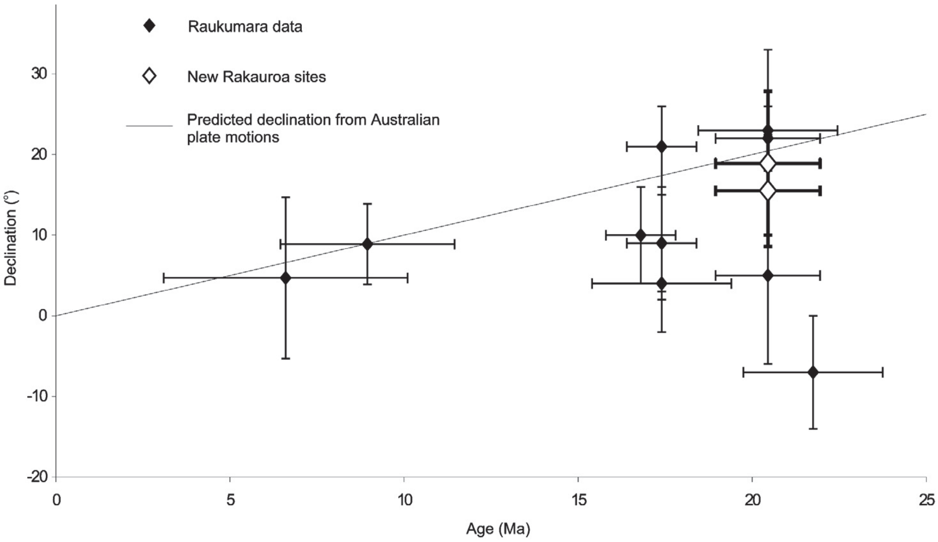
Fig. 7 Comparison of paleomagnetic directions determined for Matawai Station and Oliver Road using: (**A**) ChRM data alone, and (**B**) ChRM data combined with demagnetisation great circles using the method of McFadden & McElhinny (1988).



Matawai Station (+ 12 great circles)
D = 198.9°, I = 43.3°, α_{95} = 8.1°, k = 12.6

Oliver Road (+ 30 great circles)
D = 195.5°, I = 47.5°, α_{95} = 5.8°, k = 16.3

Fig. 8 Declinations for the new Rakauroa data (open symbols), plotted with previously reported data from the Raukumara Domain (closed symbols) (Walcott & Mumme 1982; Mumme et al. 1989). Declination errors calculated according to Demarest (1983).



directly converge on the ChRM directions (because they do not decay to the origin, unanchored ChRMs will plot away from their own demagnetisation paths on a stereographic projection). Therefore, only great circles from sites where the ChRM could be consistently anchored to the origin, which were defined by four or more points and which had MAD values <15°, were included in the analysis. Addition of the great circle data gave a mean direction of $D = 198.9°$, $I = 43.3°$, $\alpha_{95} = 8.1°$ for Matawai Station, and $D = 195.5°$, $I = 47.5°$, $\alpha_{95} = 5.8°$ for Oliver Road. The resulting mean directions from the two sites are better constrained individually, and are still indistinguishable at the 95% confidence level (Fig. 7B).

As discussed above, great circle analysis has not been commonly used in tectonic studies of New Zealand Cenozoic sediments. However, use of the great circle data in the present study does not result in directions that lie outside the 95% confidence limits of the means calculated from stable endpoint data alone; in the case of Matawai Station, there is no appreciable change in the directions derived from the combined and endpoint-only datasets (Fig. 7). This confers confidence in the reliability of the results presented here.

DISCUSSION

The Oliver Road and Matawai Station localities record declinations that are deflected clockwise with respect to the expected axial dipole field direction by 16 ± 7° and 19 ± 9°, respectively. According to the apparent polar wander path of Idnurm (1985), Neogene motions of the Australian plate have led to clockwise rotations of c. 1°/m.y. Thus, the Otaian (19–22 Ma) declination anomalies reported here do not require the Rakauroa area to have undergone any vertical axis rotations, being fully explained by large-scale plate motions (Fig. 8). The new data also compare well with declinations reported from farther north on the Raukumara Peninsula (Walcott & Mumme 1982; Mumme et al. 1989). Both localities record inclinations of c. 50°, which is less than the 60° inclination expected for Otaian rocks; however, shallow

