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Paleomagnetic constraints on the tectonic rotation of the southern Hikurangi margin, New Zealand

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Abstract Plate reconstructions of the New Zealand region indicate substantial Cenozoic tectonic rotation of the Hikurangi margin. This study was undertaken to determine the rotational history of the northern Marlborough paleomagnetic domain in the southern part of the Hikurangi margin. Most Cenozoic rocks in the Marlborough region are unstably magnetised, and useful results were obtained only from late Miocene – early Pliocene strata (c. 8–4 Ma). Clockwise rotations, with respect to the Pacific plate, between the Wairau and Kekerengu Faults are consistently about 20° and occurred after c. 4 Ma. No rotation is observed in the interval between 8 and 4 Ma, in contrast with the northern part of the Hikurangi margin where rotation has been continuous since the early Miocene. Differential rotation between northern Marlborough and eastern North Island is likely to have occurred about the northern end of the Wairau Fault in Cook Strait. Rapid rotation throughout the Hikurangi margin since the early Pliocene may be linked to a change in the motion of the Pacific plate relative to the Australian plate.

Keywords paleomagnetism; Marlborough; tectonics; rotation; Hikurangi margin; Miocene; Pliocene

INTRODUCTION

The Hikurangi margin is a zone of active deformation, on the east coast of the North Island and the northern South Island of New Zealand, that structurally links the Hikurangi Subduction Zone and the Alpine Fault (Fig. 1; Walcott 1989). Plate reconstructions of the New Zealand region (Walcott 1984a, b, 1987) based on the seafloor spreading data of Stock & Molnar (1982) indicate that substantial clockwise rotation of the Hikurangi margin has occurred during the Cenozoic. Paleomagnetism is a powerful tool for determining horizontal plane tectonic rotations in areas of continental deformation and has been widely used to determine the tectonic rotational history of the Hikurangi margin (Walcott et al. 1981; Walcott & Mumme 1982; Mumme & Walcott 1985; Wright & Walcott 1986; Mumme et al. 1989; Turner et al. 1989). These studies indicate that most of the Hikurangi margin is rotating, although the amounts and rates of rotation vary with time and location and are not uniform over the whole margin (Lamb 1988, 1989; Walcott 1989). Rocks in some areas appear to have rotated coherently and uniformly, but differently from rocks of adjacent areas. Areas where coherent patterns of rotation are recognised have been termed paleomagnetic "domains" and have lateral dimensions of the order of 100 km or so (Fig. 1; Lamb 1988).

The Marlborough Fault System links the Hikurangi Subduction Zone to the Alpine Fault at the south of the Hikurangi margin (Fig. 1). The role of block rotation within systems of strike-slip faults in areas of continental deformation has received much attention over the last two decades. The Marlborough Fault System has been the subject of much speculation in this respect (Freund 1971; Merzer & Freund 1974; Ron et al. 1984; Lamb 1988, 1989; Lamb & Bibby 1989). This study was undertaken to determine the Cenozoic rotational history of localities between the Marlborough faults, and provides important constraints for reconstructions of the southern part of the Hikurangi margin.

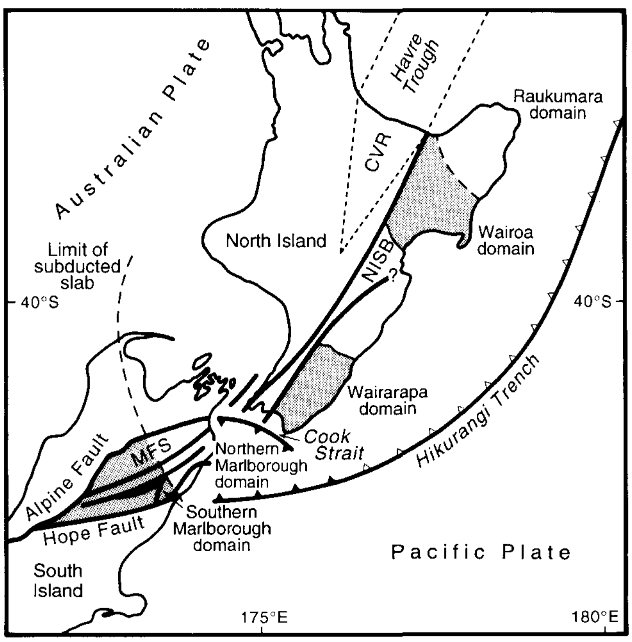

Fig. 1 Geodynamic setting and rotational domains of the Hikurangi margin, after Walcott (1989). The eastern boundary of the Hikurangi margin is taken as the Hikurangi Trench and the western boundary is taken as the North Island Shear Belt (NISB). CVR is the Central Volcanic Region and MFS is the Marlborough Fault System.

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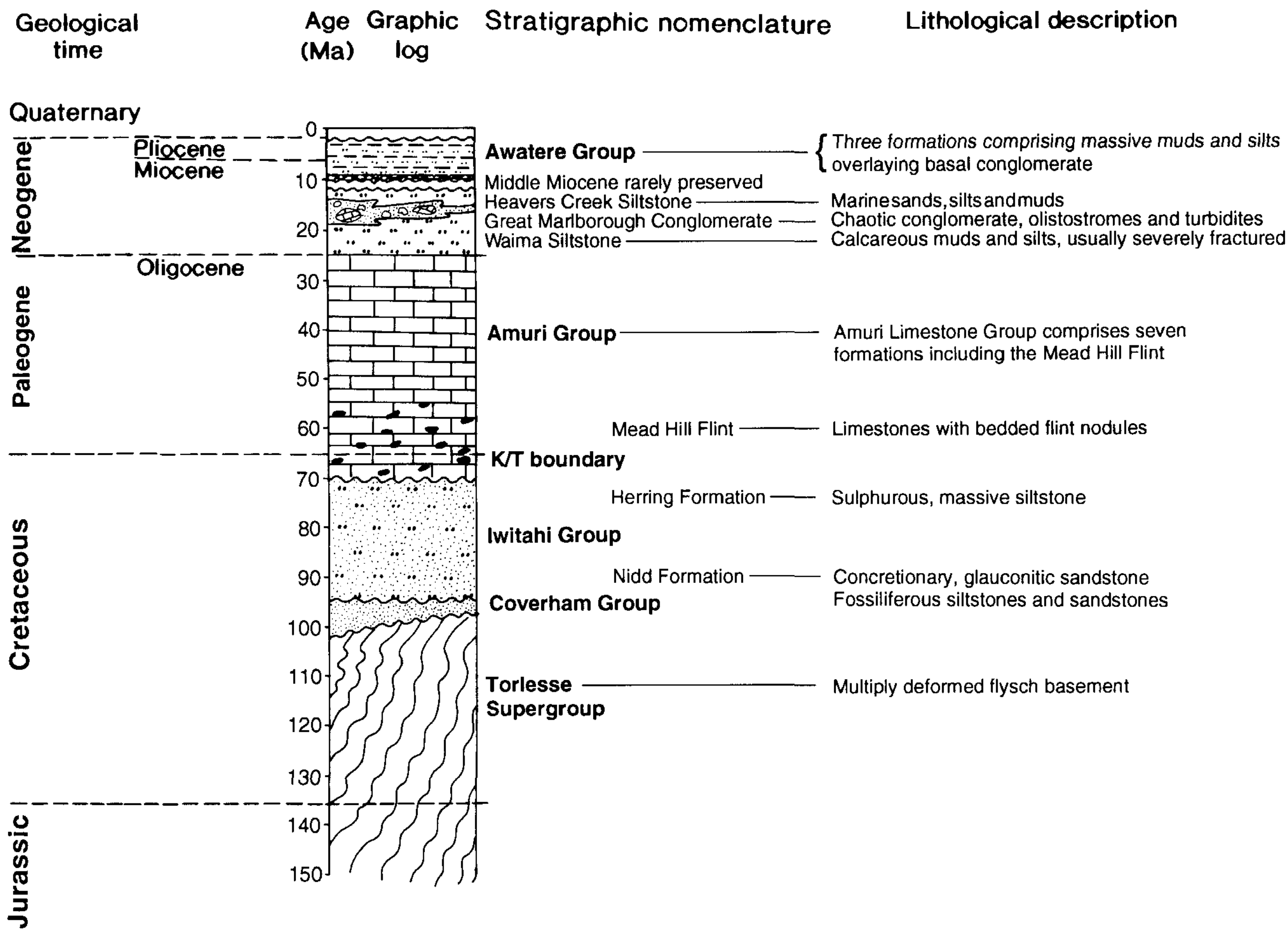

Fig. 2 Generalised stratigraphic column for the Marlborough region.

