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Tectonic rotations about vertical axes during the last 4 Ma in part of the New Zealand plate-boundary zone

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Abstract—The declinations of the primary magnetization of sedimentary rocks in the northern part of the New Zealand plate-boundary zone, after thermal or alternating field cleaning, have been used to determine tectonic rotations about vertical axes of rigid crustal blocks. The pattern of rotations during the last 4 Ma, combined with structural style and continuity, defines seven structural domains each *ca* 100 × 100–200 km across, which contain crustal blocks up to 100 km across and 20 km thick. Large crustal blocks (tens of km across) in two of these domains have rotated clockwise more than 20° relative to one of the margins of the plate-boundary zone in the last 4 Ma. Their behaviour appears to be controlled by the nature of the plate boundaries, such as the presence of an underlying subducted slab and the strength of the crust at the back of the overlying crustal wedge. Small crustal blocks (<10 km across) may have rotated clockwise through angles greater than 20° during the last 4 Ma, floating on an underlying zone of more distributed deformation. The tectonic rotations of the large crustal blocks, and the nature of the deformation at their boundaries, combined with an interpolation of the relative plate positions, can be used to reconstruct the plate-boundary zone at *ca* 4 Ma.

INTRODUCTION

PALAEOMAGNETISM is being increasingly used to analyse the behaviour of continental crust in wide zones of deformation. The declination of the primary magnetic field within sedimentary rocks, after thermal or alternating field cleaning, can sometimes be used to determine a rotation about a vertical axis. This rotation, which is referred to as a tectonic rotation, is that of a crustal block in which the internal deformation is negligible, with dimensions which are often many times greater than the individual palaeomagnetic sample.

It may not be easy to relate tectonic rotations to the deformation within a deforming zone, determined from a knowledge of the relative plate motions or from seismicity (Jackson & McKenzie 1988), repeated triangulation studies and structural mapping. Thus, rigid-body rotations about vertical axes were often unsuspected prior to palaeomagnetic analysis. It is likely that such rotations are a general feature of deformation in continental crust. However, the fundamental controls on the behaviour of crustal blocks are not clear. McKenzie & Jackson (1983) suggested that such rotations are a consequence of the vertical vorticity of an underlying and continuously deforming lithosphere, and the rotation rates will equal half this vorticity. Block models based on specific patterns of faulting in the brittle crust often predict a more complex pattern of rotations (Garfunkel 1974, Luyendyk *et al.* 1980, Ron *et al.* 1984, Garfunkel & Ron 1985). However, such patterns of faulting may not be an accurate description of the actual deformation in a plate-boundary zone.

If it is assumed that rigid-body rotations about vertical axes are controlled by the deformation in the underlying and continuously deforming lithosphere, as suggested by McKenzie & Jackson (1983), then the behaviour of isolated rigid floats on the surface of a slowly deforming continuous medium may provide insight into the expected pattern of rotations (floating block model, Lamb 1987). Of course, this will only be a useful model if the interference between neighbouring blocks in a real zone of deformation is a secondary effect. This may be the case if the horizontal dimensions of crustal blocks are small compared with the width of the deforming zone and are at least as great as their thickness. The floating block model suggests a surprisingly complex pattern of rigid-body rotations for floats with different aspect ratios and initial orientations (Appendix I, Lamb 1987). The rotation rate predicted by McKenzie & Jackson (1983) is for the special case when crustal blocks are equidimensional in plan view. One should be prepared for rigid-body rotations about vertical axes in any zone of deformation, and therefore vorticity in the underlying lithosphere may not be a requirement for rigid-body rotation, except when crustal blocks are equidimensional.

In many convergent plate-boundary zones, the deforming continental crust rests directly on the subducted plate, forming a crustal wedge generally less than 30 km thick. In such cases, the crust cannot be said to be floating on a continuously deforming medium, and hence the floating block model may not be applicable to large (>10 km across) crustal blocks. Here, the shear traction on the base and back of the crustal wedge, as well as the geometry of the subducted slab, may have an important effect on the behaviour of crustal blocks. Large elongate blocks may be confined to certain orientations if they and the plate boundaries are strong enough to resist internal deformation. However, small crustal blocks, in intense zones of deformation between the major crustal blocks, may be floating on an underlying distributed zone of deformation at a depth of a few km, controlled by the relative motion of the adjacent large crustal blocks.

An analysis of the dimensions of rigid crustal blocks and their positions within the plate-boundary zone, as well as the kinematics of their boundaries, is needed before the tectonic rotations can be fully understood. Conversely, the tectonic rotations place constraints on the behaviour of the crust. In this paper an attempt is made to reconcile the palaeomagnetic rotation data with deformation in the northern part of the New Zealand plate-boundary zone during the last 4 Ma. Here, the long-term (>3 Ma) relative plate motions, as well as the short-term (<100 Ka) deformation styles and rates, have been extensively studied. The consequences and causes of these rotations are of general significance for the behaviour of continental crust in wide zones of deformation.

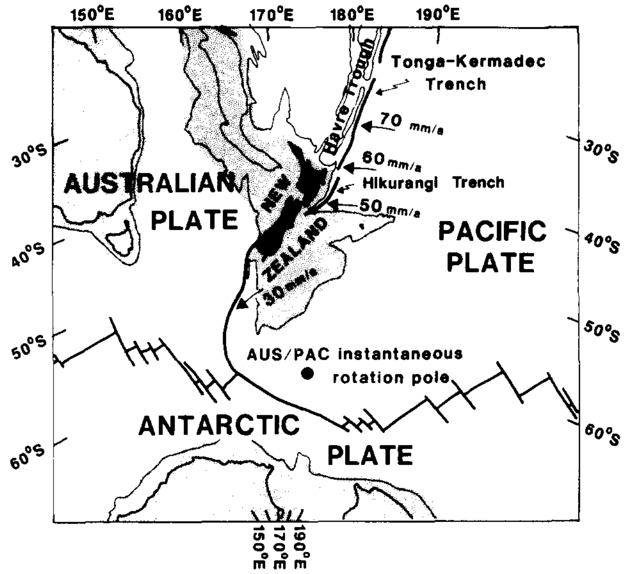

Fig. 1. Map showing the boundaries between the Australian, Pacific and Antarctic plates in the New Zealand region. Areas of continental crust are stippled. The Australian–Pacific instantaneous pole of relative plate motion (Chase 1978), and some velocities for the Pacific plate relative to the Australian plate, are also shown.

NEW ZEALAND PLATE-BOUNDARY ZONE

The northern part of the New Zealand plate-boundary zone is dominated by the subduction of the Pacific plate beneath the Australian plate (Fig. 1). The relative instantaneous motion of the plates can be described by a rotation about a pole located to the south of New Zealand (Fig. 1). In this study the instantaneous pole of Chase (1978) is adopted.

In the north, the Australian plate is composed of oceanic lithosphere, and Plio-Pleistocene back-arc spreading close to the Tonga–Kermadec subduction zone has resulted in the opening of the Havre Trough. In New Zealand, further south, the Australian plate margin is a broad zone (*ca* 200 km wide) of deforming continental crust overlying the Hikurangi subduction zone. Even further south the Pacific plate is continental lithosphere. Here the plate-boundary is a zone of transpression (*ca* 100 km wide) within continental crust, bounded on the Australian side by the Alpine Fault. The major structural features of the northern part of the New Zealand plate-boundary zone are shown in Fig. 2.

Palaeomagnetic rotation data

Numerous measurements of the declination of magnetization in sedimentary rocks of various ages from the northern part of the New Zealand plate-boundary zone

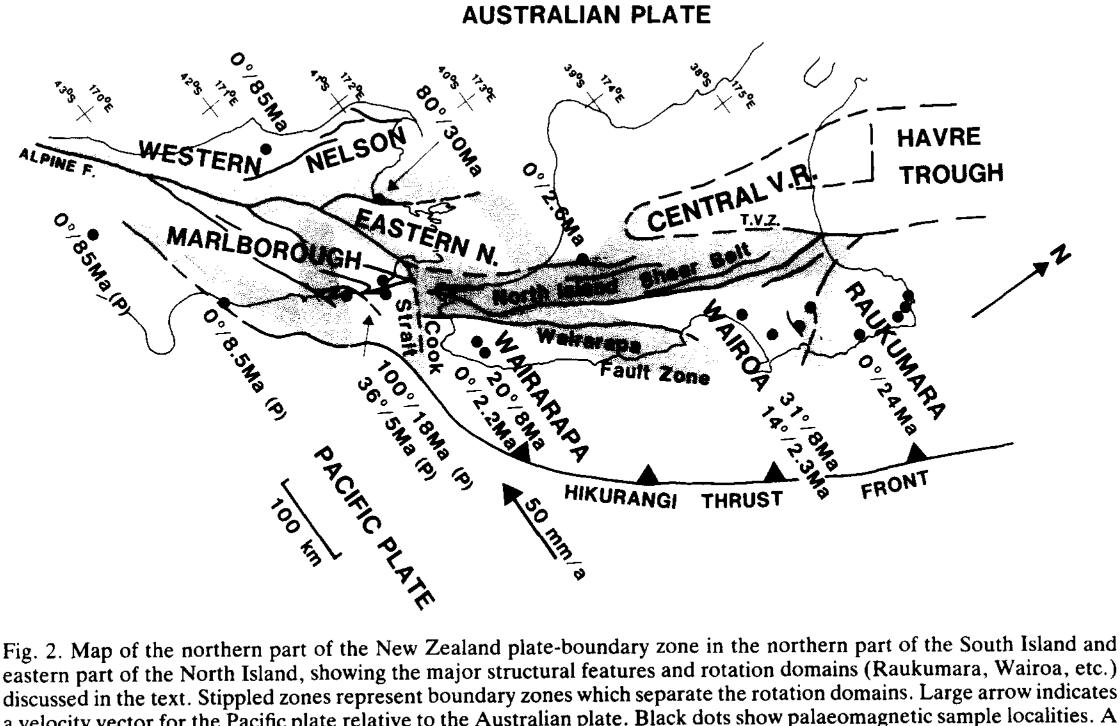

Fig. 2. Map of the northern part of the New Zealand plate-boundary zone in the northern part of the South Island and eastern part of the North Island, showing the major structural features and rotation domains (Raukumara, Wairoa, etc.) discussed in the text. Stippled zones represent boundary zones which separate the rotation domains. Large arrow indicates a velocity vector for the Pacific plate relative to the Australian plate. Black dots show palaeomagnetic sample localities. A summary of observed clockwise rotations about vertical axes is given for crustal blocks in the various domains (rotations in the Marlborough domains are relative to the Pacific plate, indicated by P in brackets; rotations in all other domains are relative to the Australian plate).