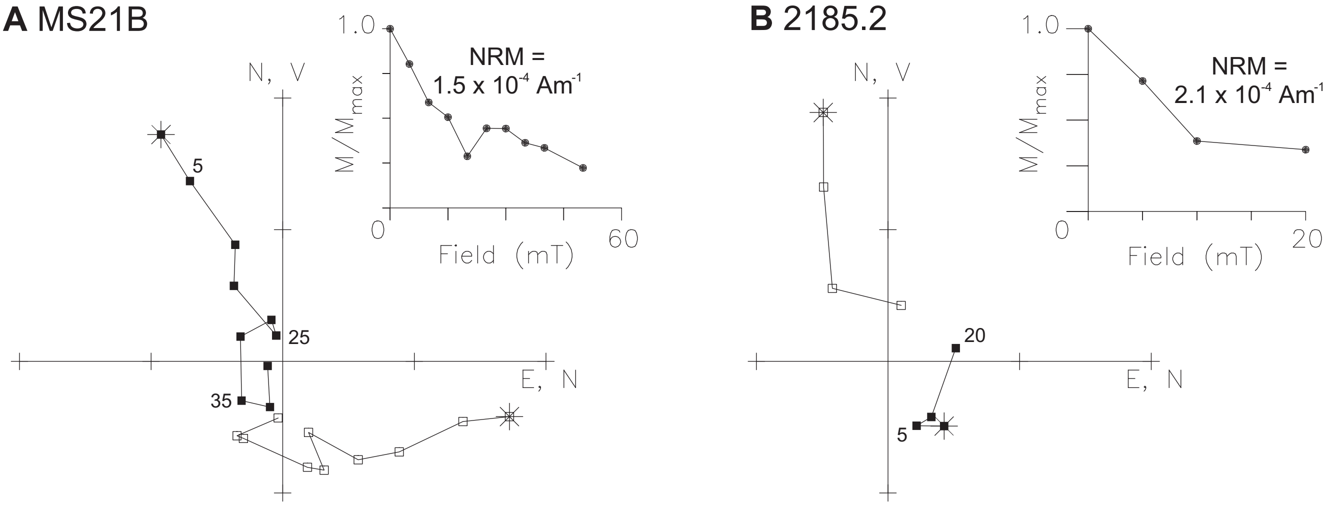


Fig. 9 Vector-component plots of: (**A**) AF demagnetisation data from Matawai Station—a viscous overprint is removed above 35 mT; (**B**) AF demagnetisation data reported by Mumme & Walcott (1985). At the maximum demagnetisation step of 20 mT, a stable end-point has yet to be reached. Labelled points indicate the demagnetisation step in mT; other symbols are as in Fig. 2.

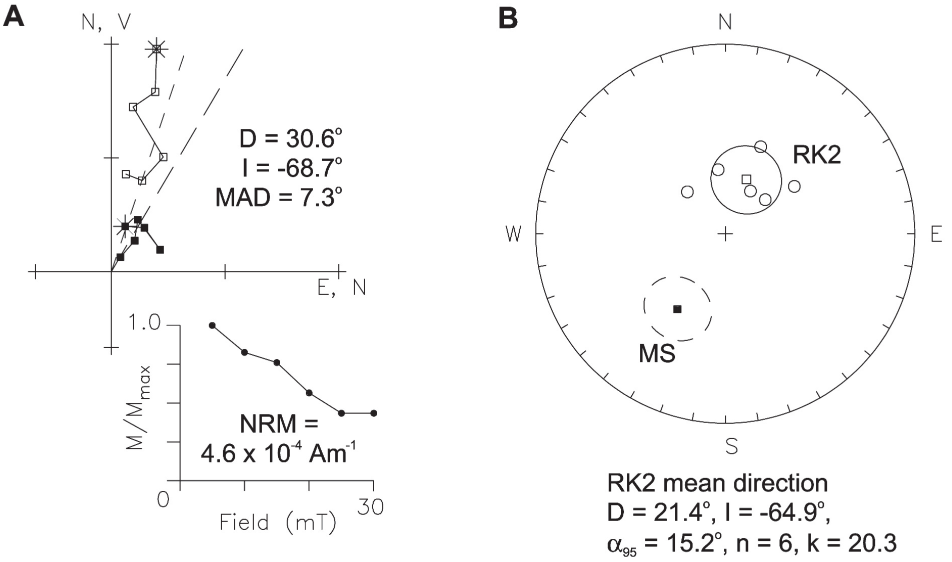


Fig. 10 **A**, Vector-component plot of data from the RK2 locality of Mumme & Walcott (1985) showing a normal polarity ChRM direction. **B**, Equal area stereographic plot of ChRM directions (open circles) and mean direction (open square) for RK2. The mean direction is antipodal to the mean direction for Matawai Station (closed square). Ellipses indicate α_{95} confidence intervals.

inclinations are quite common in the East Coast region, and possibly result from the effects of sediment compaction (Mumme et al. 1989).