METHODS

Sampling strategy

Pre-Cenozoic rocks in the Marlborough region are unsuitable for determining tectonic rotations because they have been multiply deformed and structural constraints are usually poorly known. Also, because the New Zealand landmass occupied a position close to the south geographic pole until the early Cenozoic (Grindley et al. 1977; Oliver et al. 1979), paleomagnetic inclinations are steep and declinations have large errors associated with them, making them difficult to interpret in terms of horizontal plane tectonic rotations. It was therefore intended to sample as many Cenozoic stratigraphic units as possible (Fig. 2) throughout the Marlborough region. Lack of widespread Cenozoic volcanism restricted paleomagnetic sampling to sedimentary formations.

Limestones of the Amuri Group dominate Marlborough stratigraphy from Late Cretaceous to Oligocene time (Fig. 2). Several attempts have been made by other workers to determine a magnetostratigraphic chronology in the Amuri Group around the Cretaceous–Tertiary boundary at Woodside Creek, Marlborough. These, and attempts to obtain paleomagnetic results elsewhere in the Amuri Group (Mumme & Walcott 1985; Roberts 1990), have been unsuccessful because of extremely weak intensities of magnetisation. Early Miocene deposits in Marlborough are represented by the Waima Siltstone and the Great Marlborough Conglomerate (Fig. 2). The Waima Siltstone is, at most localities, too fractured to enable paleomagnetic sampling, and the Great Marlborough Conglomerate is usually too coarse grained to be suitable for paleomagnetic study. Middle Miocene deposits are rarely preserved in Marlborough. Late Miocene and Pliocene sedimentary rocks are restricted to small areas in the Marlborough region, but where they do outcrop, they are generally suitable for paleomagnetic study.

Late Cenozoic uplift of the Marlborough region has resulted in erosion of most post-Torlesse cover rocks, except in areas of relatively low uplift. As a result, most tectonic rotations determined in this study come from the lower Awatere Valley where fine grained, late Miocene – Pliocene marine sediments have been preserved. Details of the stratigraphy of the lower Awatere Valley are given by Roberts & Wilson (in press).

Sampling

Oriented paleomagnetic cores were sampled from fresh, unweathered, water-saturated mudstone outcrops. Suitable outcrops were cut back sufficiently to avoid drilling rocks that were dry, weathered, or close to fracture planes. Cores were drilled with a diamond-tipped, brass, drill barrel (25 mm internal diameter) attached to an electric drill driven by a gasoline-powered electric generator.

Magnetostratigraphic studies of strata in the lower Awatere Valley indicate average sedimentation rates of c. 0.5 m/ka (Kennett & Watkins 1974; Turner et al. 1989;

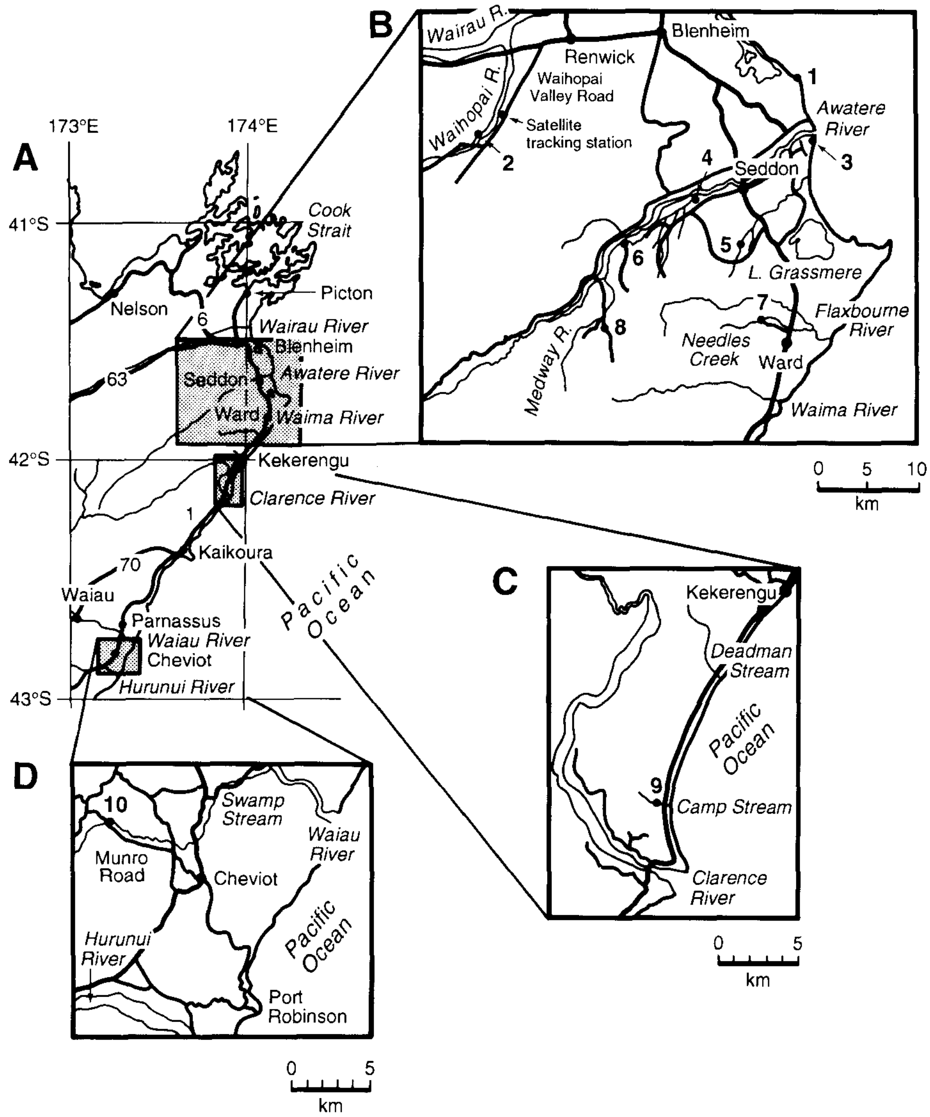

Fig. 3 A, Map of Marlborough region showing localities where stable paleomagnetic results were obtained (B, C, D). Numbers denote sampling localities. **B**, 1. White Bluffs, 2. Waihopai valley, 3. Sea View, 4. Richmond Brook, 5. Blind River, 6. Upton Brook, 7. Needles Creek, 8. Boundary Stream. **C**, 9. Camp Stream. **D**, 10. Swamp Stream.

Roberts 1990). Samples were drilled from a minimum stratigraphic range of 20 m, corresponding approximately to a time interval exceeding 40 ka, in order to average the effects of secular variation of the geomagnetic field. Greater thicknesses were sampled where possible to average over wider time intervals. A minimum of six horizons was drilled at each locality in order to diminish the possibility of sampling only extreme secular variants. Sampling details, relevant geological information, and paleomagnetic results are presented for each locality in the results section.

Low intensities of magnetisation and strong remagnetisation prevented retrieval of useful data from approximately 50% of localities sampled for this study. Details for unsuccessful localities are given by Roberts (1990). The 10 localities from which useful tectonic rotation data were obtained are shown in Fig. 3. Detailed magnetostratigraphic studies were carried out at Blind River and Upton Brook (Fig. 3), enabling determination of the rotational history over the period between 7.5 and 4.8 Ma. Sediment samples were collected from each locality in order to determine the age of the sediment from foraminiferal populations. Fossil collections from this study are housed in the paleontological collections of the Geology Department, Victoria University of Wellington.

Laboratory procedure

Measurements of magnetic remanence were made on a two-axis ScT cryogenic magnetometer at the Research School of Earth Sciences, Victoria University of Wellington, for most samples analysed. These samples were measured in four orientations and inverted and remeasured in four orientations. Data were rejected if the angular difference between averaged normal and inverted measurements exceeded 10°. Samples from Sea View and Richmond Brook (Fig. 3) were analysed on a Molspin spinner magnetometer at Victoria University, and those from Boundary Stream (Fig. 3) were analysed on a Digico spinner magnetometer at the Centre des Faibles Radioactivités, Gif-sur-Yvette, France.