Table 1. Palaeomagnetic data

Locality (domain)*	Reference†	Age (Ma)	Sites (Specimen)	D° (1)	I° (2)	κ (3)	α_{95}° (4)	δ_{PAC}° (5)	δ_{AUS}° (6)
1 (R)	MLW	20 ± 2	1 (54)	203	32		5.9	23 ± 6	+1 ± 6
2 (R)	MLW	20 ± 2	1 (19)	203	25		8.9	23 ± 8	+1 ± 5
3 (R)	MLW	18 ± 2	1 (27)	201	36		5.0	21 ± 5	+1 ± 5
4 (R)	MLW	18 ± 2	1 (5)	200	40		13.6	20 ± 14	0 ± 14
5 (R)	MLW	18 ± 2	1 (35)	189	44	33.7	4.0	9 ± 6	−11 ± 6
6 (W)	WW	2.3 ± 0.1	1 (31)	197	57	65.1	3.1	17 ± 5	14 ± 5
7 (W)	WW	6 ± 0.05	39 (100)	206	54	8.4	8.4	26 ± 11	20 ± 11
8 (W)	WW	8 ± 0.05	19 (70)	041	61	110.1	3.2	41 ± 5	31 ± 5
9 (W)	WW	10 ± 0.05	30 (102)	047	−57	76.9	3.0	47 ± 4	35 ± 5
10 (W)	WM	11 ± 0.05	24	045	−44	15.9	7.2	45 ± 8	32 ± 8
11 (W)	WM	12 ± 0.05	16	250	67	6.4	13.9	70 ± 30	56 ± 30
12 (W)	MW	24 ± 1.0	40	070	−50	6.4	8.8	70 ± 12	42 ± 12
13 (Aus)	S	2.6 ± 1.6	25	179	65		8	−1 ± 19	−4 ± 19
14 (Wai)	L	2.2 ± 0.2	2 (48)	176	52	28.5	3.8	−4 ± 6	−7 ± 6
15 (Wai)	WCM	8 ± 1.5	21	030	−63	82.3	3.4	30 ± 8	20 ± 8
16 (NM)	R	5 ± 0.5	58	216	60		6.0	36 ± 10	—
17 (NM)	WCM	8 ± 1.5	12	024	−61	56.2	5.4	24 ± 11	—
18 (NM)	MW	18 ± 1.0	46	279	59	10.5	6.4	99 ± 12	—
19 (EN)	MW	30 ± 5	39	280	76	12.8	6.3	100 ± 27	79 ± 27
20 (WN)	MW	40 ± 5	21	36	−64	108	2.9	36 ± 7	9 ± 7
21 (Pac)	WCM	8.5 ± 1.0	36	354	−58	6.7	9.0	−6 ± 17	—
22 (Pac)	O	84 ± 6	46 (78)	354	−75		3.8	−6 ± 17	—

* Domains: Aus—Australian plate; R—Raukumara; W—Wairoa; Wai—Wairarapa; NM—northern Marlborough; EN—eastern Nelson; WN—western Nelson; Pac—Pacific plate.

† References: MLW (Mumme *et al.* in preparation; WW (Wright & Walcott 1986); WM (Walcott & Mumme 1982); MW (Mumme & Walcott 1985); S (Seward *et al.* 1986); L (this study); WCM (Walcott *et al.* 1981); R (Roberts 1986); O (Oliver 1979).

Notes: (1) Declination (w.r.t. True North) of remanent magnetization after cleaning (thermal or alternating field) and tilt correction.
(2) Inclination of remanent magnetization as in (1).
(3) Fisher precision parameter.
(4) 95% cone of confidence about the mean direction.
(5) Rotation about vertical axis w.r.t. to Pacific plate
(6) Rotation about vertical axis w.r.t. to Australian plate
(5), (6): Error = $\sin^{-1}(\sin \alpha_{95}/\cos I)$

have now been published by a number of workers (Table 1, Figs. 2–9). Full details of the measurement techniques and results are given in the various publications listed in Table 1. The measurements are considered to be representative of the Earth's average magnetic field close to the time of the formation of the sedimentary rock samples if they fulfil the following criteria.

(1) Secular variation has been averaged out by sampling a sufficient stratigraphic thickness at any particular locality. In general, a stratigraphic thickness representative of at least 10 Ka of continuous sedimentation is required.

(2) Samples have been stepwise cleaned, either thermally or with an alternating field, and show a progressive stripping off of a secondary overprint, resulting in a convergence to a stable direction of magnetization with an intensity at least an order of magnitude greater than the detection limit of the magnetometer. Most measurements were made with a cryogenic magnetometer after thermal cleaning up to 500°C.

(3) At least some of the data have a reversed polarity, relative to the present day field, which is consistent with the magnetostratigraphy for these rocks.

(4) The inclination, after correcting for the tilt of the strata, is closer than before the tilt correction to that expected for the latitude of the sample at the time of its formation, and in general is within 10° of this inclination. In some cases, flatter inclinations for reversed samples are accepted (Raukumara domain) if the declinations are consistent with those for normal samples, which have the expected inclination for the sample latitude after the tilt correction. Most samples come from strata which dip less than 30° and can be shown to be part of gently plunging (<10°) fold structures. Only in a very few cases has it been possible to sample both limbs of a fold (Wairoa domain). Confidence is placed in groups of measurements which are well clustered on a stereographic plot ($\alpha_{95} < 10°$) with a large Fisher precision parameter (>10).

The departure of the mean locality declination from True North, after correcting for stratal tilt, is assumed to be the result of rigid-body rotation about a vertical axis since the formation of the sample. This is a unique rotation of the associated crustal block, as most samples form part of nearly horizontally plunging folds. A clockwise rotation is defined as positive and an anticlockwise rotation as negative. In addition, only rotations relative to the margins of the plate-boundary zone are considered, which can be calculated from the polar wander paths of the Australian and Pacific plates. The Australian plate in the New Zealand region has not rotated relative to True North more than 1.5°/Ma clockwise in the last 40 Ma, while the Pacific plate has undergone negligible rotation relative to True North (Wright & Walcott 1986).

Rotation domains

The palaeomagnetic rotation data, combined with structural style and continuity, are used to define domains which cover most of the on-shore part of the plate-boundary zone (Fig. 2). The domains are not necessarily single crustal blocks, but rather clusters of blocks which have similar rotation histories or rotation histories which can be conveniently grouped together. Large crustal blocks (tens of km across) in two of these domains show large clockwise rotations (>20°) relative to one of the plates in the last 4 Ma, while the other domains show either small or no rotations.

The boundaries to the various domains are marked by narrow zones of deformation, which in general have not been palaeomagnetically sampled.

WAIROA DOMAIN

The Wairoa domain is a broad regional syncline trending NNE for more than 100 km (Figs. 2 and 4). The finite

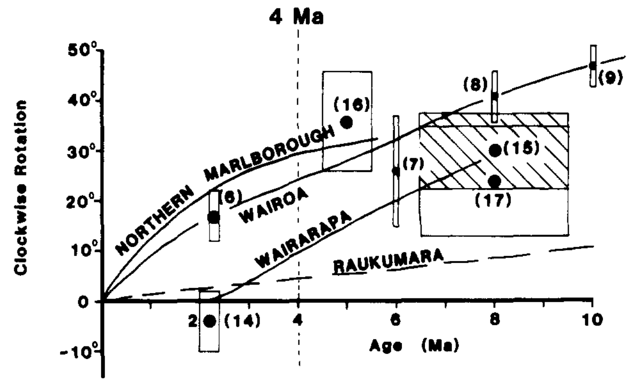

Fig. 3. Graph of rotation, relative to True North (equivalent to rotation relative to the Pacific plate), plotted against time for crustal blocks in the various domains. Curves suggest that all crustal blocks in any particular domain have had the same rotation history. Rotation of the Australian plate in the New Zealand region is approximately that of crustal blocks in the Raukumara domain.

deformation is small (dips generally less than 20°), and, except on its eastern and northern margins, it can be treated as an essentially rigid block with horizontal dimensions of *ca* 100 × 100 km and a vertical thickness of between 10 and 20 km. Extensive palaeomagnetic sampling of both limbs of the syncline (Table 1, localities 6–12, Figs. 3 and 4) (Walcott & Mumme 1982, Mumme & Walcott 1985, Wright & Walcott 1986) shows that a

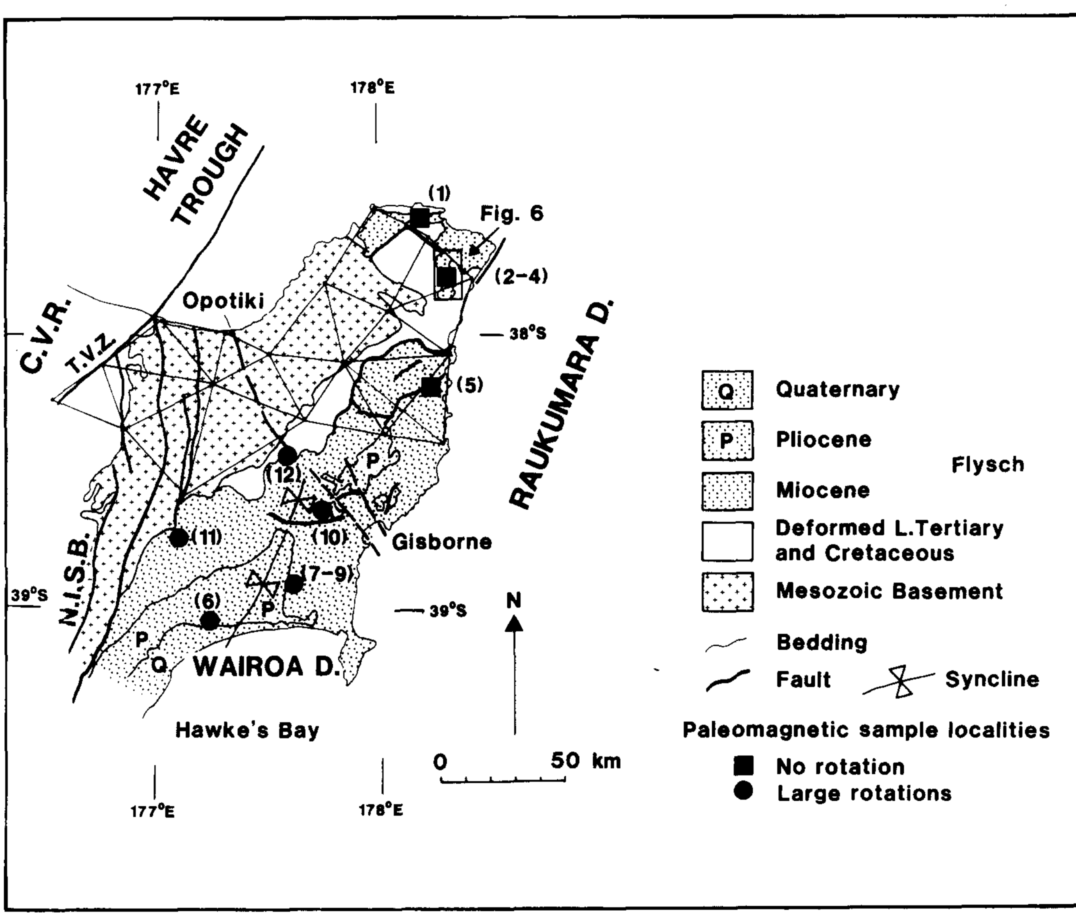

Fig. 4. Geological map of the Wairoa and Raukumara domains in the northeastern part of North Island, New Zealand (after New Zealand Geological Survey 1972, 1: 1,000,000 geological maps). Major Neogene and Quaternary structural features, the location of palaeomagnetic sample sites (Table 1) and repeated triangulation networks are also shown.

substantial clockwise rotation (*ca* 20°), relative to the Australian plate, has occurred in the last 4 Ma, with an increase in the rate of rotation towards the present (*ca* 14° in 2.3 Ma). Undisturbed sedimentation occurred in the Pliocene during rotation.