Our new data indicate that the Rakauroa area should be regarded as part of the unrotated Raukumara Domain, in agreement with the regional structural trends discussed above. However, they conflict with the large rotations reported from the same sites by Mumme & Walcott (1985). Data published in their appendix show that 50% of samples were AF demagnetised at only 10–20 mT, the level at which stable behaviour had been observed in pilot samples demagnetised to 30 mT. This blanket demagnetisation approach is no longer considered adequate (Opdyke & Channell 1996), especially in the presence of the strong magnetic overprints common in New Zealand Cenozoic mudstones; several studies have demonstrated that detailed stepwise thermal demagnetisation of all samples is required to properly isolate primary components in such rocks (Turner et al. 1989; Turner & Kamp 1990; Roberts 1992; Pillans et al. 1994; Roberts et al. 1994; Roberts 1995; Turner 2001).

The limited AF demagnetisation data obtained in this study indicate that the viscous overprint observed in the Rakauroa localities has a high coercivity, typically >20 mT (Fig. 9A), which would have been incompletely removed in the fields used by Mumme & Walcott (1985). Vector-component plots indicate that many of their samples, particularly those that were demagnetised at lower peak fields, have yet to demonstrably converge onto a stable endpoint (Fig. 9B), and thus may not accurately represent the ChRM. The overprint appears to be weakest at the RK2 locality, where a normal polarity ChRM could be isolated in six samples (Fig. 10), giving a mean direction of $D = 21.4°$, $I = –64.9°$, $\alpha_{95} = 15.2°$. Whilst there are too few samples for this to be a statistically rigorous result, it is antipodal to the reversed polarity direction from the nearby Matawai Station locality. It therefore appears that the large declination anomaly reported by Mumme & Walcott (1985) from the Rakauroa localities is due to the inclusion of data from incompletely demagnetised samples.

Demonstrating that the Rakauroa area is unrotated with respect to the Australian plate removes a major obstacle to the reconciliation of existing paleomagnetic data with regional geology. Both are now consistent with the boundary between the Wairoa and Raukumara Domains being associated with a 20 km wide zone between the Rakauroa and Waerenga-o-Kuri Faults (Fig. 11). Structures that have accommodated the differential rotations between these two domains are still not immediately obvious within this corridor. However, now that a clear structural difference has been demonstrated between unrotated and rotated parts of the margin, further structural work should enable the filling in of gaps left by paleomagnetic measurements.

Reassignment of the Rakauroa locality to the Raukumara Domain also has a bearing on the assumed rotation history of the Wairoa Domain. Previously reported paleomagnetic data (Fig. 12A) indicate clockwise rotations of 40–60° with respect to the Australian plate since 10 Ma. The data for the early and middle Miocene are less coherent; the line of best fit used by Wright & Walcott (1986) and Walcott (1989) is significantly constrained by the RK1 declination anomaly reported by Mumme & Walcott (1985), which requires further clockwise rotation, albeit at a reduced rate, during the early and middle Miocene. With the removal of the RK1 constraint, this interpretation needs to be reassessed.

Much of the published paleomagnetic data for the Wairoa Domain predates widespread recognition of the need for detailed stepwise demagnetisation to ensure the reliable isolation of primary magnetisations; samples were commonly only subjected to blanket AF or thermal demagnetisations at low fields or temperatures. We have shown that these techniques do not adequately isolate a ChRM in the presence of a strong secondary overprint. This raises the possibility that other published declination anomalies may be unreliable due to the incomplete removal of such overprints. In Fig. 12B, we exclude localities where these uncertainties exist (refer to Table 1 for details). It is unlikely that all of the excluded data are unreliable, because strong overprints are not ubiquitous: samples from the HR1 locality (Walcott & Mumme 1982; resampled by Mumme & Walcott 1985) are not appreciably overprinted, which allows reasonable confidence in the published declination anomaly—the position of this locality (Fig. 11) also means that reliable paleomagnetic data are still consistent with the boundary between the Raukumara and Wairoa Domains being placed between the Rakauroa and Waerenga-o-Kuri Faults. However, the limited availability of complete demagnetisation data precludes detailed assessment of many localities. The majority of the data remaining are from Wright & Walcott (1986), who employed more rigorous stepwise thermal demagnetisations that allowed them to remove a strong viscous overprint. Antipodal normal and reversed polarity ChRM directions were also identified at each of their localities, which provide a robust reversals test.