Previous studies have shown that thermal demagnetisation is superior to alternating field (A.F.) demagnetisation in determining primary remanence directions in New Zealand Cenozoic mudstones (Kennett & Watkins 1974; Wright & Vella 1988; McGuire 1989; Turner et al. 1989). In many cases, A.F. demagnetisation fails to remove significant secondary

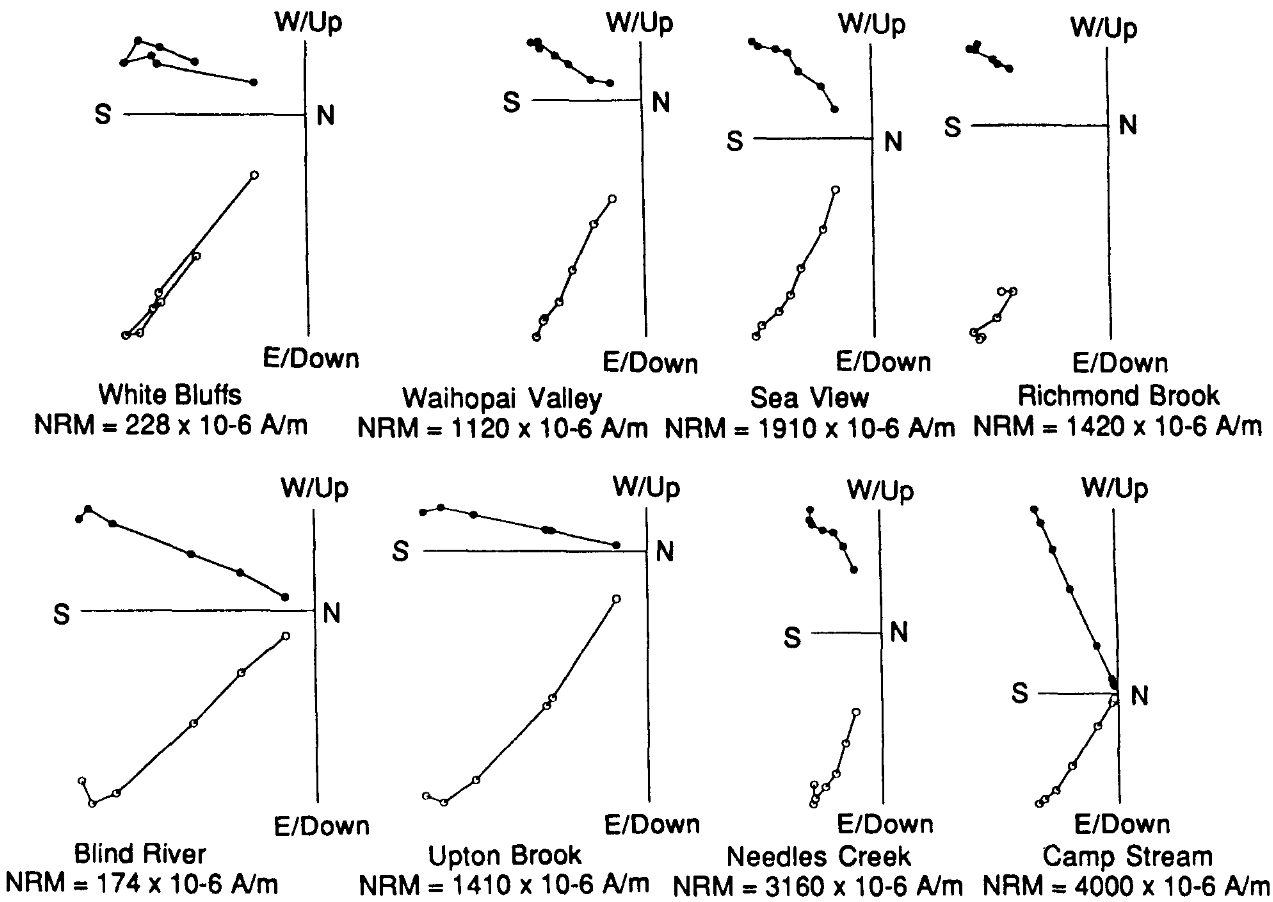

Fig. 4 Vector component plots showing typical thermal demagnetisation behaviour of samples from eight localities sampled. All plots show reversed polarity data corrected for bedding, except Camp Stream. Solid circles represent projections onto the horizontal plane, and open circles represent projections onto the vertical plane. All samples were measured at steps of 20°, 100°, 150°, 200°, 250°, and 300°C. Data are included at 350° and 380°C for samples that were still stably magnetised at those temperatures.

components of magnetisation (e.g., Turner et al. 1989). Thermal demagnetisation was therefore the sole demagnetisation technique used in this study. Thermal demagnetisation was carried out in a zero field electric oven with temperature control within ± 5°C of the desired temperature. Magnetic remanence and susceptibility were measured after heating to 100°, 150°, 200°, 250°, 300°, 350°, and 380°C. Magnetic susceptibility was measured with a Bartington Instruments MS1 magnetic susceptibility meter. Large increases in susceptibility, usually of the order of 30% and greater, accompanied heating betweeen 300° and 380°C, marking the appearance of a magnetic phase displaying unstable, wildly fluctuating remanence directions. Remanence measurements at temperatures where such dramatic changes in susceptibility occurred were not included in later analyses because the effects of mineralogical changes obliterate or mask any remaining primary magnetisation.

Paleomagnetic directions were determined from individual samples only after full stepwise thermal demagnetisation and analysis of orthogonal vector component plots. In stably magnetised samples, a "soft" secondary magnetisation is usually removed well before 250°C, and the primary component is directed towards the origin of the vector component plot (Fig. 4). More strongly remagnetised samples that do not reach stable end points after demagnetisation are rejected. At some horizons, there appears to be a secondary component in the higher end of the blocking temperature spectrum, which is difficult to isolate due to thermal alteration and low intensities of magnetisation. The component residing in the middle of the blocking temperature spectrum is the most persistent and stable component and is often interpreted to be the primary component. It can be identified as straight lines that do not tend towards the origin of vector component plots. Best-fit lines through these directions are usually within a few degrees of those from single-component samples from nearby horizons. The high temperature component has been observed in other paleomagnetic studies of New Zealand Cenozoic mudstones (McGuire 1989; Turner & Kamp 1990) and is considered to be a postdepositional chemical remanence residing in secondary minerals that have grown to stable, single-domain size.

Most strata sampled here dip at angles <25°, and simple corrections about horizontal axes have been applied. In plunging strata that dip at angles <30°, the error resulting from correction about a horizontal axis is low (Tarling 1983). Strata at Camp Stream are part of a steeply plunging structure, and correction has therefore been made for fold axial plunge followed by a tilt correction. All structural tilt corrections are given with Fig. 6.

Data were accepted only if stable paleomagnetic behaviour was evident on demagnetisation (Fig. 4). This ensured that 95% confidence limits about horizon means were usually <10°. Similarly, 95% confidence limits for locality means were generally ≪10°, with inclinations close to those expected for an axial dipole field. These factors suggest that secular variation has been adequately averaged and that the observed declination anomalies are due to tectonic rotation about vertical axes. Standard errors associated with declination anomalies are calculated following the approach of Demarest (1983).

Rock magnetic investigations of sediments in the lower Awatere Valley indicate that the major contributors to magnetic remanence are ferrimagnetic iron sulphide (pyrrhotite and greigite) and iron-titanium oxide minerals (Roberts 1990). Dissolution of detrital titanomagnetite grains has occurred as a result of iron sulphide formation during early diagenesis, and the paleomagnetic signal due to titanomagnetite in such rocks is usually weak with significant remagnetisation having occurred. Samples where ferrimagnetic iron sulphide minerals are dominant are usually intensely and stably magnetised. It is therefore probable that iron sulphide minerals are largely responsible for the paleomagnetic signals recorded in this study. Available evidence suggests that sedimentary iron sulphide formation is severely restricted below the surface metre of marine sediments (Westrich & Berner 1984; Canfield & Berner 1987). If so, iron sulphides will form during early diagenesis, within 2 ka of deposition for sediments deposited at rates ≥0.5 m/ka. The age of the magnetisation will therefore be the same as that indicated by foraminiferal biostratigraphy, which will give a maximum age for the tectonic rotation recorded at a locality. All adopted biostratigraphic stages, and dates for stage boundaries, follow the New Zealand timescale of Edwards et al. (1988).

RESULTS

Tectonic rotations of the northeastern South Island are reported with respect to the Pacific plate because this area is contiguous with the Pacific plate. Cenozoic paleomagnetic pole positions from the Pacific plate show no apparent polar wander (Grindley et al. 1977), indicating that the Pacific plate has not undergone significant rotation relative to true north since 35 Ma. The amount of tectonic rotation of a rock unit of age <20 Ma on the Pacific plate is therefore equal to the mean paleomagnetic declination minus the axial dipole declination (0° for normal polarity and 180° for reversed polarity), provided the mean inclination is equal to that expected at the sampling latitude for a geocentric axial dipole field. Paleomagnetic declinations divergent from those expected from the stable Pacific plate are referred to as "declination anomalies" and are interpreted as tectonic rotations about vertical axes.