Instantaneous velocity field

The instantaneous velocity field for the northeast part of the North Island (Sissons 1979, Walcott, 1984a), derived from repeated triangulation measurements over the last 50 years, shows that the Wairoa domain, treated as rigid, is rotating clockwise relative to the Australian plate at *ca* 7°/Ma, accommodated by SE extension (*ca* 18 mm/a) at the northern end of the North Island relative to further south (Fig. 5).

Long-term kinematics

The zone of extension coincides with a large triangular region of Plio-Pleistocene volcanism, referred to as the Central Volcanic Region (CVR). The eastern margin of the CVR is a NE–NNE-trending area of active rhyolitic and andesitic volcanism, referred to as the Taupo Volcanic Zone (TVZ). The Central Volcanic Region passes off-shore into the NNE-trending Havre Trough (Figs. 1 and 2) (Lewis & Pantin 1984), which less than a 150 km north of New Zealand is a 80–100 km wide back-arc basin, floored by Plio-Pleistocene oceanic crust (Malahoff *et al.* 1982). The age and migration of andesitic volcanism in the CVR suggests that the CVR and Havre Trough opened in the last 4 Ma (Stern 1987). Back-arc extension increases from essentially zero at the southern end of the CVR to *ca* 90 km in a distance of 250–300 km along strike. Therefore, the eastern margin of the CVR, relative to the Australian plate, may have rotated *ca* 20° clockwise in the last 4 Ma, pivoted about the southern end of the CVR. Palaeomagnetic measurements (Table 1, locality 13, Figs. 5a and 8a) (Seward *et al.* 1986) show that there has been essentially no rotation relative to the Australian plate (−4° ± 19°) in the last *ca* 2.6 Ma in the regions immediately south of the zone of extension.

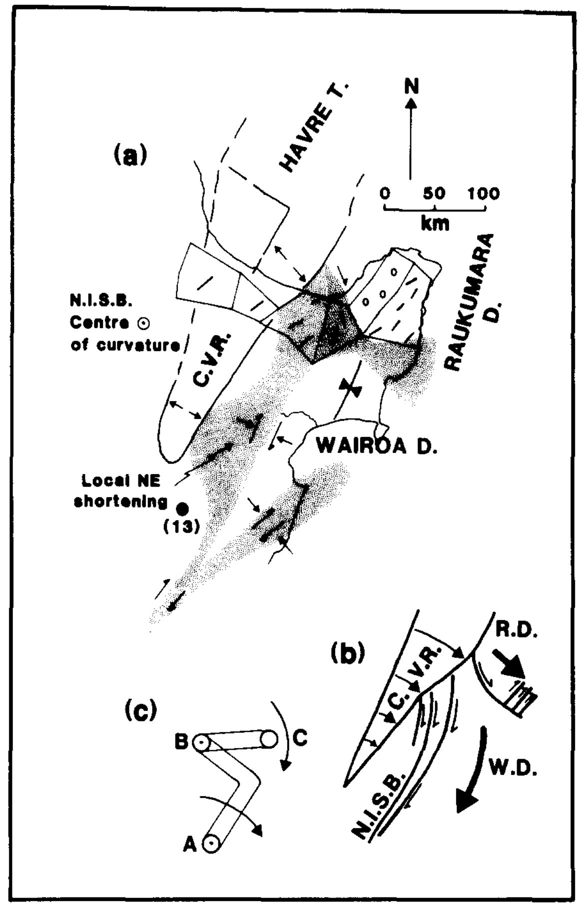

Fig. 5. (a) Map of the northeastern part of the North Island, showing the boundaries (stippled zones) to the Wairoa and Raukumara domains inferred from the geodetic deformation (Walcott 1984a, personal communication). Use Fig. 4 to locate geology relative to networks. The solid bars within the networks show the local trend of the instantaneous axis of compression, suggesting SE extension across the northern end of the Central Volcanic Region (maximum shear strain rate *ca* 2×10^{-7}/a), dextral shear with a small component of compression on the N-trending northern end of the North Island Shear Belt (NISB; maximum shear strain rate *ca* 2×10^{-7}/a), and SE extension in the eastern part of the Raukumara domain (maximum shear strain rate *ca* 4.5×10^{-7}/a). Zeros in the western part of the Raukumara domain indicate areas of negligible shear strain. Note zone of NE shortening near the southern end of the CVR. (b) Cartoon showing the principal kinematics of the boundaries to the Wairoa and Raukumara domains. See text. Large arrows show motion of domains relative to the Australian plate. (c) Simple mechanical model showing how the effects of rotation of the NISB (rotation about A) and slip on the curved end of the NISB (rotation about B) add to accommodate the rapid rotation in the Wairoa domain at C.

Short-term kinematics of major structures

The region between the CVR and the Wairoa domain is a zone of active dextral strike-slip faults at least 40 km wide, referred to as the North Island Shear Belt (NISB, Fig. 2). It extends 400 km up the entire length of the North Island and terminates abruptly at the edge of the CVR (Figs. 2 and 5b). The motion of the Wairoa domain relative to the Australian plate is related to the kinematics of the NISB. Thus, the extension in the CVR has been accommodated by some combination of slip on the NISB and rotation (bending) of the whole northern end of the NISB (Fig. 5b).

Repeated triangulation measurements across the northern end of the NISB (Sissons 1979, Walcott 1984a, personal communication) over the last 50 years, suggest a total dextral strike-slip rate of 10–15 mm/a with a small reverse component (*ca* 4 mm/a). Assuming that the reverse component is similar or increases further south, then because of the curvature of the northern end of the NISB (radius of curvature is *ca* 180 km) dextral slip on the NISB will result in a 3–5°/Ma clockwise rotation, relative to the western margin of the NISB, of the regions to the east of the NISB. If the total instantaneous rotation rate of the Wairoa domain is to be consistent with the palaeomagnetic data for the last 2 Ma (*ca* 7°/Ma relative to the Australian plate), then in addition the NISB itself must be rotating at 1–4°/Ma relative to the Australian plate. A simple mechanical model (Fig. 5c) illustrates the kinematics of bending and slip on the NISB. NE shortening near the southern end of the CVR

(Fig. 5a) (Spörli 1987), roughly at right angles to the trend of the NISB, suggests that deformation between the major faults in the NISB, such as that required by a tangential–longitudinal strain mechanism of folding, is accommodating the bending of the NISB. The increase in the radius of curvature of the NISB near Hawke's Bay would require a component of thrusting on the NISB if the Wairoa domain is to remain rigid. In this region a large component of shortening is associated with the Mohaka Fault in the NISB, which in places dips at 26°NW (Cutten personal communication).

RAUKUMARA DOMAIN

Palaeomagnetic declination measurements (Table 1, localities 1–5, Figs. 4 and 6) (Walcott & Mumme 1982, Mumme *et al.* in review) from Neogene sediments in the regions to the north of the Wairoa domain, referred to as the Raukumara domain (Figs. 2, 4 and 5), show negligible rotation (<10°) of crustal blocks relative to the Australian plate in the last 20 Ma.

Internal deformation

Detailed mapping in the northeastern part of the Raukumara domain shows that the Neogene deformation is complex, involving NE-, ESE- and NW-trending high and low angle normal faults, defining blocks less than 5 km across (Fig. 6). Pervasive normal faulting in Tertiary strata, with displacements of several km on individual faults, is also found further south in the Raukumara domain (Mazengarb 1984, Kenny personal communication). Repeated triangulation measurements over the last 50 years (Walcott 1984a, personal communication) suggest that the deformation is principally SE extension (maximum shear strain rate of 4×10^{-7}–5×10^{-7}/a), perpendicular to the general structural trend, and thus the vorticity of bulk deformation is likely to be small (Figs. 5a and 6b). In this case, if crustal blocks are small relative to the dimensions of the Raukumara domain, equidimensional and floating, then the lack of tectonic rotation in the Raukumara domain is consistent with the floating block model (McKenzie & Jackson 1983, Lamb 1987).