Geodetic measurements show that the Hikurangi margin is currently rotating at a rate of 2–4°/m.y. with respect to the Australian plate (Wallace et al. 2004). The velocity field derived from known Quaternary fault slip rates provides a minimum estimate of 3–4°/m.y. (Beanland & Haines 1998). The reduced paleomagnetic dataset (Fig. 12B) suggests that the Wairoa Domain has rotated at rates of 4–5°/m.y. with respect to the Pacific plate (3–4°/m.y. with respect to the Australian plate) since the late Miocene (5–10 Ma), which is within the range of geodynamic estimates. Sparse reliable data for the middle and early Miocene make any interpretation of the rotation history during this earlier time interval tentative; it is possible that rotations have occurred at a similar rate throughout the Neogene. However, a marginally better fit to the data requires no rotation of the margin with respect to the Australian plate before 10 Ma (Fig. 12B). Whilst this interpretation is constrained purely by data that are demonstrably reliable, with the exclusion of the erroneous RK1 declination anomaly, it is a reasonable fit for the whole dataset (Fig. 12). Nevertheless, reliable paleomagnetic data from early and middle Miocene strata are needed to confirm any interpretation.

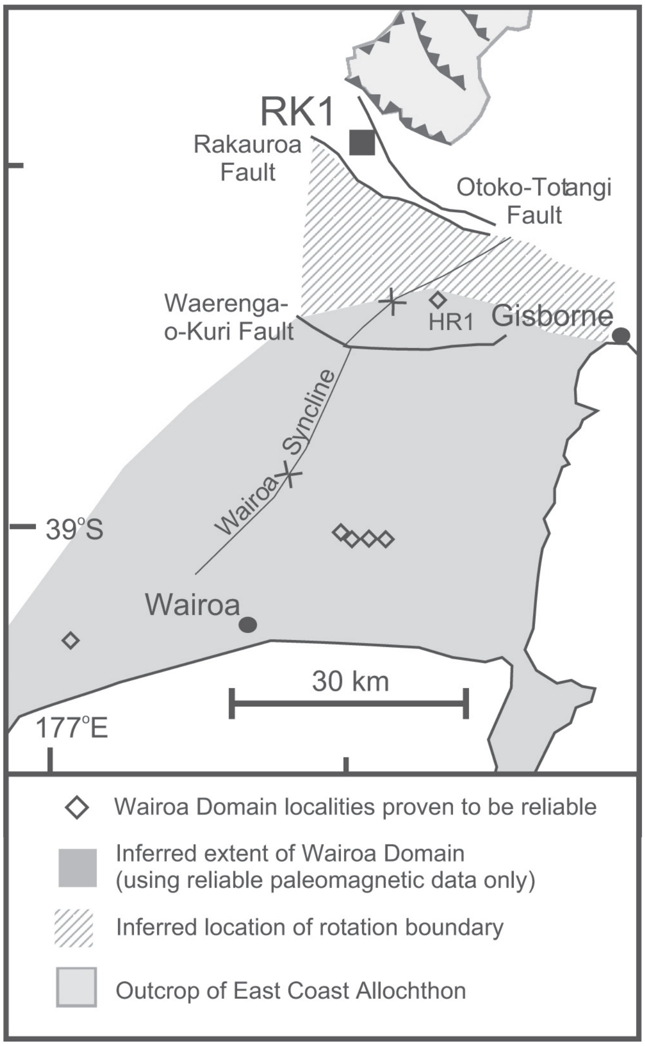


Fig. 11 New paleomagnetic constraints on the rotation boundary between the Raukumara and Wairoa Domains. Reassignment of the RK1 locality to the Raukumara Domain, and the removal of potentially unreliable data (see discussion and Table 1 for details), has shifted the inferred boundary south, to a zone between the Rakauroa and Waerenga-o-Kuri Faults.