Useful tectonic rotation data were obtained from 10 localities including the 2 magnetostratigraphic localities, Blind River and Upton Brook. The field setting, age, sampling details, and paleomagnetism of each locality are described below. Results are summarised in Fig. 4, 5, 6, 7, 8 and Table 1.

Lower Wairau Valley

1. White Bluffs The White Bluffs are prominent calcareous coastal bluffs between the mouths of the Wairau and Awatere Rivers (Fig. 3A, B). The bluffs consist of lenses of calcareous mudstone up to 15 m thick within a conglomeratic sequence. Only one lens is accessible at the coast as access to mudstones further up the 250 m sheer bluff is impossible. Twenty-nine cores were drilled from eight horizons in this mudstone lens (Fig. 3; N.Z. topographic map grid reference NZMS 260 P28/056606). Assemblages of *Globorotalia crassaconica* indicate either an Opoitian or a Waipipian (4.8–3.1 Ma) age (Hornibrook et al. 1989).

NRM directions generally displayed reversed polarity with variable amounts of "soft", normal overprinting. Primary components directed towards the origin of vector component plots were isolated at temperatures above 200°C (Fig. 4). A small proportion of samples were less stably magnetised, but generally primary directions were readily identified. Distributions of primary remanence directions are shown in Fig. 5 and 6. Uncorrected data (Fig. 5) have inclinations near that expected for an axial dipole field (60.6°) at the latitude of White Bluffs. Application of a tilt correction steepens the inclination to 67.0°. Such a steep inclination may result from failure to sample a sufficient stratigraphic thickness to average the effects of secular variation. A declination anomaly of 24 ± 7° should be regarded with caution, given the failure of the inclination to average to an axial dipole value within the given limits of error. This declination anomaly is nevertheless consistent with other values determined in this study (Table 1).

Table 1 Paleomagnetically determined tectonic rotation data from the Marlborough region

Locality	Latitude (°)	Thickness (m)	Horizons	D (°)	I (°)	Expected I (°)	α_{95} (°)	N	κ	D Anomaly $\Delta \pm \delta$ (°)	Age (Ma)
This study											
White Bluffs	41.54	15	8	204.2	67.0	60.6	3.6	29	58.1	24 ± 7	3.9 ± 0.8
Waihopai valley	41.63	100	8	199.6	60.6	60.6	2.4	42	84.6	20 ± 4	8 ± 1
Sea View	41.63	18	9	223.5	58.7	60.6	3.1	33	67.1	44 ± 5	3.9 ± 0.8
Richmond Brook	41.67	22	11	211.6	61.8	60.7	3.9	25	56.5	32 ± 7	4.2 ± 0.6
Blind River	41.72	990	32	212.6	59.5	60.7	2.0	132	37.5	33 ± 3	4.8 ± 0.2
Upton Brook	41.75	783	28	201.3	59.0	60.7	1.8	132	48.2	21 ± 3	4.8 ± 0.2
Needles Creek	41.75	14	7	215.4	59.8	60.7	3.5	31	61.1	35 ± 6	5.4 ± 0.6
Boundary Stream	41.83	88	14	196.6	63.3	60.8	7.4	14	29.6	17 ± 13	8 ± 1
Camp Stream	42.13	45	8	174.8	59.3	61.1	2.8	52	50.8	−5 ± 4	3.3 ± 0.3
Swamp Stream	42.75	30	6	183.7	61.8	61.6	4.6	29	34.8	4 ± 8	4.2 ± 0.6
Other studies											
Cape Campbell	41.75	300	–	024.4	−60.5	60.7	5.4	12	56.2	24 ± 9	8 ± 1
Deadman Stream	42.08	36	–	279.3	59.1	61.0	6.4	46	10.5	99 ± 10	18 ± 1

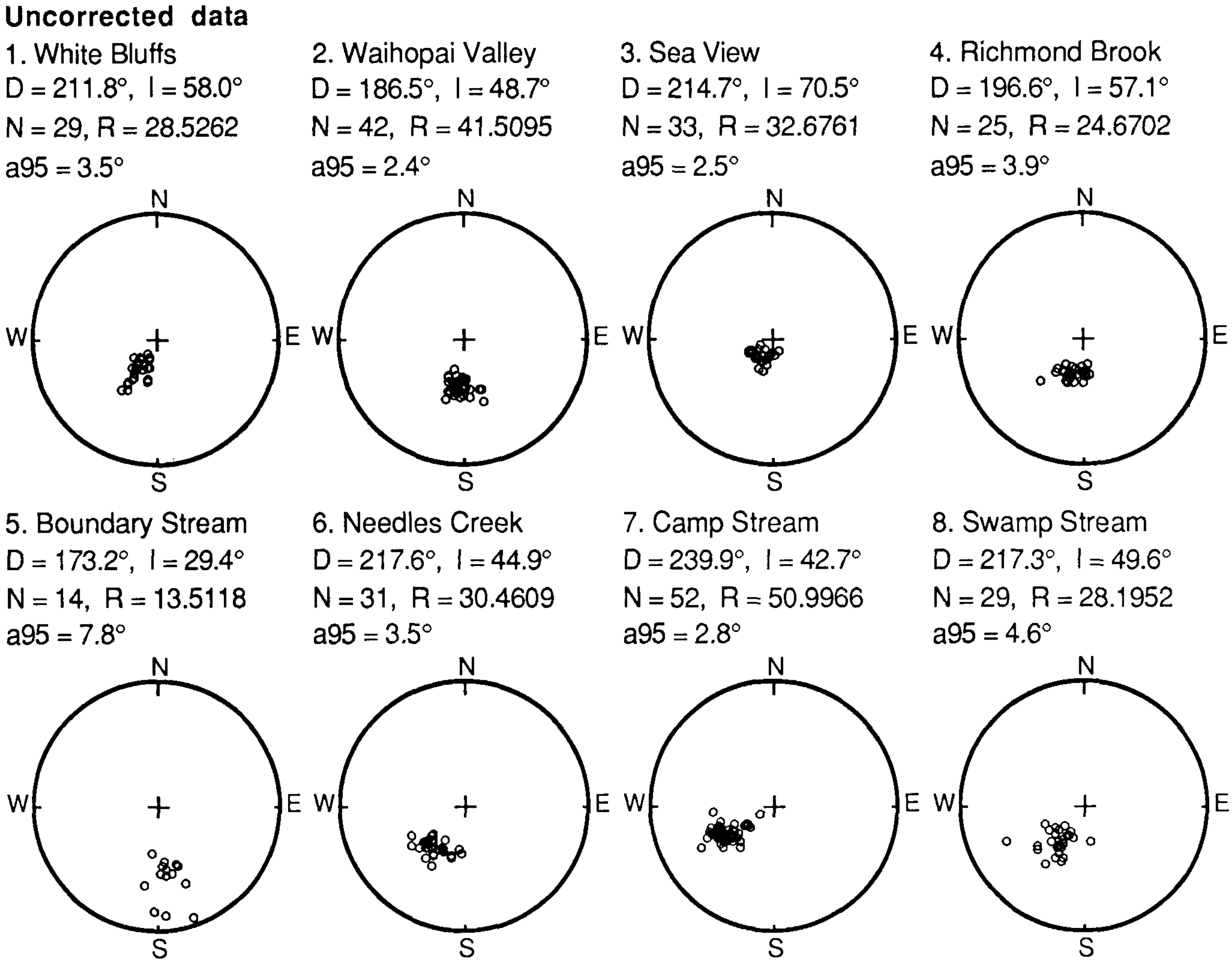

Fig. 5 Equal angle stereographic projections of, and statistics for, primary remanence directions from eight localities sampled, prior to bedding correction. Open circles denote lower hemisphere projections.