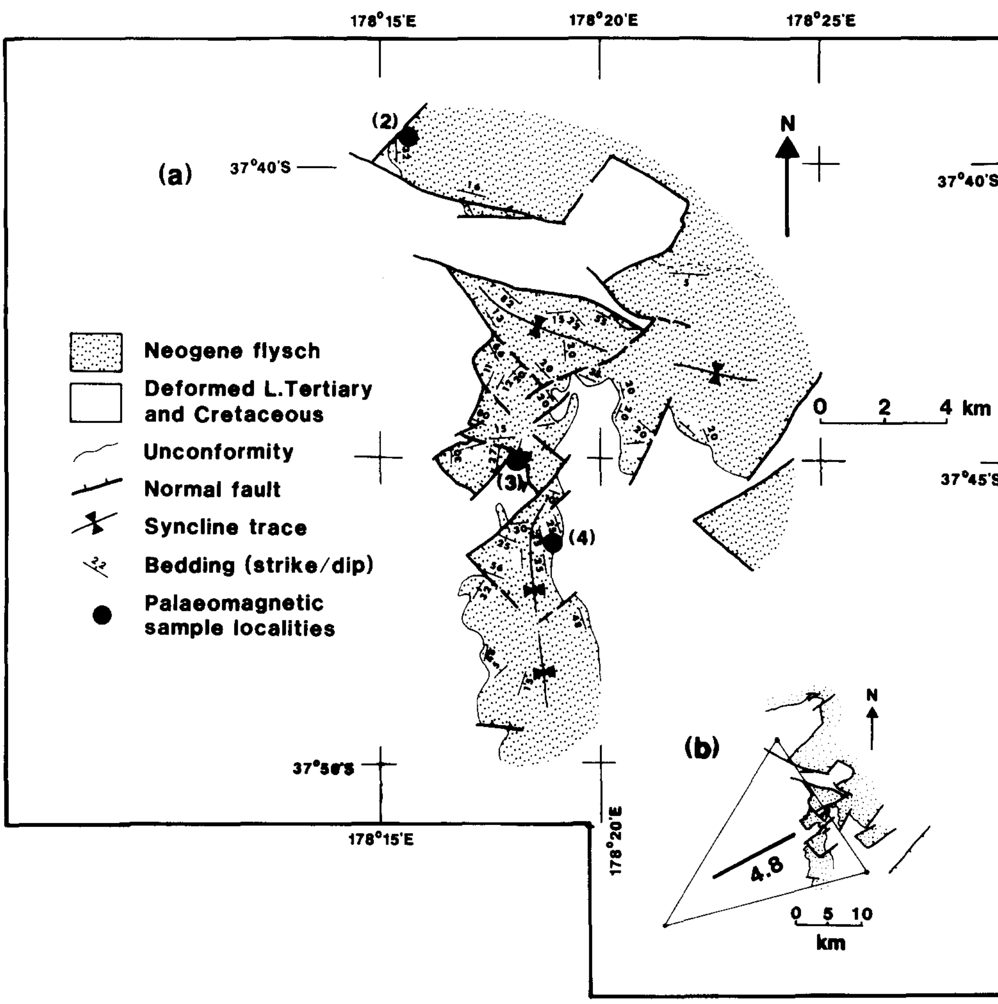

Fig. 6. (a) Geological map of Neogene mudstone and siltstone sequences juxtaposed with deformed Lower Tertiary and Cretaceous rocks in the northeastern part of the Raukumara domain. See Fig. 4 for location. Most dips in the Neogene are moderate, defining broad synclines. The locations of palaeomagnetic sample sites are also shown. (b) Map as in (a), but including surrounding regions. Solid bar within triangular network shows the trend of the compressive axis during the last 50 years determined from repeated triangulation in the triangular network (Walcott personal communication). Maximum shear strain rate is 4.8×10^{-7}/a.

The following evidence suggests that crustal blocks may not be floating. Repeated triangulation studies in the western part of the Raukumara domain, where the Mesozoic basement rocks outcrop, show no deformation (Fig. 5a, Walcott 1984a, personal communication), while uplift data (Yoshikawa *et al.* 1980) for the last 100 Ka show a smooth pattern of regional uplift and tilting. Thus, it appears that this area has remained internally rigid. The normal faulting seen in the Tertiary cover rocks probably terminates near the basement interface in a zone of décollement, and thus the deformation in the Neogene rocks may be of limited vertical extent (<10 km) and may be due to the gravitational instability of uplifted Neogene cover rocks which are resting on smectitic early Tertiary horizons. Walcott (1987) has suggested that regional uplift in this area may be a consequence of underplating at the base of the crust where it rests on the subducted Pacific plate. Thus, the lack of tectonic rotation may be because the basement to the cover sequences has not rotated, while the deformation in the cover is controlled by gravitational body forces in the cover rocks and not horizontal deformation in the basement. In this case, the Raukumara domain may be regarded as forming part of the Tonga–Kermadec Ridge which has only translated during the opening of the Havre Trough.

Decoupling zone

A decoupling zone which separates the rotating Wairoa domain from the unrotating regions to the north should be detected by geodetic measurements. The decoupling zone, in order to satisfy both the palaeomagnetic rotation data and the geodetic data, must extend from the CVR/Havre Trough in an approximately SE direction passing through or near Opotiki, to the south of the region of rigid basement (Figs. 4 and 5a). This boundary marks a distinct change in structural trend of an Oligocene–early Miocene fold and thrust belt (Stoneley 1968). Northeast of the boundary, fold axial traces have a consistent NW trend, while further south the trend is N or NE. The boundary may also coincide with a tear fault in the underlying subducted Pacific plate, though there is some uncertainty in the precise location of the tear fault (Kuge & Satake 1987). Active faults with a dextral strike-slip component have been identified in this region, suggesting that the decoupling zone is essentially an arcuate dextral shear zone striking towards Gisborne. The latter is an area of marked Quaternary deformation, where the rotation of the Wairoa domain may be accommodated by dextral strike-slip on NE-trending faults (Fig. 5b). This region also marks the southern termination of thick continuous sequences of Miocene–Pliocene sediments. Further south Pliocene rests directly on Middle Miocene. However, individual active decoupling zone structures have not been clearly defined in the Tertiary cover rocks. In addition, as the Raukumara domain and also the northern margin of the Wairoa domain are deforming internally themselves, the decoupling zone is unlikely to be a single simple structure.

The arcuate dextral strike-slip nature of the decoupling zone, where it passes through basement rocks, suggests that the relative motion of the basements to the Raukumara and Wairoa domains can be described by a pole of rotation northwest of Gisborne and east of Opotiki, within 50 km of the decoupling zone. In this case the slip rate across the whole decoupling zone will be less than 6 mm/a, with much smaller rates across individual faults.

WAIRARAPA DOMAIN

The regions to the south of the Wairoa domain form a continuous nearly straight NE–NNE-trending fold and thrust belt, referred to as the Wairarapa domain (Fig. 2), which has undergone 3–5 km of on-shore shortening perpendicular to the structural trend in the last 1 Ma, though normal faulting, which may be part of a regional high-level slump (Pettinga 1985, Hull 1986), similar to that in the Raukumara domain, occurs at the northern end. The Wairarapa Fault, which is part of the North Island Shear Belt (NISB), is defined as the western margin of the Wairarapa domain (Figs. 7 and 8a). Lamb & Vella (1987) have shown that deformation to the east of the Wairarapa Fault is essentially pure compression, and therefore the vorticity of bulk deformation is small. The component of plate motion parallel to the plate-boundary zone is taken up on the strike-slip faults in the NISB. The Wairarapa domain consists of large back-tilted blocks (5–15 km wide × tens of km long and up to 15 km thick) of Mesozoic basement rocks covered mainly by thin (<5 km) Tertiary and Quaternary sequences, resting on the subducted Pacific plate (Fig. 7). Palaeomagnetic data from one of these crustal blocks

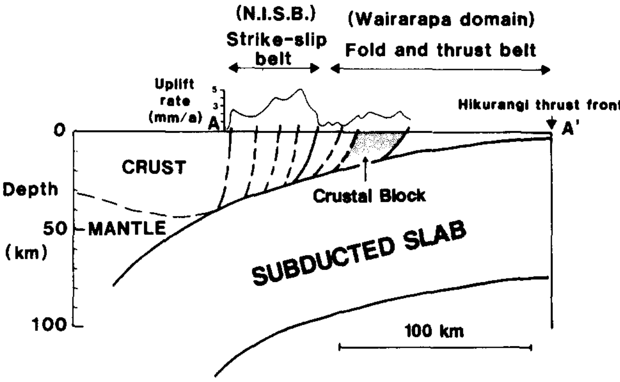

Fig. 7. Vertical cross-section through the plate-boundary zone in the vicinity of the Wairarapa domain (line of cross-section shown in Fig. 8a), showing the position of the subducted Pacific plate and major faults in the overlying crust (after Lamb & Vella 1987). The plate-boundary zone is divided into a fold and thrust belt (Wairarapa domain) which is accommodating the component of plate motion perpendicular to the plate-boundary zone, and a strike-slip belt (NISB) which is accommodating the parallel component. Also shown is the pattern of uplift for the last 200 Ka (Lamb & Vella 1987), which suggests that large crustal blocks of Mesozoic basement rocks are back-tilting. Stippled region shows the inferred palaeomagnetically sampled crustal block.