It is illuminating to compare this potential rotation history for the Wairoa Domain with data from the southern Hikurangi margin. Based on the data of Roberts (1992, 1995), Little & Roberts (1997) described clockwise vertical axis rotations of 30–50° since the early Pliocene (c. 4 Ma) in northeastern Marlborough, hinged about a northwest-trending kink in the structural trend of basement rocks. A second crustal scale boundary farther to the east appears to have accommodated

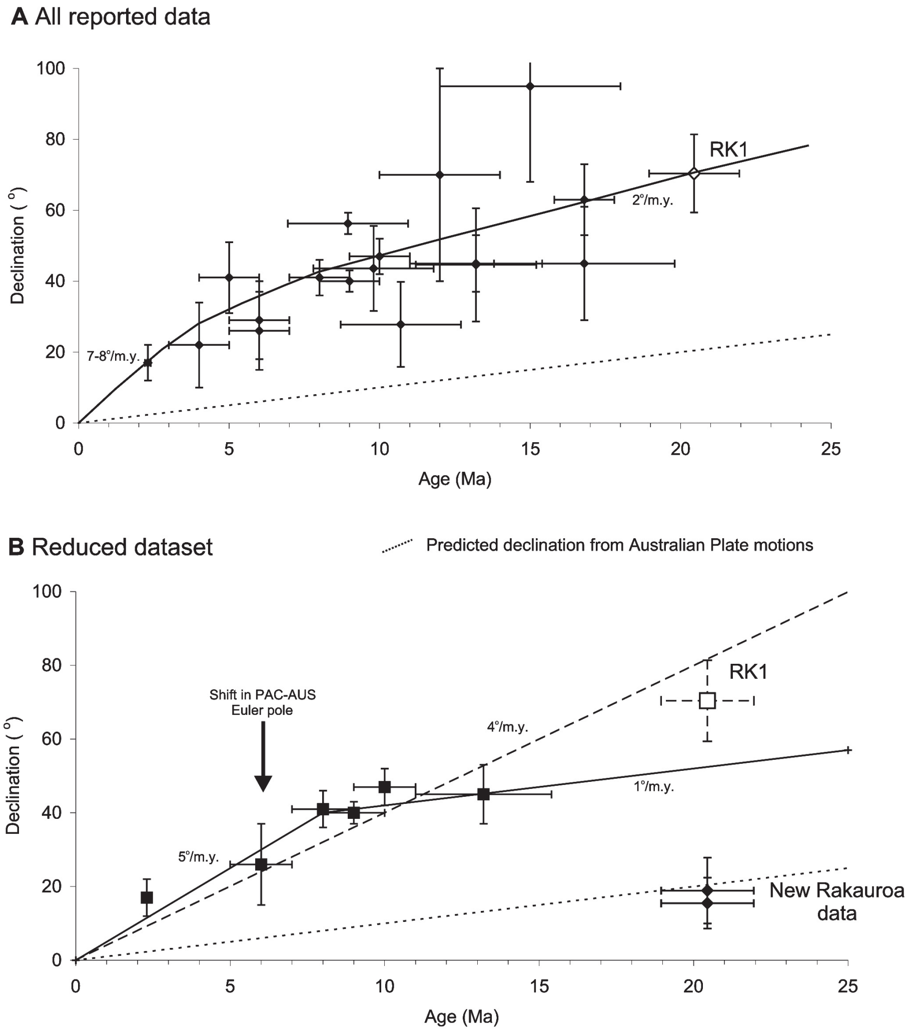


Fig. 12 **A**, Previously published paleomagnetic declinations for the Wairoa Domain (Walcott et al. 1981; Walcott & Mumme 1982; Mumme & Walcott 1985; Wright & Walcott 1986; Thornley 1996) plotted versus age. Some sites have been re-dated by Mazengarb (pers. comm. 2002). The best fit interpretation of Wright & Walcott (1986) and Walcott (1989) (solid line) is significantly constrained by the RK1 declination. **B**, Same as Fig. 11A, but including only localities with demonstrably reliable paleomagnetic data (see text and Table 1 for details). Rotations of 4–5°/m.y. are indicated for the late Miocene; rotations may have continued throughout the Neogene, but with the exclusion of the RK1 declination anomaly (open square with dashed error bars), an interpretation involving no rotation with respect to the Australian plate before 5–10 Ma is possible. Both possibilities are illustrated.

Table 1 Reported declinations from the Wairoa region of the Hikurangi margin. Those data proven to be reliable and included on Fig. 12B are highlighted in bold.