2. Waihopai valley Late Miocene rocks of the Wairau Valley are largely Taranakian freshwater conglomerates (Lensen 1962). A thick succession (>100 m) of fine-grained sediments that unconformably overlie Torlesse greywacke is exposed in a large bend in the Waihopai River, a major tributary of the Wairau River at NZMS 260 O28/676551 (Fig. 3A, B). The succession is dominated by fine-grained olive-green mudstones with occasional grit bands in the basal part. The sediments were probably deposited in a shallow lake that was subject to occasional marked dry seasons, as indicated by the presence of several paleosols with distinct gammate structures. Palynological analysis of sediment samples failed to identify age-diagnostic fossil pollens. Other freshwater sediments in the area were mapped by Lensen (1962) as Taranakian, thus this broad age range is adopted (c. 8 ± 1 Ma). Thirty-nine cores were drilled from eight horizons over a stratigraphic interval of c. 100 m.

A large proportion of the samples subjected to thermal demagnetisation possessed only a single, primary component of magnetisation (Fig. 4). Samples from coarser grained parts of the sequence displayed more erratic behaviour, but primary directions were still recognisable. Gentle stratal dip means that application of a structural tilt correction causes only a minor change from the uncorrected directions (Fig. 5 and 6). The corrected inclination is identical to the expected axial dipole value. The results are well grouped (α_{95} = 2.4°) with a declination anomaly of 20 ± 4° (Fig. 4; Table 1).

Lower Awatere Valley

3. Sea View Mudstones of the Starborough Formation crop out in coastal bluffs from the Awatere River mouth to Lake Grassmere. Samples were collected from coastal cliffs c. 0.5 km south of the Awatere River mouth at NZMS 260 P28/070540 (Fig. 3A, B). Normal faulting in the area makes it difficult to estimate the thickness of the stratigraphic interval sampled, but it is probably c. 18 m thick. Twenty-eight cores were sampled from nine horizons in this interval. Assemblages of *Globorotalia puncticulata* indicate an Opoitian or a Waipipian (4.8–3.1 Ma) age (Hornibrook et al. 1989).

Samples from Sea View displayed stable magnetic behaviour during thermal demagnetisation (Fig. 4), and primary paleomagnetic directions were obtained from every sample demagnetised. Secondary overprints were usually removed by heating to 100°C, but directional scatter was sometimes observed up to 200°C. Results from this locality

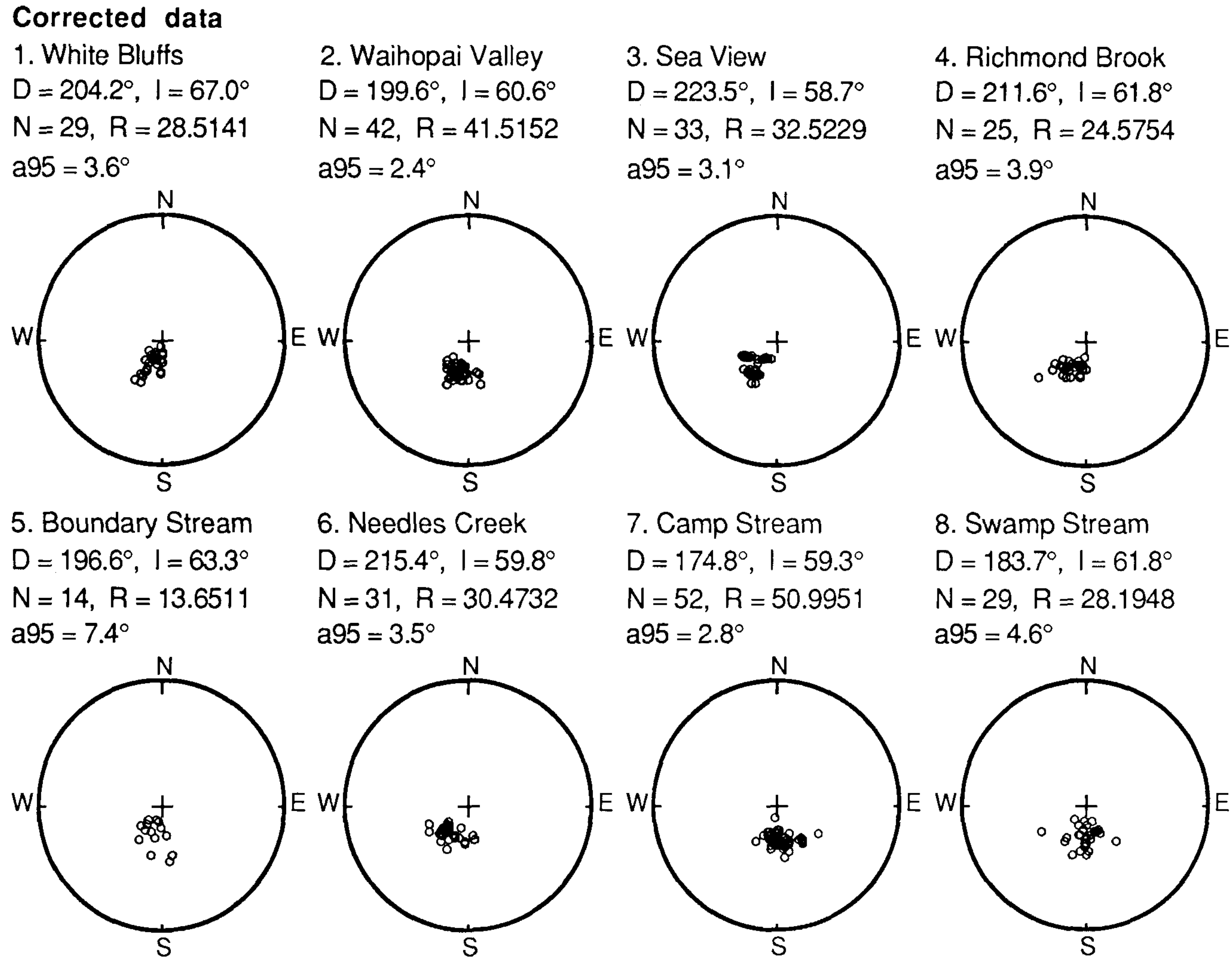

Fig. 6 Equal angle stereographic projections of bedding corrected data. Average bedding corrections are: White Bluffs 10NE/321; Waihopai valley 15NW/245; Sea View 13SW/153; Richmond Brook 10NW/233; Boundary Stream 42NW/239; Needles Creek 15NE/313; Camp Stream plunge 20S/079, dip 50E/354; Swamp Stream 25E/353.

are well grouped, with $\alpha_{95} = 3.1°$ (Fig. 5 and 6). The average directions indicate a declination anomaly of 44 ± 5°, which is higher than others recorded from the lower Awatere Valley in this study (Fig. 6; Table 1). It is possible that secular variation has not been accounted for sufficiently; however, the inclination is as predicted for an axial dipole field.

4. Richmond Brook A 22 m succession of mudstone was sampled at Richmond Brook, just upstream of its confluence with the Awatere River. Thirty-seven cores were collected from 11 horizons in uniformly massive mudstones of the Starborough Formation (Fig. 3A, B; NZMS 260 P29,Q29/936475). The age of these sediments could not be constrained better than between Taranakian and Opoitian from the microfauna collected for this study; however, its stratigraphic relationship with other rocks in the lower Awatere Valley (Roberts & Wilson in press) suggests that they are probably of Opoitian (4.8–3.6 Ma) age.

Various patterns of magnetic behaviour were observed from the Richmond Brook samples. One-third were stably magnetised, and reversed primary directions were readily determined (Fig. 4). Another third were so strongly remagnetised that no consistent primary direction was observable. Intermediate blocking temperature components that were not directed towards the origin of vector component plots were interpreted as the primary directions for the remaining third of the samples. Consistency was observed between the directions obtained from single-component samples and those from samples with intermediate components. Paleomagnetic directions from Richmond Brook are closely grouped with average directions of $D = 211.6°$, $I = 61.8°$, $\alpha_{95} = 3.9°$ (Fig. 6). A tectonic rotation of c. 32 ± 7° is inferred from these data.

5. Blind River Paleomagnetic directions from an earlier study of the upper Blind River section ($D = 216°$, $I = 60°$, $N = 60$) indicate a clockwise rotation of 36° (Turner et al. 1989). Three data points that are profoundly affected by normal overprinting and have in no way approached stable end points were included in the earlier study. Recalculation of the mean paleomagnetic direction without the three spurious data points gives a modified direction of $D = 214.0°$, $I = 58.4°$, $\alpha_{95} = 3.2°$, $N = 57$.