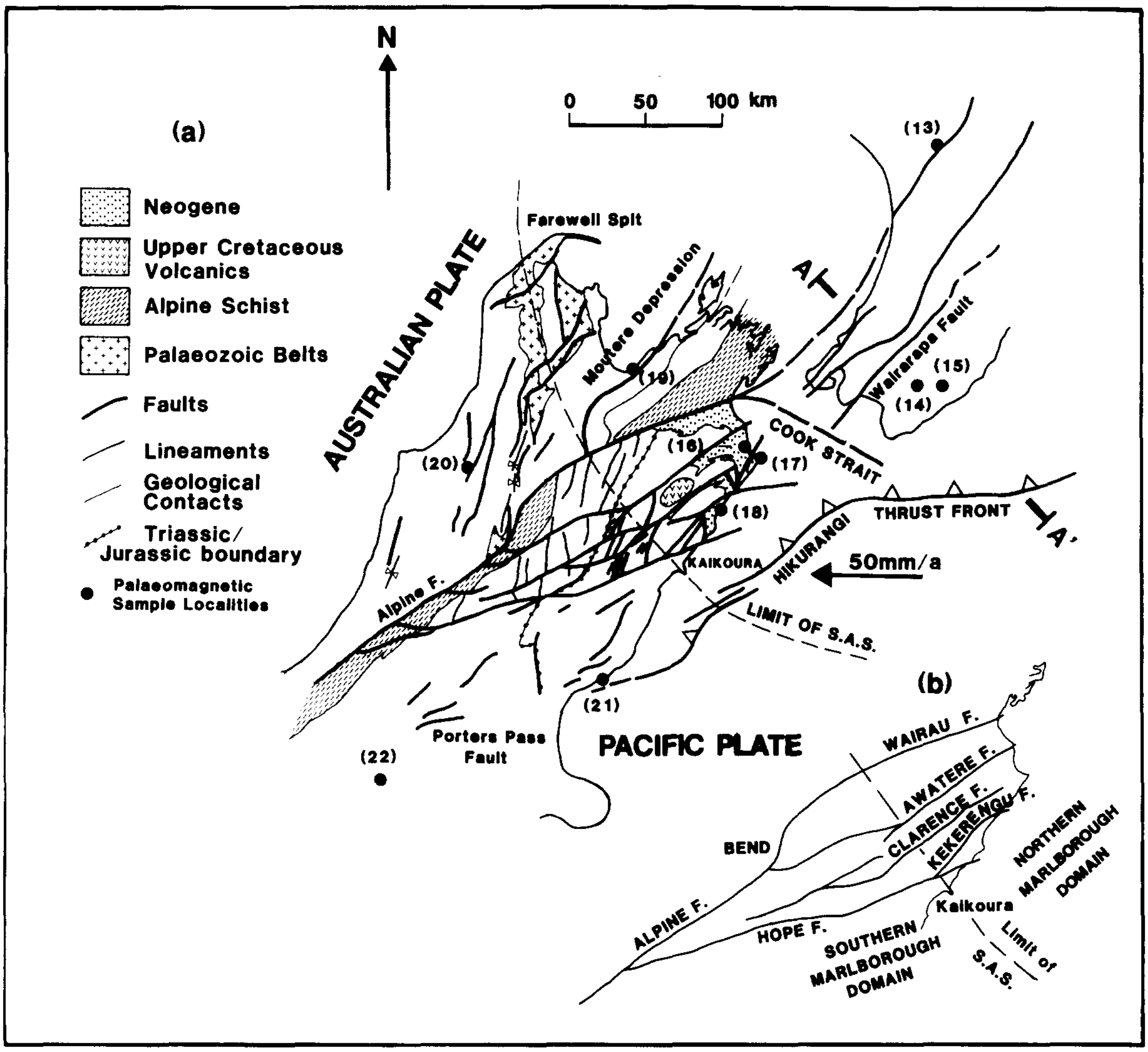

Fig. 8. (a) Geological map (after New Zealand Geological Survey 1972, 1: 1,000,000 geological maps) of the plate-boundary zone near the northern end of South Island, showing the major structural features in the Marlborough domains, eastern and western Nelson domains and the southern part of the Wairarapa domain (see Fig. 2). Note the position of the southern limit of the seismically active subducted Pacific plate (SAS, Ansell & Adams 1986) and the numerous N-trending faults and lineaments to the southwest of this. Palaeomagnetic sample sites are also shown (Table 1). Cross-section AA′ is shown in Fig. 7. (b) Map showing the principal faults in the Marlborough fault system, and the division into the northern and southern Marlborough domains, depending on the trend of the faults.

(Table 1, localities 14 and 15, Figs. 3, 7 and 8a) show that there has been virtually no tectonic rotation relative to the Australian plate in the last *ca* 2.2 Ma (−7° ± 6°), but 20° ± 8° clockwise in the last *ca* 8 Ma (Walcott *et al.* 1981). It is not clear how far to the northeast this pattern of rotation extends.

The lack of tectonic rotation in the Wairarapa domain during the last *ca* 2.2 Ma is consistent with the floating block model, given that the vorticity of bulk deformation is small, if crustal blocks are small and either equidimensional or elongate and aligned parallel to the margins of the deforming zone. However the large size and position of crustal blocks, resting on the subducted slab, suggests that the floating block model may not be applicable. The regions to the northwest of the Wairarapa domain (Table 1, locality 13 Figs. 5a and 8a) (Seward *et al.* 1986) have also undergone negligible rotation relative to the Australian plate in the last *ca* 2.6 Ma. Thus, the Australian plate, at the back of the crustal wedge forming the Wairarapa domain, appears to have acted as a strong barrier, unlike further north, inhibiting large rotations of large elongate crustal blocks in the crustal wedge (Wairarapa domain).

Decoupling zone

The boundary between the Wairoa and Wairarapa domains is not clear, though it is likely to be the northeastern continuation of the Wairarapa Fault, referred to as the Wairarapa fault zone (Figs. 2 and 5a), which extends from the southern end of the North Island into Hawke's Bay. The Wairarapa Fault, which is part of the NISB, has a dextral strike-slip rate, averaged over the last 10 Ka, of 12 mm/a (R. Grapes personal communication), and is one of the most rapidly moving faults in New Zealand. Deformation has been localized near the Wairarapa fault zone since the early Pliocene (P. Wells personal communication). The Wairarapa fault zone, further north, is a distributed zone of dextral transpression (>15 km wide) containing en échelon fold structures, and is oblique to the NISB (*ca* 15–20°).

The Wairarapa fault zone may have only decoupled the Wairarapa domain from the Wairoa domain during the last 2.2 Ma, when the Wairoa domain was rotating most rapidly, though the detailed kinematics are not clear.

Cook Strait

Seismic reflection studies in Cook Strait (Ghani 1978, L. Carter personal communication) show that the major faults in the northeastern part of the South Island (Marlborough fault system) cannot be directly linked up with those in the North Island (Fig. 8a). Cook Strait also marks a change in the pattern of Holocene uplift, with subsidence in Cook Straight compared to uplift onland. Furthermore, a structural boundary must have existed through Cook Straight, at least during the last 2.2 Ma, separating the rapidly rotating crustal blocks in the northern Marlborough domain from the unrotating blocks in the Wairarapa domain (Figs. 2 and 8a). This boundary coincides with a major SE-trending tear in the subducted slab across which the trend and dip of the subducted Pacific plate changes (Robinson 1986). Walcott (1978a) suggested that Cook Strait marks the disrupted and rotated former northern end of the Alpine Fault.

MARLBOROUGH DOMAINS

The Marlborough fault system marks the southern end of the Hikurangi subduction system, where the plate-boundary zone passes through continental crust (Figs. 2 and 8). Here the component of plate motion parallel to the plate-boundary zone is greater than the normal component, in contrast to the plate-boundary zone further north. Major dextral strike-slip faults, extending for over 100 km and spaced 5–20 km apart, have strike-slip rates between 4 and 15 mm/a averaged over the last 10 Ka (Wellman 1983, personal communication). Repeated triangulation studies of networks spanning this part of the plate-boundary zone (Bibby 1981) show that during the last 100 years about 80% (*ca* 40 mm/a) of the relative plate motion is occurring across the Marlborough fault system, implying average strain rates over this period with a simple shear component of 4.3×10^{-7}/a and normal compressional component of 1.2×10^{-7}/a.

There is a distinct change in trend of the Marlborough faults from *ca* 070° in the southwest to *ca* 055° in the northeast. The change in trend coincides with the southern limit of the seismically active subducted Pacific plate (Fig. 8, Ansell & Adams 1986). Only the northeastern part of the Marlborough fault system is underlain by the seismically active subducted Pacific plate. This is likely to have important structural consequences, and in this study two domains within the Marlborough fault system are distinguished: northern and southern Marlborough domains, marked by the change in trend of the major faults (Fig. 8b).

NORTHERN MARLBOROUGH DOMAIN

The continuity of Middle Miocene to Pliocene sedimentary sequences (Lensen 1962, Kennett 1966) suggests that most of the latest phase of deformation in the northern Marlborough domain occurred in the last 4 Ma.

Rotation data

Palaeomagnetic rotation data for the northern Marlborough domain are confined to three localities (Table 1, localities 16–18, Figs. 2, 3, 8a and 9). These show clockwise rotations relative to the Pacific plate of 99° ± 12° for *ca* 18 Ma sediments between the Kekerengu and Hope Faults (Mumme & Walcott 1985), 24° ± 10° for *ca* 8 Ma sediments (Walcott *et al.* 1981) and 36° ± 10° for *ca* 5 Ma sediments east of the Awatere Fault (Roberts 1986).

Rotation of small crustal blocks

Detailed mapping in the region between the Kekerengu and Hope Faults in the northern Marlborough domain (Fig. 9) has revealed a complex pattern of intense deformation, in which all tilting of the sediments (generally greater than 60°) has occurred since the Pliocene. Pervasive faulting has resulted in crustal blocks much less than 5 km across. Palaeomagnetic sampling of one of these blocks (Table 1, locality 18, Fig. 9b) shows that it has rotated clockwise *ca* 100° in 18 Ma relative to the Pacific plate (Mumme & Walcott 1985).

Experiments with brittle material floating on a highly viscous medium (J.-P. Brun personal communication) suggest that the horizontal spacing of the dominant block boundaries is roughly equal to the thickness of the blocks. Thus, small crustal blocks with horizontal dimensions much less than the thickness of the crust, such as those in the intense zone of deformation associated with the Kekerengu Fault, may be floating on a zone of more distributed deformation in the underlying crust at a depth roughly equal to the block width (<5 km). Figure 10 shows possible rotation rates as a consequence of intense deformation in the northern Marlborough domain, calculated using the model of floating crustal blocks (Appendix I, Lamb 1987), assuming that the deformation (geodetic) determined from repeated triangulation studies (Bibby 1981) is representative of a continuously deforming underlying crust and that there are no velocity gradients along the length of the deforming zone. Markedly elongate blocks (aspect ratio (k) $\ll$ 1) could experience instantaneous rotation rates up to 35°/Ma, while rotation rates over long periods are more likely to be closer to those of equidimensional blocks