Locality	Source	Age (Ma)	Declination (°)	Retained	Rationale
RK1	MW	20.5 ± 1.5 *	70 ± 11	No	Blanket demagnetisation incompletely removing strong overprint (see text)
HR1	**WM/MW**	**13.2 ± 2.2 ***	**45 ± 8**	**Yes**	**Blanket demagnetisation but data indicate negligible overprint**
WK1	WM	12 ± 2	70 ± 30	No	Blanket demagnetisation; data unavailable
MK1	WM	17 ± 1 *	63 ± 10	No	Blanket demagnetisation; data unavailable
MK2	WM	17 ± 3 *	45 ± 16	No	Blanket demagnetisation; data unavailable
MK3	WM	15 ± 3	95 ± 27	No	Blanket demagnetisation; data unavailable
MK4	WM	4 ± 1	22 ± 12	No	Blanket demagnetisation; data unavailable
MK5	WM	5 ± 1	41 ± 10	No	Blanket demagnetisation; data unavailable
MK6	WM	6 ± 1	29 ± 11	No	Blanket demagnetisation; data unavailable
MK7	**WW**	**10 ± 1**	**47 ± 5**	**Yes**	**Stepwise demagnetisation, reversals test**
MK8	**WW**	**9 ± 1**	**40 ± 3**	**Yes**	**Stepwise demagnetisation, reversals test**
MK9	**WW**	**8 ± 1**	**41 ± 5**	**Yes**	**Stepwise demagnetisation, reversals test**
MK10	**WW**	**6 ± 1**	**26 ± 11**	**Yes**	**Stepwise demagnetisation, reversals test**
WH1	**WW**	**2.3 ± 0.1**	**17 ± 5**	**Yes**	**Stepwise demagnetisation, reversals test**

WM = Walcott & Mumme 1982; MW = Mumme & Walcott 1985; WW = Wright & Walcott 1986.
* = Site redated by Mazengarb (pers. comm. 2002). The unpublished data of Thornley (1996) are also considered to be unreliable, and have also been excluded from Fig. 11B.

another 50° of early–middle Miocene clockwise rotation (using data from Vickery & Lamb 1995). The most recent of these two phases of rotation has a clear correlative in the revised rotation history of the Wairoa Domain proposed here. In both cases, the beginning of large-scale rotations may have been associated with an abrupt shift in the position of the PAC-AUS Euler rotation pole at 5–6.5 Ma (Cande et al. 1995; Sutherland 1995; Walcott 1998), which increased convergence across the plate boundary in the New Zealand region. This event coincided with a number of tectonic events, including a southward shift in the locus of strike-slip displacement on the Marlborough Fault System (King 2000) and a period of rapid uplift in the Wairoa region (Buret et al. 1997). In the early and middle Miocene, rotations with respect to the Australian plate may have been much more spatially restricted, possibly being absent in the Wairoa region, and confined to a much smaller area near the coast in northeast Marlborough. However, this interpretation remains speculative until additional early Neogene paleomagnetic data are obtained from the Wairoa region. The rotation history of the intervening Wairarapa region is also currently unconstrained.

CONCLUSIONS

Early Miocene rocks from the Rakauroa area have not rotated with respect to the Australian plate during the Neogene, and are therefore part of the Raukumara Domain, in agreement with observed structural trends. The large declination anomaly previously reported from this area resulted from the use of low-field, blanket AF demagnetisation that failed to remove a strong secondary overprint. Our reconciliation of paleomagnetic data with regional geology will aid attempts to locate and characterise the nature of the tectonic boundary between the unrotated Raukumara and rotated Wairoa domains.

Reassignment of the Rakauroa locality to the Raukumara Domain also requires a reappraisal of the rotation history of the Wairoa Domain. A reduced paleomagnetic dataset, excluding data from early studies that utilised potentially unreliable blanket demagnetisation techniques, suggests that clockwise vertical axis rotations of 4–5°/m.y. have occurred since the late Miocene (5–10 Ma), with possibly no rotations other than those expected from large-scale plate motions before this. This interpretation remains reasonable even when potentially unreliable Wairoa Domain data are reintroduced to the dataset. On the Hikurangi margin, the only reliable data that indicate vertical axis rotations with respect to the Australian plate in the early and middle Miocene are now restricted to a small coastal area in northeastern Marlborough (Vickery & Lamb 1995; Little & Roberts 1997). It is possible that rotations during this period were local to the intersection between the Hikurangi subduction interface and the Alpine-Wairau Fault.