Reversed polarity data dominate the magnetostratigraphic subdivisions at Blind River and Upton Brook (Roberts 1990),

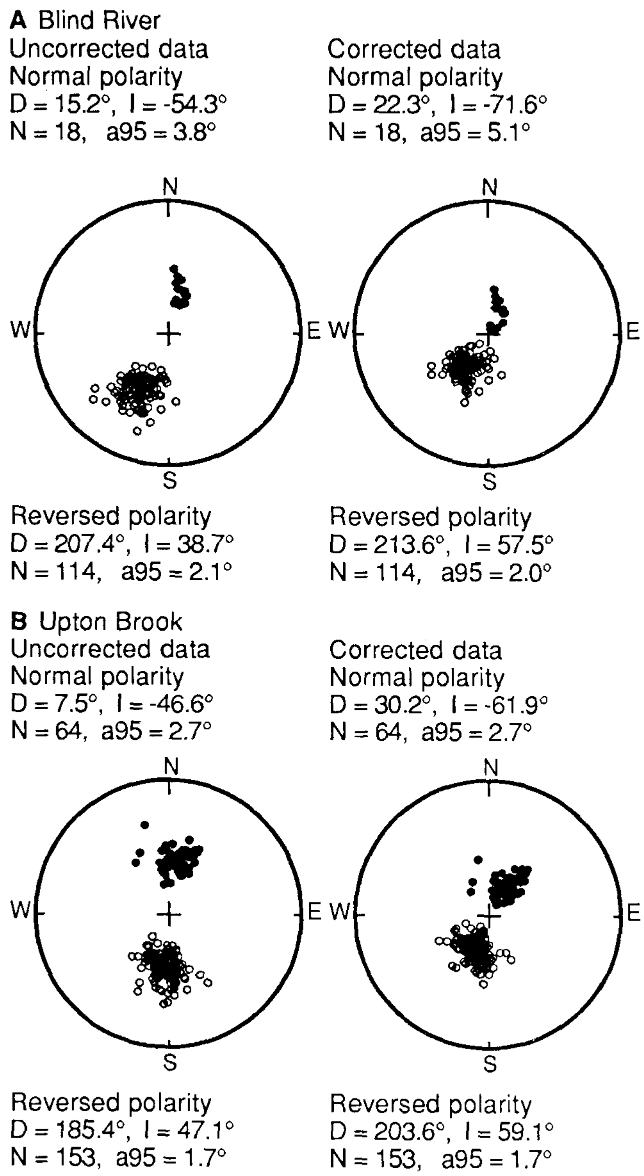

Fig. 7 Equal angle stereographic projections of uncorrected and bedding corrected primary remanence directions for samples from magnetostratigraphic localities: A, Blind River; B, Upton Brook. Open and solid circles denote lower and upper hemisphere projections, respectively.

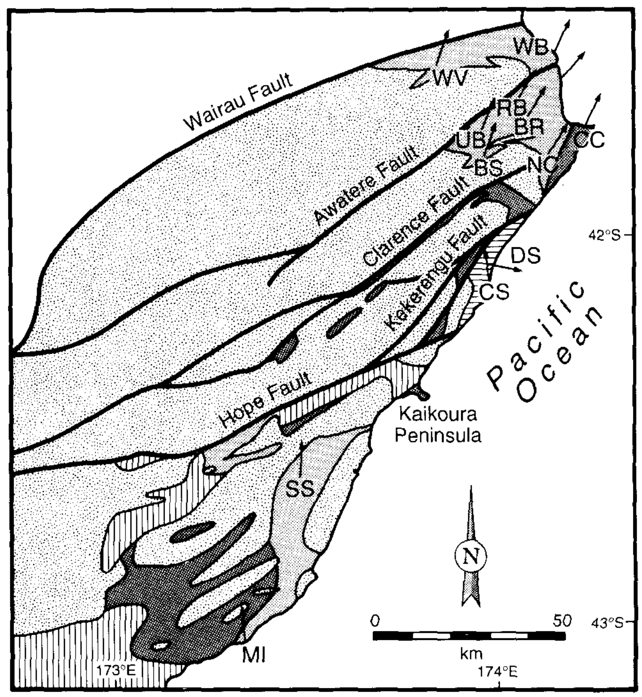

Fig. 8 Map of Marlborough region showing major faults, sampling localities, and amounts of rotation relative to the Pacific plate (i.e. relative to true north). WV is Waihopai valley, WB is White Bluffs, SV is Sea View, RB is Richmond Brook, UB is Upton Brook, BR is Blind River, CC is Cape Campbell, BS is Boundary Stream, NC is Needles Creek, DS is Deadman Stream, CS is Camp Stream, SS is Swamp Stream, and MI is Motunau Island. Vertical lines represent Quaternary alluvium; light shading represents late Miocene and Pliocene siliciclastic sediments; horizontal lines represent early Miocene siliciclastic sediments; dark shading represents undifferentiated Late Cretaceous – Oligocene sediments; stippled pattern represents basement outcrop of the Torlesse Supergroup southeast of the Wairau Fault; simplified after Lensen (1962) and Gregg (1964).

therefore the antipodes of normal polarity data have been averaged with reversed polarity data for ease of calculation and presentation (Tables 2 and 3). Data from Blind River and Upton Brook cover an interval from 7.5 to 4.8 Ma and were partitioned stratigraphically under criteria similar to those for other tectonic localities in this study. That is, that sufficient data are grouped in order to define a mean paleomagnetic direction from a stratigraphic interval large enough to average the effects of secular variation. A minimum of 20 samples from at least 4 horizons covering a stratigraphic range of at least 20 m was used to subdivide the 2 magnetostratigraphic localities.

Partitioning of the Blind River data did not reveal any significant variations in time (Table 2). Averaging data from this study with those of Turner et al. (1989) reduces the mean declination slightly ($D = 212.6°$, $I = 59.5°$, $\alpha_{95} = 2.0°$, $\kappa = 38$, $N = 132$; Fig. 7A, Table 2). The amount of tectonic rotation at Blind River recognised here is 33 ± 3°. These data suggest that all of the observed tectonic rotation has occurred since the youngest sediments were deposited (i.e. since the beginning of Opoitian time, 4.8 Ma).

6. Upton Brook A 1400 m stratigraphic interval was sampled at Upton Brook. The data were initially partitioned into eight groups in order to meet the minimum requirements adopted for averaging secular variation (Table 3A). Almost all inclinations in Table 3 are consistent with the expected axial geocentric dipole inclination of 60.7°, within 95% confidence limits. It is therefore likely that secular variation has been averaged and that the divergence of declinations from the axial dipole value is due to clockwise tectonic rotation. Data are well grouped with $\alpha_{95} < 5°$ in all cases, and estimates of Fisher's (1953) precision parameter, κ, are all sufficiently high to place confidence in the reliability of the data.

The declinations from groups 1–5 in Table 3A lie consistently near 200°, except for group 3 which has a significantly high declination of 210°. Groups 6–8 also have significantly higher declinations than the other groups. These variations may be real or may be artefacts of the way the data were partitioned. A significant feature of this partitioning is that group 3 contains both normal and reversed polarity data, while groups 1, 2, 4, and 5 contain data that are either all of reversed polarity or all of normal polarity. Analysis of the mean directions of normal and reversed polarity samples indicates that a small but significant difference in mean declination exists, while inclinations are indistinguishable from those of an axial dipole field. The mean declination from 64 normal polarity samples shows a 30.2° clockwise offset from the axial dipole declination (α_{95} = 2.7°) and a 23.3° offset (α_{95} = 1.7°) for the 153 reversed polarity samples (Fig. 7B). The 7° difference is statistically significant, but could itself be subject to bias, because approximately one-third of the normal polarity data come from the lower part of the section where declinations appear to be significantly higher.

A second grouping of horizons was made over wider stratigraphic intervals in order to examine the effects of the differences between normal and reversed polarity data (Table 3B). This grouping shows the same trend as that in Table 3A. The discrepancy between normal and reversed polarity data appears again but is not significant at a 95% confidence level. Marginally significant polar offsets have been observed in data from the last 6 Ma by Livermore et al. (1983) and Schneider & Kent (1986). Any evidence for persistent nondipole field behaviour from Upton Brook data is likewise only marginally significant, at best.

Group d from Table 3B has a mean declination that is significantly higher than those of groups a, b, and c, while the mean of group e is even higher. This pattern indicates that groups a–c have undergone c. 20° of tectonic rotation, while groups d and e have undergone greater rotations. Group e consists of a small number of samples of mixed polarity, and it is possible that secular variation has not been sufficiently accounted for within this group. It is not possible to resolve this uncertainty, thus a third grouping (Table 3C) is adopted to preserve the generalities observed in Table 3A and B. This grouping indicates that the sediments deposited after c. 6.3 Ma have been rotated uniformly by c. 21°, with no rotation observed between 6.3 Ma and the top of the interval sampled (c. 4.8 Ma). Sediments in group B are estimated to have been deposited in the upper middle Tongaporutuan, between 7.5 and 6.7 Ma. The average declination of samples from this interval indicates c. 32° of tectonic rotation.