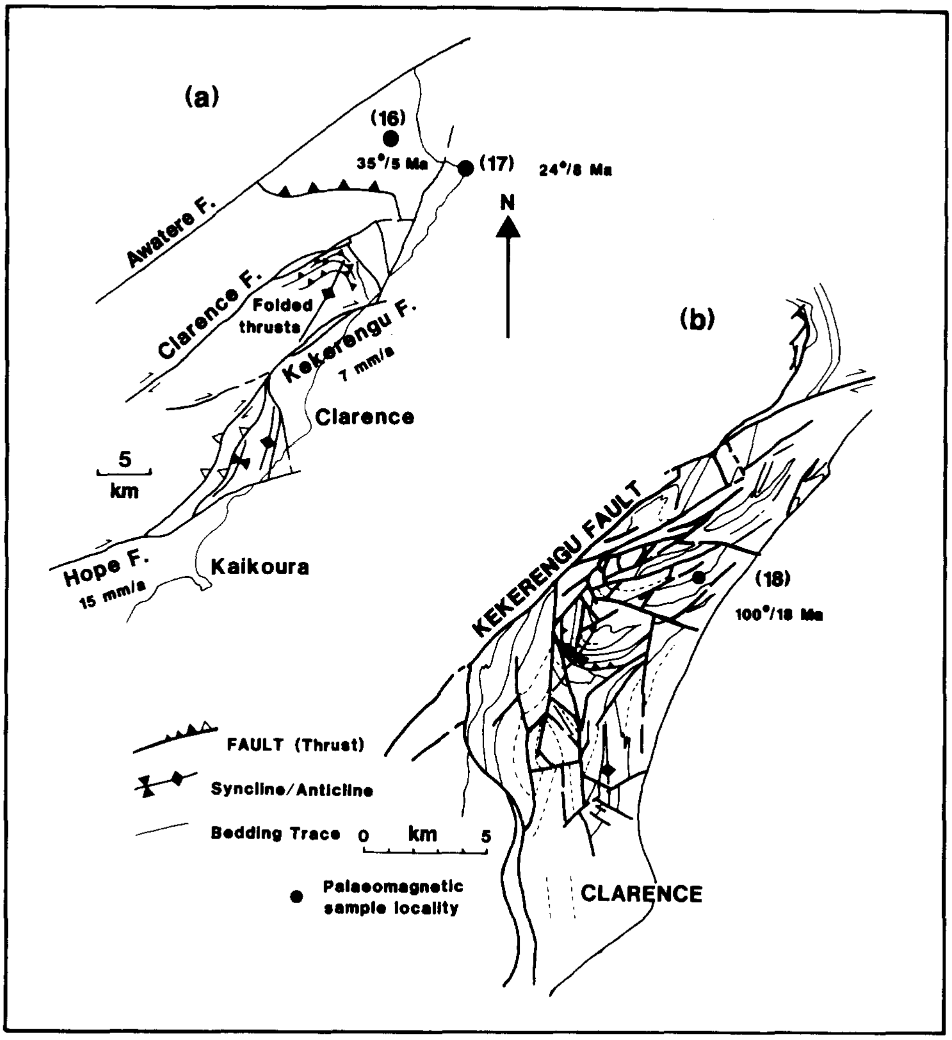

Fig. 9. (a) Structural map of the Kekerengu–Kaikoura region (partly based on Lensen 1962) in the northeastern part of South Island (see Fig. 8) where the Marlborough faults change trend, showing the region between the northeastern end of the Hope Fault (trending *ca* 070°) and the Clarence and Kekerengu Faults (trending *ca* 055°). This is an area of structural complexity and major thrust faults and Holocene slip rates (R. Van Diessen personal communication) suggest that *ca* 50% of the motion on the Hope Fault is being transferred to the Kekerengu Fault. Note folded thrust faults near the northeastern end of the Clarence Fault. The locations of palaeomagnetic sample sites are also shown. (b) Detailed geology of Upper Cretaceous–Pliocene sequences overlying deformed Mesozoic basement rocks in the Kekerengu–Clarence area, immediately east of the Kekerengu Fault. Offset of Upper Cretaceous–early Miocene sequences suggests *ca* 10 km strike-slip displacement across the Kekerengu Fault. Location of palaeomagnetic sample site is also shown.

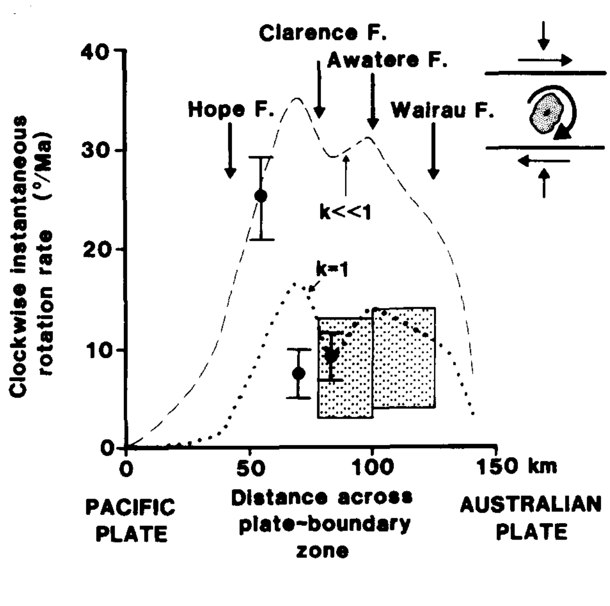

Fig. 10. Graph showing the variation in instantaneous rotation rate, calculated for small crustal blocks with different aspect ratios (equidimensional, $k = 1$; elongate, $k \ll 1$) using the floating block model (Appendix I, Lamb 1987) and the geodetic deformation (Bibby 1981), assuming no velocity gradient parallel to the general structural trend, for an approximately SE-trending traverse across the northern part of the Marlborough fault system. Also shown are the average palaeomagnetically determined rotation rates (solid dots with 95% confidence limits), assuming that all rotation occurred in the last 4 Ma. Dotted boxes show range of instantaneous rotation rates (95% confidence limits) for large crustal blocks between the Wairau and Awatere Faults, calculated from the short-term velocities (see Fig. 11).

(k = 1), with rotation rates up to 16°/Ma. Thus a substantial amount of the rotation (50–60°) observed in a crustal block from between the Kekerengu and Hope Faults could have occurred as a consequence of the deformation in the last 4 Ma.

Rotation of large crustal blocks

Slip rates on the principal faults in the northern Marlborough domain (Wellman 1983, personal communication) show that most of the deformation (>60%) expected from geodetic and plate-tectonic observations is occurring on or very close to (within 2 km) the faults. The gentle structure of the Neogene cover rocks, and also the obvious lack of deformation in an Upper Cretaceous dyke swarm which intrudes basement rocks between the Awatere and Clarence Faults (Fig. 8), show that during the Neogene most of the crust between the major faults in the northern Malborough domain has only experienced a regional tilt, generally les than 25°. Thus, crustal blocks may measure tens of km across and up to 80 km long. An estimate of the instantaneous rotation rate of such a large crustal block can be made from the variation in the short term velocity azimuths and magnitudes along the length of an individual crustal block.

Short-term velocity field

Haines (1982) and Walcott (1984a) have attempted to obtain the velocity field for the whole of the South Island by assuming a smooth distribution of the geodetic strain rates between the available observations. However their strains are averaged over areas (40 × 40 km) comparable in size to the crustal blocks considered here. A marked swing in velocity azimuth is apparent in the northern Marlborough domain, as would be expected if large crustal blocks are rotating.

An estimate of the velocities at the northern end of the northern Marlborough domain can be made by integration of the geodetic strain rates across the boundary zone, assuming zero velocity gradients along the dominant structural trend (Table 2, Fig. 11a) (Bibby 1981). A good estimate of velocities further south (northern end of southern Marlborough domain) can be made from Holocene slip vectors and rates on the major faults combined with some geodetic information (Table 2, Fig. 11a). Here the major faults trend within 15° of the relative plate velocity vector, with cumulative slip rates which are at least 60% of the plate convergence rate. The long-term slip vectors on the faults are well constrained by the large ratio of horizontal to vertical movement on steeply-dipping faults (>60°), pull-apart basins, and also slip vectors from fault plane solutions. It is assumed that the velocity of the southwestern end of the crustal block between the Wairau and Awatere Faults (Wairau block), when combined with the slip vector on the Alpine Fault and the observed NW–WNW shortening further west (western Nelson domain), has a resultant direction which is the same as that of the plate convergence vector.

Short- and long-term rotation rates

The instantaneous velocities suggest that large crustal blocks in the northern Marlborough domain, bounded

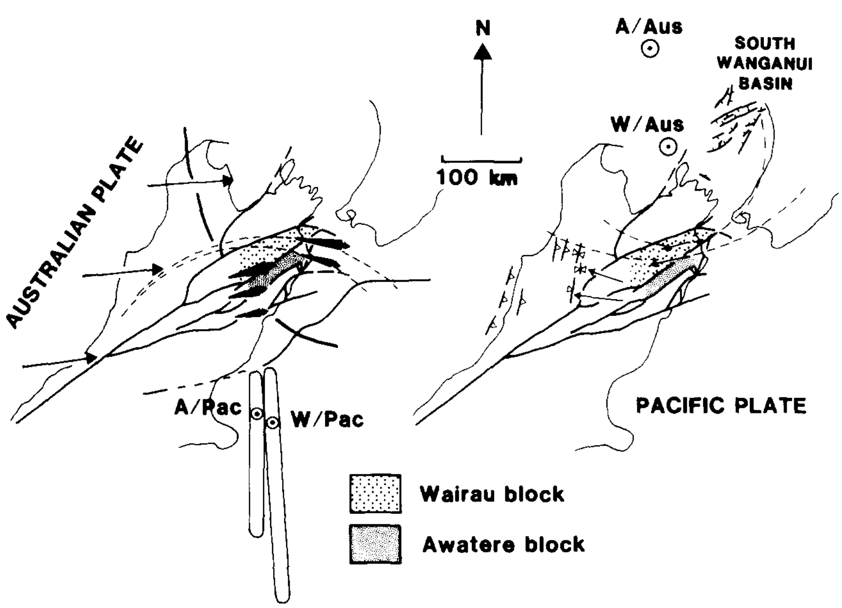

Fig. 11. (a) Map of the northern part of South Island, showing the instantaneous velocities relative to the Pacific plate at both ends of the Wairau and Awatere blocks. Black wedge indicates uncertainty in velocity azimuth (velocity towards wide end of wedge, Table 2) and the length of the thin bar at the wide end of wedge represents one standard error in magnitude (total length of solid fan and thin bar is proportional to the mean + one standard error). Also shown are the ranges of rotation poles (two standard errors) with mean position suggested by velocity azimuths. Large arrows represent relative plate velocities. Thin dotted lines show tracks of the northern ends of the blocks if they have rotated about the mean rotation pole for the particular crustal block. (b) As in (a), except that velocities are relative to the Australian plate. These velocities imply compression relative to the Australian plate at the southern end of the blocks, and strike-slip or extension (South Wanganui basin) at the northern ends.

Table 2. Motion of large crustal blocks in the northern Marlborough domain

	Velocity		Rotation	
	Azimuth (°)	Magnitude (mm/a)	Rate (°/Ma)	Mean rotation pole (°longitude/ °latitude)
Relative to Pacific plate:				
Wairau block —northern end	095 ± 5	35 ± 5	9 ± 5	173.7/43.6
—southern end	075 ± 8	29 ± 5		
Awatere block—northern end	105 ± 5	25 ± 5	7 ± 4	173.4/43.5
—southern end	078 ± 8	25 ± 5		
Relative to Australian plate:				
Wairau block —northern end	255 ± 5	17 ± 5	8 ± 5	173.7/40.5
—southern end	288 ± 8	23 ± 5		
Awatere block—northern end	259 ± 5	25 ± 5	6 ± 4	173.4/39.5
—southern end	275 ± 8	31 ± 5		

by the Wairau, Awatere and Clarence Faults, are rotating clockwise relative to the Pacific plate about poles *ca* 100–400 km south of Kaikoura (Table 2, Fig. 11a). The Wairau block is rotating at 9° ± 5°/Ma, and the Awatere block at 7° ± 4°/Ma.