The difficulties with secondary overprints encountered in this study re-emphasise the need for caution when interpreting paleomagnetic data from New Zealand Cenozoic mudstones. A stable reversed polarity ChRM was isolated in only 16% of samples; the combination of a weak NRM, strong viscous overprints, and the effects of thermal alteration resulted in a ChRM that was at best observable over a 100°C temperature range. Detailed stepwise demagnetisation of samples is therefore essential if reliable results are to be obtained.

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REFERENCES

Ballance PF, Spörli KB 1979. Northland Allochthon. Journal of the Royal Society of New Zealand 9: 259–275.

Beanland S, Haines J 1998. The kinematics of active deformation in the North Island, New Zealand, determined from geological strain rates. New Zealand Journal of Geology and Geophysics 41: 311–323.

Buret C, Chanier F, Ferrière J, Proust JN 1997. Individualization of a forearc basin during the active margin evolution: Hikurangi subduction margin, New Zealand. Comptes Rendus de l'Academie des Sciences – Series IIA 325: 615–621.

Cande C, Raymond CA, Stock J, Haxby WF 1995. Geophysics of the Pitman Fracture Zone and Pacific-Antarctic plate motions during the Cenozoic. Science 270: 947–953.

Collot J-Y, Delteil J, Lewis KB, Davy B, Lamarche G, Audru JC, Barnes P, Chanier F, Chaumillon E, Lallemand S, deLepinay BM, Orpin A, Pelletier B, Sosson M, Toussaint B, Uruski C 1996. From oblique subduction to intra-continental transpression: structures of the southern Kermadec-Hikurangi margin from multibeam bathymetry, side-scan sonar and seismic reflection. Marine Geophysical Researches 18: 357–381.

Davy B, Wood R 1994. Gravity and magnetic modelling of the Hikurangi Plateau. Marine Geology 118: 139–151.

Demarest HH 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data. Journal of Geophysical Research 88: 4321–4328.

DeMets C, Gordon RG, Argus DF, Stein S 1994. Effect of recent revisions to the geomagnetic reversal time-scale on estimates of current plate motions. Geophysical Research Letters 21: 2191–2194.

Field BD, Uruski CI and others 1997. Cretaceous-Cenozoic geology and petroleum systems of the East Coast region. Institute of Geological & Nuclear Sciences Monograph 19. Lower Hutt, New Zealand, Institute of Geological & Nuclear Sciences.

Fisher RA 1953. Dispersion on a sphere. Proceedings of the Royal Society, London 217A: 295–305.

Herzer RH 1995. Seismic stratigraphy of a buried volcanic arc, Northland, New Zealand and implications for Neogene subduction. Marine and Petroleum Geology 12: 511–531.

Idnurm M 1985. Late Mesozoic and Cenozoic palaeomagnetism of Australia. 1. A redetermined apparent polar wander path. Geophysical Journal of the Royal Astronomical Society 83: 399–418.

King PR 2000. Tectonic reconstructions of New Zealand: 40 Ma to the present. New Zealand Journal of Geology and Geophysics 43: 611–638.

Kirschvink JL 1980. The least squares line and plane and the analysis of palaeomagnetic data. Geophysical Journal of the Royal Astronomical Society 62: 699–710.

Lamb SH 1988. Tectonic rotations about vertical axes during the last 4 Ma in part of the New Zealand plate boundary zone. Journal of Structural Geology 10: 875–893.

Little TA, Roberts AP 1997. Distribution and mechanism of Neogene to present-day vertical axis rotations, Pacific-Australian plate boundary zone, South Island, New Zealand. Journal of Geophysical Research 102: 20447–20468.

McFadden PL, McElhinny MW 1988. The combined analysis of remagnetisation circles and direct observations in palaeomagnetism. Earth and Planetary Science Letters 87: 161–172.

Mazengarb C, Speden IG 2000. Geology of the Raukumara area. 1: 250 000 geological map 6. Lower Hutt, New Zealand, Institute of Geological & Nuclear Sciences Limited.

Mumme TC, Walcott RI 1985. Paleomagnetic studies at Geophysics Division 1980–1983. Geophysics Division Research Report 204. Wellington, New Zealand, Department of Scientific and Industrial Research.

Mumme TC, Lamb S, Walcott RI 1989. The Raukumara paleomagnetic domain: constraints on the tectonic rotation of the East Coast, N Island, New Zealand, from paleomagnetic data. New Zealand Journal of Geology and Geophysics 32: 317–326.