It is therefore evident that a period of rapid tectonic rotation of at least 11° in a period of c. 1 m.y. occurred in the middle Tongaporutuan, but ceased by the late Tongaporutuan (Table 3). This episode of rotation correlates well with a period of middle Tongaporutuan thrust faulting recorded

Table 2 Stratigraphic partitioning of paleomagnetic data from Blind River.

Partition	Stratigraphic range (m)	*D* (°)	*I* (°)	α_{95} (°)	*N*	κ	Thickness (m)
Group 1	1025–1050	212.0	57.7	4.9	31	29.2	25
Group 2	917–1024	214.6	59.4	3.7	32	48.4	107
Group 3	295–850	212.0	59.1	3.0	36	65.6	555
Group 4	60–276	211.8	61.6	5.0	33	25.6	216
Turner et al.*	920–1050	214.0	58.4	3.2	57	35.6	133
All data†	60–1050	212.6	59.5	2.0	132	37.5	990

*Data set of Turner et al. (1989) with 3 points removed.
†Includes data from Turner et al. (1989) and this study.

Table 3 Stratigraphic partitioning of paleomagnetic data from Upton Brook.

Partition	Stratigraphic range (m)	*D* (°)	*I* (°)	α_{95} (°)	*N*	κ	Thickness (m)	Approximate age (Ma)
A								
Group 1	1408–1658	198.1	56.1	3.7	27	56.5	250	4.8
Group 2*	1153–1204	201.7	63.9	4.0	29	45.7	51	5.8
Group 3*	1073–1151	210.5	61.2	4.3	22	55.5	78	5.9
Group 4	921–1009	198.8	58.4	4.7	25	39.3	88	6.0
Group 5	875–912	200.4	56.7	3.0	30	76.0	37	6.1
Group 6	823–870	210.3	63.5	3.3	31	60.6	47	6.2
Group 7	772–811	209.5	60.7	4.5	31	34.2	39	6.3
Group 8*	256–732	218.6	57.5	4.7	22	44.1	476	7.0
All groups	256–1658	205.4	60.0	1.5	217	43.0	1402	4.8–7.5
B								
(a) Reversed	1408–1658	198.1	56.1	3.7	27	56.5	250	4.8
(b) Normal*	1146–1204	205.6	63.1	3.0	46	49.3	58	5.8
(c) Reversed	875–1140	200.0	57.6	2.6	59	52.8	265	6.0
(d) Reversed	772–870	209.9	62.1	2.8	62	43.8	98	6.3
(e) Mixed*	256–732	218.6	57.5	4.7	22	44.1	476	7.0
C								
Group A*	875–1658	201.3	59.0	1.8	132	48.2	783	6
Group B*	256–870	212.4	61.0	2.4	84	42.2	514	7

*All normal polarity directions have been given opposite polarity (see text).

nearby in the Medway valley by Melhuish (1988). No further tectonic rotation is evident until some point after 4.8 Ma when the area was rotated a further 21°.

These data, and those from Blind River, suggest that the most recent episode of rotational deformation postdates the early Pliocene. A similar amount of rotation is recorded from Opoitian or Waipipian strata at White Bluffs, suggesting that regional rotation may not have commenced until the late Pliocene.

7. Needles Creek Needles Creek exposes strata that have been folded by the Ward Syncline, southeast of the termination of the Clarence Fault (Fig. 8). A thin stratigraphic interval (c. 14 m) was sampled from a bluff cut by a meander in the creek c. 700 m from the end of Needles Rd, near Ward (Fig. 3A, B; NZMS 260 P29,Q29/019324). The unit sampled is a massive mudstone of the Upton Formation and is probably Kapitean (6.0–4.8 Ma) in age, although no age-diagnostic fauna were retrieved. Thirty cores were sampled from seven horizons.

Magnetic behaviour on demagnetisation was variable, with only 25% of samples possessing primary components that were directed towards the origin of vector component plots (Fig. 4). Another 15% of samples displayed erratic behaviour on demagnetisation, while 60% of samples possessed stable intermediate components that were not directed towards the origin of vector component plots. Analysis of the directions of the two groups displaying magnetic stability was carried out in order to test the validity of the interpretational method used. Within the limits of error involved, the mean directions of the two groups were indistinguishable. Both types of samples are therefore interpreted to be reliably recording paleomagnetic field directions. Data are well clustered ($D = 215.4°$, $I = 59.8°$, $\alpha_{95} = 3.5°$, $N = 31$) and indicate a declination anomaly of $35 \pm 6°$.

8. Boundary Stream A thick and continuous sequence of sandy siltstones that unconformably overlies Torlesse greywacke crops out in Boundary Stream, a tributary of the Medway River. Paleomagnetic samples were collected from a stratigraphic interval of 88 m, exposed c. 800 m upstream of Medway Rd at NZMS 260 P29,Q29/818322 (Fig. 3A, B). Sediment samples from this locality yielded no microfossils; however, stratigraphic correlation indicates a mid-Tongaporutuan (8 ± 1 Ma) age (Roberts & Wilson in press).

Only a small number of samples responded favourably to thermal demagnetisation because of a low signal/noise ratio. Paleodirections were obtained from 14 samples. A declination anomaly is recorded at this locality, but it is not well constrained ($17 \pm 13°$) because of poor data quality.

Clarence district

9. Camp Stream Camp Stream flows into the Pacific Ocean c. 5 km north of the Clarence River mouth (Fig. 3C) in an area referred to here as the Clarence coastal area. The Clarence coastal area has been deformed by numerous generations of faults and folds (Lamb & Bibby 1989). Pliocene mudstones crop out underneath thrust-emplaced, early Miocene Great Marlborough Conglomerate, c. 600 m west of State Highway 1. Eight horizons were drilled from a 45 m interval of mudstone that crops out on the eastern limb of a southward-plunging anticline (Fig. 3A, C; NZMS 1 S42,43/183245). Bedding orientations were measured across the structure in order to determine its axial plunge. Corrections for fold axial plunge were applied to paleomagnetic data, followed by a correction for the remaining stratal tilt.

The unit is a fine-grained mudstone that coarsens to a sandy mud with grit bands in places. Fine-grained mudstone is predominant in the interval sampled. *Globorotalia inflata* and *Globorotalia puncticulata* restrict the age of the mudstone to late Opoitian or Waipipian (Hornibrook et al. 1989). The most likely age is thus Waipipian (3.6–3.1 Ma).

NRM intensities range from 0.1 to 16×10^{-3} A/m. Samples with NRM intensities $<1 \times 10^{-3}$ A/m were usually less stably magnetised than those with higher intensities, although primary directions were still recognisable. Samples with higher NRM intensities were stably magnetised, with virtually no change in direction of the remanence vector on thermal demagnetisation (Fig. 4).

Primary remanence directions from Camp Stream are closely grouped ($D = 240°$, $I = 43°$, $\alpha_{95} = 2.8°$, $N = 52$). After correction for a southward fold axial plunge of 20°, and subsequently for an eastward dip of 52°, the mean remanence direction is: $D = 175°$, $I = 59°$, $\alpha_{95} = 2.8°$. Confidence can be placed in the corrected direction obtained because the uncorrected mean vector has a low inclination that becomes as predicted for an axial dipole field when corrected for bedding. The tilt correction has rotated the mean declination 65° to a position near the axial dipole direction (Fig. 4). This illustrates the problem of structural tilt corrections in steeply dipping beds. In this case, however, good structural control exists, and confidence can be placed in the corrected direction. No significant tectonic rotation can therefore be inferred at Camp Stream. This result is in marked contrast to the 99° clockwise rotation inferred from paleomagnetic data from early Miocene strata at Deadman Stream (Mumme & Walcott 1985), less than 10 km northeast of Camp Stream (Fig. 8). The contrast between these results is discussed below.

North Canterbury

10. Swamp Stream Swamp Stream is located well south of the main area studied here (Fig. 3A, D). The purpose of sampling at this locality was to delineate any boundary between rotating and nonrotating domains north of Motunau Island, North Canterbury, where Walcott et al. (1981) recorded no rotation (Fig. 8). Swamp Stream was sampled at a locality c. 7 km northwest of Cheviot, immediately downstream of a large culvert on Munro Rd (Fig. 3A, D; NZMS 1 S62/526432).