The instantaneous rotation rates cannot be directly compared with palaeomagnetic observations, as sample sites are in different crustal blocks. For instance, a *ca* 35° clockwise rotation of Pliocene sediments (locality 16 in Fig. 9a) (Roberts 1986) is representative of a crustal block near the northeastern ends of the Awatere and Clarence Faults (Lamb & Bibby in review). The rotation of this block appears to have taken up dextral shear on the Clarence Fault, accommodated by N–S shortening along an E-trending thrust zone (Fig. 9a), which increases towards the east. However, estimates of the shortening across this thrust zone, as well as estimates of the total slip on the Clarence Fault (*ca* 10 km), suggest that the clockwise rotation of this block is unlikely to be more than 15 times greater than that of the crustal blocks further to the south (Lamb & Bibby in review). Therefore, assuming that all the observed clockwise rotation (*ca* 35°) occurred during the last 4 Ma, and that in addition to the rotation of the Awatere block, *ca* 15° is related to accommodating slip on the Clarence Fault, then the Awatere block, and also the Wairau and Clarence blocks, may have rotated at an average rate of *ca* 5°/Ma (20° in 4 Ma). This rate is identical, within the errors, to that deduced from the short-term velocities. The short-term velocities over less than 100 years appear to be representative of the long-term (>3 Ma) velocity pattern, though it is likely that the poles of rotation have migrated during the development of the northern Marlborough domain. The rate of rotation may have also changed through time. This rotation must be accommodated by slip on the Hikurangi subduction thrust, increasing towards the north.

Large 'floating' crustal blocks

The model of 'floating' rigid blocks is not strictly applicable to large crustal blocks, such as those in the northern Marlborough domain, which are comparable in size to the width of the zone of deformation and are resting on the subducted Pacific plate. However, it is interesting to note that the model suggests, given the aspect ratio and orientation of the large crustal blocks, and using the average strain rates across the northern Marlborough domain, that their rotation rate has decreased with time from greater than 14°/Ma before 3 Ma to *ca* 6°/Ma today, which is compatible with the rotation rates estimated from the short-term velocities (Table 2). The model predicts that the rotation rate will further decrease in the future.

Southern Marlborough domain

The marked swing in azimuth of the instantaneous velocities (Fig. 11), which appears to record the rotation of large crustal blocks in the northern Marlborough domain, probably does not occur further south in the southern Marlborough domain. Here the Marlborough fault system is not underlain by the seismically active subducted Pacific plate and the trends of the principal faults are within 15° of the plate convergence vector. The region between the Hope and Porters Pass Faults (Fig. 8a) is a region of intense active deformation, and Pliocene strata are locally subvertical. Here and further north, numerous N-trending faults and distinct topographic lineaments occur between the major faults (Fig. 8a), suggesting that the southern Marlborough domain consists of a large number of crustal blocks (<10 km across) between the major faults. Though much of the deformation (>60%) during the last 10 Ka and possibly 100 Ka has been concentrated on the major faults, these blocks may have also rotated, especially over periods longer than 100 Ka, accommodated by reverse sinistral strike-slip faulting between them. Thus, the long-term behaviour of the southern Marlborough domain may be predominantly distributed dextral shear parallel to the plate convergence vector and subparallel to the major faults, resulting in bending of passive linear markers, such as the Triassic–Jurassic boundary (Fig. 8a).

Rotation of crustal blocks, relative to the Pacific plate, has not occurred at the palaeomagnetic sample site at Motunau in the last *ca* 8.5 Ma (Table 1, locality 21 in Fig.

8a) (Walcott *et al.* 1981), and south of the Porters Pass Fault (Table 1, locality 22, Fig. 8a) (Oliver 1979). These sites may be close to the boundary between the southern Marlborough domain and the essentially undeforming Pacific plate (Fig. 2).

Simple mechanical model for the Marlborough domains

Deformation in a trellis system linked to a large rigid block (Fig. 12a) produces a similar velocity field to the inferred short-term velocity field in the Marlborough domains. Dextral shear across the trellis results in rotation of the cross-bars and pivoting of the large rigid block. This model implies that the rotation rate of crustal blocks is equal to the vorticity of deformation as a consequence of motion on the trellis system (McKenzie & Jackson 1983, 1986). If crustal blocks are not pinned but floating, then their rotation rate will be different to that required by the trellis system, though the trellis system may still produce the same velocity field as that in the underlying and continuously deforming lithosphere (McKenzie & Jackson 1983, 1986).

The trellis system may describe the motion of small crustal blocks between the major faults in the southern Marlborough domain, while the pivoting block may describe the motion of the large blocks in the northern Marlborough domain. Thus, depending on the slip rates on the major faults in the northern Marlborough domain, the rotation of these large blocks may accommodate the shear across the whole of the southern Marlborough domain, or that part which is not taken up by slip on the major faults in the southern Marlborough domain. Similarly, displacement on the Clarence Fault (shear in the trellis system) is taken up by rotation of the crustal block at the northern end of the Clarence Fault.

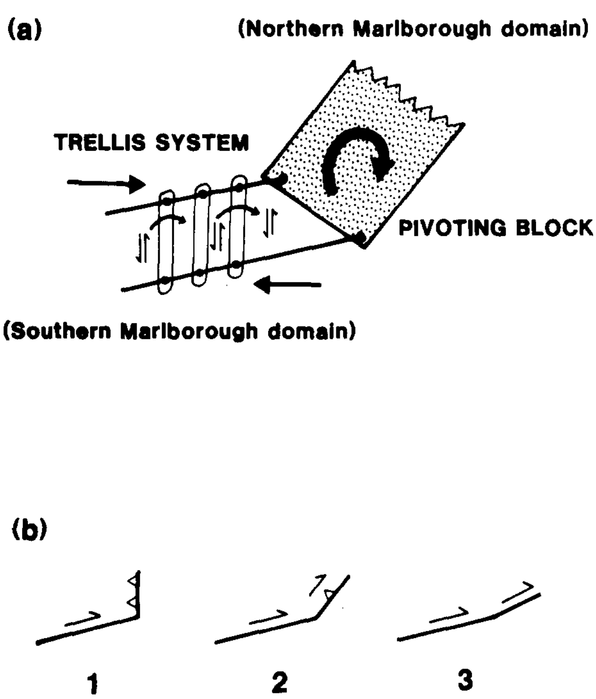

Fig. 12. (a) Simple mechanical model for the Marlborough domains. See text. (b) Diagram illustrating the possible fault geometry in the Marlborough domains at three stages during the Neogene, illustrating the evolution of the fault system from stage 1 to 3. The main faults in the northern Marlborough domain may have rotated from predominantly thrust (stage 1) to predominantly strike-slip faults (stage 3), while the faults in the southern Marlborough domain may have remained predominantly strike-slip.

The model suggests that the angular relation between the faults in the northern and southern Marlborough domains has not remained constant but has decreased through time (Fig. 12b). Thus, early in the evolution of the system the faults in the northern Marlborough domain may have been markedly oblique to those in the southern Marlborough domain, and were predominantly thrust faults, reactivating early to Middle Miocene thrust faults which have been documented in the Kekerengu–Clarence area (Fig. 9) (Prebble 1976, Lamb & Bibby in review). The faults in the southern Marlborough domain may have always had an orientation close to their present orientation, and remained predominantly strike-slip faults. The link between the southern and northern Marlborough domains can therefore be considered as a hinge zone. Detailed mapping in such a zone between the Hope and Kekerengu Faults (Fig. 9) shows that this is an area of structural complexity.

EASTERN AND WESTERN NELSON DOMAINS

Eastern Nelson domain

The eastern Nelson domain lies east of the Moutere depression and north of the Wairau Fault (Figs. 2 and 8a). This region contains a series of thin (*ca* 10 km across) belts defined on age and lithology, which can be traced, along with a distinctive magnetic anomaly, into the west side of the North Island, extending right up to the Northland Peninsula. This continuity in structure clearly distinguishes the eastern Nelson domain from the northern Marlborough domain, which is structurally disconnected from the North Island across Cook Strait.

Palaeomagnetic measurements from Oligocene sediments at Magazine Point in Nelson indicate a poorly determined clockwise rotation of *ca* 80° relative to the Australian plate in the last 30 Ma (Table 1, locality 19, Fig. 8a) (Mumme & Walcott 1985).

Western Nelson domain

The western Nelson domain lies west of the Moutere depression and north of the Alpine and Wairau Faults (Figs. 2 and 8a). It mainly consists of N-trending Palaeozoic belts and Cretaceous granites. Palaeomagnetic measurements (Table 1, locality 20, Fig. 8a) (Mumme & Walcott 1985) show that the trend of these belts has undergone less than 10° clockwise rotation in the last 40 Ma. However, there has been a large amount of Neogene WNW–NW shortening, with a substantial amount in the Plio-Pleistocene. It is actively occurring on NE-trending thrusts and N-trending folds and reverse sinistral strike-slip faults.

Kinematics of Nelson domains

If one assumes that the instantaneous motion of large crustal blocks in the northern Marlborough domain can be described by rotations about poles determined from geodetic velocity considerations (Table 2, Fig. 11b), then the motion of the crustal block immediately southeast of the Wairau Fault (Wairau block), would require transtension relative to the Australian plate at the northeastern end of the Wairau Fault, strike-slip further southwest, and transpression in the vicinity of the bend region where the Wairau Fault becomes the Alpine Fault (Figs. 8b and 11b). The repeated triangulation data, and also a history of subsidence in the northeastern part of the Marlborough sounds and South Wanganui basin, show that transtension is indeed occurring at the northeastern end of the Wairau Fault. Thrusting, folding and uplift since the Pliocene (Nathan 1978, Cutten 1978) show that a large amount of compression is occurring in the western Nelson domain at the southwestern end of the Wairau Fault. The Plio-Pleistocene (last 4 Ma) shortening is causing part of the Alpine Fault to migrate northwest. Therefore the prominent bend at the southwestern end of the Wairau Fault may have accommodated clockwise rotation of the Wairau block, involving a 15 km NW–WNW translation and *ca* 10° clockwise rotation of part of the Alpine Fault (i.e. Wairau Fault) in the last 4 Ma. The linear belts in the eastern Nelson domain may have rotated by a similar amount, and therefore the large clockwise rotations observed near Nelson (locality 19 in Fig. 8) are either a local effect or occurred prior to 4 Ma.