Opdyke ND, Channell JET 1996. Magnetic stratigraphy. Academic Press.

Pillans BJ, Roberts AP, Wilson GS, Abbott ST, Alloway BV 1994. Magnetostratigraphic, lithostratigraphic and tephrostratigraphic constraints on lower and middle Pleistocene sea-level changes, Wanganui Basin, New Zealand. Earth and Planetary Science Letters 121: 81–98.

Rait GJ 2000. Thrust transport directions in the Northland Allochthon, New Zealand. New Zealand Journal of Geology and Geophysics 43: 271–288.

Rait GJ, Chanier F, Waters DW 1991. Landward- and seaward-directed thrusting accompanying the onset of subduction beneath New Zealand. Geology 19: 230–233.

Reyners M, Eberhart-Phillips D, Stuart G 1999. A three-dimensional image of shallow subduction: crustal structure of the Raukumara Peninsula, New Zealand. Geophysical Journal International 137: 873–890.

Roberts AP 1992. Paleomagnetic constraints on the tectonic rotation of the southern Hikurangi margin, New Zealand. New Zealand Journal of Geology and Geophysics 35: 311–323.

Roberts AP 1995. Tectonic rotation about the termination of a major strike-slip fault, Marlborough Fault System, New Zealand. Geophysical Research Letters 22: 187–190.

Roberts AP, Turner GM, Vella PP 1994. Magnetostratigraphic chronology of Late Miocene to Early Pliocene biostratigraphic and oceanographic events in New Zealand. Geological Society of America Bulletin 106: 665–683.

Spörli KB 1982. Review of paleo-strain/stress directions in Northland, New Zealand, and of the structure of the Northland Allochthon. Tectonophysics 87: 25–36.

Stoneley R 1968. A lower Tertiary décollement of the East Coast, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 11: 128–156.

Sutherland R 1995. The Australian-Pacific boundary and Cenozoic plate motions in the SW Pacific: some constraints from Geosat data. Tectonics 14: 819–831.

Tauxe L, Watson G 1994. The fold test: an eigen analysis approach. Earth and Planetary Science Letters 122: 331–341.

Thornley S 1996. Neogene tectonics of Raukumara Peninsula, northern Hikurangi margin, New Zealand. Unpublished PhD thesis, Victoria University of Wellington, Wellington, New Zealand.

Turner GM 2001. Toward an understanding of the multicomponent magnetization of uplifted marine sediments in New Zealand. Journal of Geophysical Research 106: 6385–6397.

Turner GM, Kamp PJJ 1990. Paleomagnetic location of the Jaramillo Subchron and the Matuyama-Brunhes transition in the Castlecliffian stratotype section, Wanganui Basin, New Zealand. Earth and Planetary Science Letters 100: 42–50.

Turner GM, Roberts AP, Laj C, Kissel C, Mazaud A, Guitton S, Christoffel DA 1989. New paleomagnetic results from Blind River—revised magnetostratigraphy and tectonic rotation of the Marlborough region, South Island, New Zealand. New Zealand Journal of Geology and Geophysics 32: 191–196.

Van der Voo R 1993. Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans. Cambridge University Press.

Vickery S, Lamb S 1995. Large tectonic rotations since the Early Miocene in a convergent plate-boundary zone, South Island, New Zealand. Earth and Planetary Science Letters 136: 43–59.

Walcott RI 1989. Paleomagnetically observed rotations along the Hikurangi margin of New Zealand. In: Kissel C, Laj C ed. Paleomagnetic rotations and continental deformation. Kluwer. Pp. 459–471.

Walcott RI 1998. Modes of oblique compression: late Cenozoic tectonics of the South Island of New Zealand. Reviews of Geophysics 36: 1–26.

Walcott RI, Mumme TC 1982. Paleomagnetic study of the Tertiary sedimentary rocks from the East Coast of the North Island, New Zealand. Geophysics Division Research Report 189. Wellington, New Zealand, Department of Scientific and Industrial Research.

Walcott RI, Christoffel DA, Mumme TC 1981. Bending within the axial tectonic belt of New Zealand in the last 9 Myr from paleomagnetic data. Earth and Planetary Science Letters 52: 427–434.

Wallace LM, Beavan J, McCaffrey R, Darby D 2004. Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. Journal of Geophysical Research 109: 12406–12427.

Wright IC, Walcott RI 1986. Large tectonic rotation of part of New Zealand in the past 5 Ma. Earth and Planetary Science Letters 80: 348–352.