The unit sampled at Swamp Stream is a micaceous muddy siltstone, mapped by Gregg (1964) as the Greta Siltstone. *Globorotalia crassaformis, Cibicides deliquatus,* and *Notorotalia hurupiensis* constrain the age to Opoitian (Hornibrook et al. 1989), consistent with determinations by Gregg (1964) and Browne & Field (1985). Paleomagnetic samples were collected from six horizons over a 30 m stratigraphic interval.

NRM intensities were uniformly low, ranging from 0.7 to 4.5×10^{-4} A/m. On demagnetisation, intensities increased as a normal overprint was removed, and intensities remained sufficiently high to enable the isolation of primary remanence directions from 29 samples. These directions were well grouped with $D = 183.7°$, $I = 61.8°$, and $\alpha_{95} = 4.6°$. Within the limits of accuracy involved, the direction corresponds to the axial geocentric dipole direction expected for the latitude of Swamp Stream, thus no tectonic rotation has occurred there since Opoitian (4.8–3.6 Ma) time.

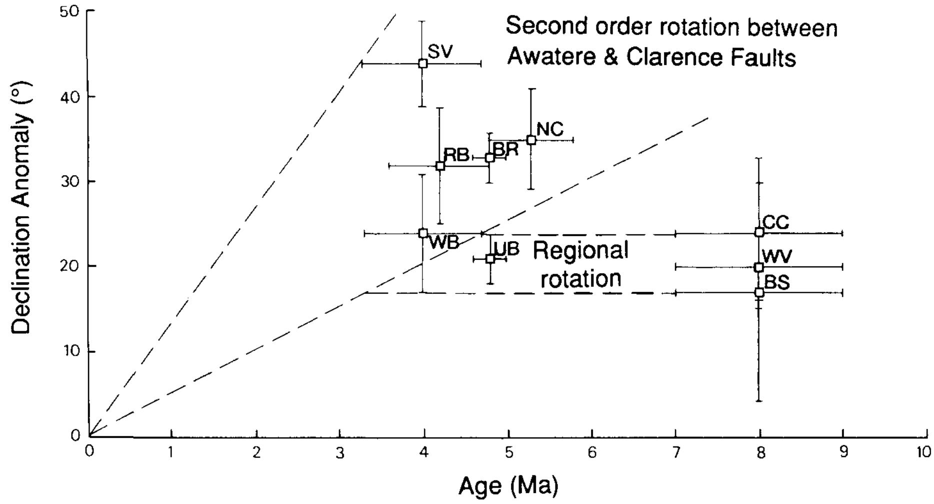

Fig. 9 Rotational history of the northern Marlborough paleomagnetic domain between the Wairau and Kekerengu Faults. Tongaporutuan (c. 8 Ma) data indicate the same amount of rotation as younger data, implying that regional rotation occurred since the Pliocene. Additional rotation is evident in the area between the Awatere and Clarence Faults.

DISCUSSION

Widespread remagnetisation and low intensities of magnetisation in the Cenozoic sediments of the Marlborough region make it difficult to obtain high-quality paleomagnetic data. The results presented above are from rocks that are stably magnetised, over stratigraphic intervals sufficient to average the effects of secular variation, and are from regional-scale geological structures. It is therefore likely that the declination anomalies recorded (Table 1) indicate regionally significant tectonic rotations about vertical axes.

Despite narrow sampling intervals in time and space, distinct features of the rotational history of the northern Marlborough domain are evident. Clockwise rotations between the Wairau and Kekerengu Faults (Fig. 8) are consistently about 20° (Waihopai valley, White Bluffs, Boundary Stream, Upton Brook, and Cape Campbell), with an additional rotation above the regional value evident at many localities east of the northern end of the Awatere Fault (Sea View, Richmond Brook, Blind River, and Needles Creek; Fig. 8). Data from Blind River and Upton Brook indicate that the regional rotation occurred after c. 4.8 Ma. Furthermore, the regional rotation is observed in even younger rocks at White Bluffs (c. 4 Ma), implying that the regional rotation occurred after this time (Fig. 9). Apart from local rotation recorded at Upton Brook, associated with an episode of synsedimentary thrust faulting in the Medway valley (Melhuish 1988), no rotation is evident between 8 and 4 Ma (Fig. 9).

Most late Cenozoic rocks between the Marlborough faults are tilted, generally <25°. Lack of macroscopic textural evidence of shearing on an outcrop scale suggests that penetrative shear is unlikely to be responsible for rotation in the Marlborough region. Similarity in amounts of tectonic rotation (c. 20°) between the Wairau and Kekerengu Faults suggests that the area is rotating as a large, rigid block. The regional rotation can be explained by progressive change in orientation of the underlying subducted plate, as inferred from plate reconstructions (Walcott 1984a, 1989). An additional rotation is apparent in the higher amounts of clockwise rotation in the lower Awatere Valley and is probably due to a second-order rotational mechanism. Further details of the kinematics of these rotations are being prepared for publication elsewhere (Roberts in prep. "Kinematics and timing of large-scale crustal rotations in the Australia–Pacific plate boundary zone, New Zealand").

Paleomagnetic data from the structurally complex Clarence coastal area southeast of the Kekerengu Fault are less coherent than those from the region between the Wairau and Kekerengu Faults. Data from Camp Stream indicate essentially no rotation since Waipipian time (c. 3.5 Ma), whereas those from Deadman Stream (Mumme & Walcott 1985) indicate a clockwise tectonic rotation of 99° (Table 1) since Altonian time (c. 18 Ma). This area is dominated by the poorly bedded Great Marlborough Conglomerate, which makes identification of structures difficult. Lamb & Bibby (1989) nevertheless identified nine, small (<5 km across), fault-bounded structural domains in the area. Lamb (1988) and Lamb & Bibby (1989) suggested that these small crustal blocks may be floating on a zone of distributed shear in the underlying crust at a depth roughly equal to the block width (i.e. <5 km). If the Clarence coastal area is undergoing intensive dextral shear, then clockwise rotations of similar amount would be expected, as is the case in other dextral shear zones (e.g., Las Vegas shear zone; Nelson & Jones 1987). Variation in tectonic rotation data in the Clarence coastal area suggests that dextral shear is less pervasive than suggested by Lamb & Bibby (1989) and that this area has a different rotational history from the northern Marlborough domain. Results from this study indicate that no rotation has occurred in the Camp Stream area since the Pliocene — the interval when the northern Marlborough domain was rotating at rates of 7–8°/Ma. It is therefore likely that the anomalously large rotation recorded at Deadman Stream resulted from localised early Miocene deformation.

Paleomagnetic data provide important constraints that should be considered in future reconstructions of the Hikurangi margin. The above evidence suggests that tectonic rotation has not occurred continuously since the early Miocene in the southern part of the Hikurangi margin as it has in the northern part (Wright & Walcott 1986). Thus, it is likely that differential rotation has occurred between the northern Marlborough domain and eastern North Island (Fig. 1), and it is unlikely that the northern Marlborough domain has been involved in the large-scale rotations that have affected the eastern North Island. Cook Strait is considered to represent a structural discontinuity (Carter et al. 1988) between the Wairarapa domain and the northern Marlborough domain (Fig. 1). Walcott (1984a) suggested that Cook Strait marks the position of the former northern end of the Alpine Fault which has been rotated and disrupted. Cook Strait is probably therefore the hinge zone about which the eastern North Island has rotated with respect to the Pacific plate and the northern Marlborough domain. Rapid tectonic rotation of 7–8°/Ma started in the northern Marlborough domain after the early Pliocene (c. 4 Ma). An acceleration in the rate of clockwise rotation to 7–8°/Ma is also evident from Pliocene time onwards in the northern part of the Hikurangi margin (Wright & Walcott 1986). Numerous other deformation events appear to have begun in the New Zealand region during the late Pliocene, including: the onset of NNE-trending folding in Marlborough (Roberts 1990); the onset of uplift on the Waimea Fault and deposition of the extensive late Pliocene Moutere Gravels in the southeastern Nelson area (Johnston 1990); the onset of Pliocene–Pleistocene folding and thrust faulting associated with uplift of the Ruahine Ranges in the eastern North Island (Melhuish 1990); and back-arc spreading in the Central Volcanic Region (Stern 1987). Similarity in the timing of the onset of these deformation events indicates that these phenomena may be linked to a late Pliocene (3.4–3.9 Ma) change in the absolute motion of the Pacific plate (Harbert & Cox 1989) and its resulting change in motion relative to the Australian plate.

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