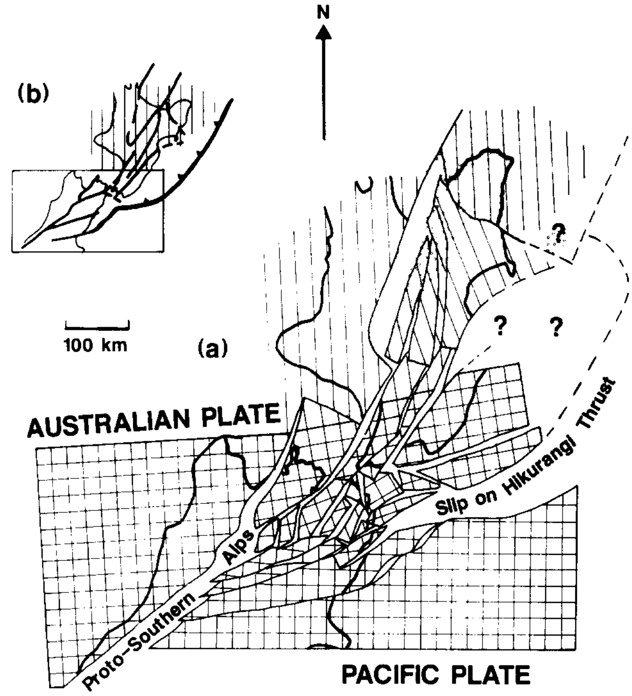

Fig. 13. (a) Diagram showing a 4 Ma 'cut-out' reconstruction of the northern part of the New Zealand plate-boundary zone. Relative plate positions are based on an interpolation of the present and 10 Ma positions (Stock & Molnar 1982). Individual blocks are cut-out along major faults and repositioned according to the nature of the deformation at their boundaries and the observed or inferred tectonic rotations. The gaps between blocks represent the amount of shortening that has occurred in the last 4 Ma, while regions overlain with circle ornament represent overlaps as a consequence of extension in the same period. Some of this deformation may be taken up by distributed deformation within the blocks—for instance in the Nelson domains. Region covered by 25 × 25 km grid is enclosed by the rectangular box in (b). Grid lines trend E–W and N–S today, while parallel lines outside the box trend N–S today (shown in b).

4 Ma RECONSTRUCTION

A good interpolation of the relative plate positions can be made for the last 4 Ma, as the instantaneous rate of relative plate motion is essentially an average over the last 3 Ma. Therefore, using the kinematic analysis of the various rotation domains, a reconstruction at 4 Ma can be attempted (Figs. 13–15). An estimate of the horizontal finite strains during this time can be obtained from the smoothed-out deformation of a 4 Ma latitude–longitude grid (Fig. 14). The principal features of the reconstruction are as follows:

(1) The age and migration of andesitic volcanism (Stern 1987) suggest that the extension in the Havre Trough and Central Volcanic Region began at this time, though there may have been an already existing zone of strike-slip in this region (Figs. 13 and 15). The northern end of the NISB had a NNW-trend, markedly oblique to the plate-boundary zone, and may have reactivated older thrusts.

(2) The Hikurangi Thrust front may have migrated east during the last 4 Ma, progressively deforming more of the thick sequence of sediments on the Pacific plate. This migration would preserve continuity with the thrust front further north. The Hikurangi Thrust front trended *ca* NNE at 4 Ma, compared to *ca* NE today.

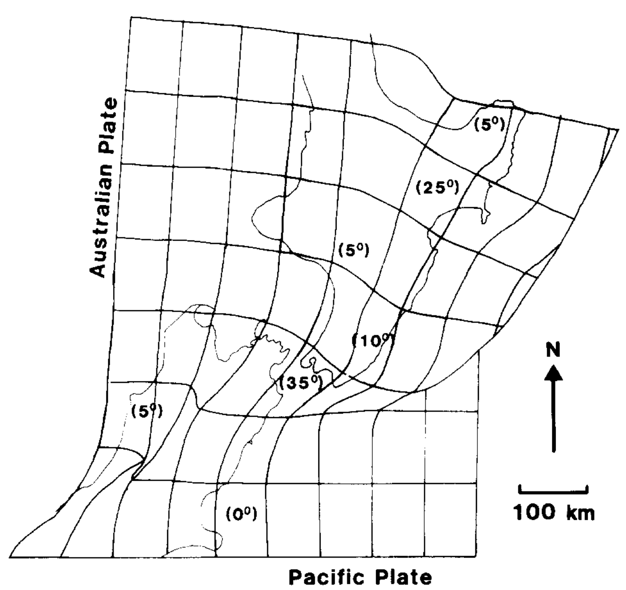

Fig. 14. Diagram showing the smoothed out estimate of the deformation of a 1° longitude–latitude grid system during the last 4 Ma. Grid was orthogonal at 4 Ma, orientated N–S and E–W. Observed or inferred tectonic rotations relative to the Pacific plate are shown in brackets.

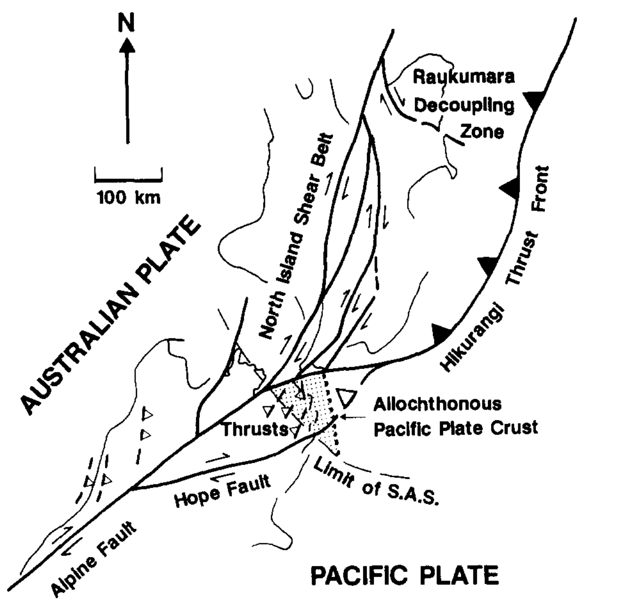

Fig. 15. Diagram showing an interpretation of the major structural features in the northern part of the New Zealand plate-boundary zone at 4 Ma (based on Fig. 13). Note the thrust faults in the Marlborough and western Nelson domains. Note also the southern limit of the seismically active subducted slab (SAS), and also the presence of allochthonous Pacific plate crust (ornamented with dot pattern) resting on the subducted Pacific plate.

(3) The Alpine Fault extended as a nearly straight line up into the southern part of the North Island, linking up with the North Island Shear Belt and also the Hikurangi thrust front through what was to become Cook Strait. The NISB is assumed to have been active prior to 4 Ma (Fig. 15).

(4) Most of the shortening (>75%) in the Southern Alps, and also the internal deformation in the northern Marlborough domain, occurred in the last 4 Ma (Figs. 13 and 14). At 4 Ma the major faults in the northern Marlborough domain formed with a trend of *ca* 035° compared to 055° today.

PLATE-BOUNDARY ZONE PRIOR TO 4 Ma

Palaeomagnetic data suggest clockwise rotations, relative to the Australian plate, of at least 10° in the Wairoa domain prior to 4 Ma (Fig. 3) (Wright & Walcott 1986), and 20° ± 8° in the Wairarapa domain in the last *ca* 8 Ma (Fig. 3) (Walcott *et al.* 1981). It is possible that the Wairapa domain and Wairoa Syncline formed a single domain prior to *ca* 2.2 or 4 Ma in which crustal blocks rotated coherently clockwise *ca* 10–20° relative to the Australian plate since *ca* 8 Ma. The structural consequences of this rotation are not clear, though it is likely to have been accommodated by dextral shear on a series of strike-slip faults (part of NISB) splaying from the northern end of the Alpine Fault, as well as shortening on the west side of the North and South Islands.

The 4 Ma reconstruction (Fig. 15) shows that part of the northern Marlborough domain overlays the subducted Pacific plate and therefore emplacement, presumably involving rotation, of the northern Marlborough domain on to the Pacific plate must have occurred prior to 4 Ma. Early to Middle Miocene (18–10 Ma) low-angle thrusting and uplift in the northern Marlborough domain, resulting in extensive erosion so that in places late Miocene rests directly on Mesozoic basement (Prebble 1976, Lamb & Bibby in review), may be related to this emplacement. Slip on these thrusts, in their present orientation, is towards the SE (Prebble 1976). However, assuming 60–90° of clockwise Neogene and Quaternary tectonic rotation in this part of the plate-boundary zone, the slip direction would have been towards the NE–E in the early to Middle Miocene, at a high angle to the likely plate-boundary zone at this time (Lamb & Bibby in review).

DISCUSSION

The previous descriptions have revealed a complex pattern of deformation during the last 4 Ma in the northern part of the New Zealand plate-boundary zone. Why did the crust behave in this way? Much of the crust in the northern part of the plate-boundary zone, where large tectonic rotations have been observed, rests on the subducted Pacific plate. The subducted slab is likely to have had an important effect on the behaviour of the overlying crust.

Size of crustal blocks

Holocene slip rates on the major faults in the crust overlying the subducted Pacific plate (Wellman 1983, personal communication) suggest that at least 60% of the geodetic deformation represents elastic strain which will ultimately be released as slip on these faults (Lamb & Vella 1987). The wide zone of geodetic deformation either side (>20 km) of some of these faults, and the wide spacing of the faults (5–20 km), suggest that a large proportion of the crust above the subducted slab in the on-shore part of the plate-boundary zone is strong and behaving elastically (Fig. 7). Microseismicity in the overlying crust in the Wairarapa and northern Marlborough domains (Robinson 1986) extends down to the subducted slab interface, but is very infrequent in the top *ca* 15 km. Thus, basement rock in the Raukumara, Wairarapa and northern Marlborough domains, which are resting on the subducted Pacific plate, deforms as large crustal blocks. Deformation in continental crust away from the subducted Pacific plate, such as in the southern Marlborough domain and the Southern Alps, appears to be more penetrative and even aseismic (Walcott 1978a). Thus the subducted slab may exert a control on the size of crustal blocks, especially in the well-indurated Mesozoic basement rocks, perhaps because it depresses the geothermal gradient in the overlying crust which remains 'cool' and strong. If crustal blocks resting on the subducted slab are large, then their motion will be controlled by the main boundary conditions in the plate-boundary zone.

Trend of the subducted slab

Walcott (1984b, 1987) has suggested that an important mechanism for crustal rotations in the New Zealand plate-boundary zone is the rotation of the trend of the subducted slab. If the hinge line of the subducted slab does not sink at a uniform rate along its length, then the trend of the slab will change. This may be the case in the northern part of the New Zealand plate-boundary zone, where the southern end of the subducted Pacific plate is attached to continental crust which makes it more buoyant than further north where the Pacific plate is being overridden by Australian plate oceanic lithosphere and has also regressed during back-arc spreading (Fig. 1). Thus, the trend of the intervening slab may have progressively rotated clockwise. If the overlying Australian plate is sufficiently weak, the plate-boundary zone may remain parallel to the trend of the subducted slab, resulting in the rotation of crustal blocks, rather than be obducted onto the Pacific plate. The lack of tectonic rotation relative to the Australian plate in the Raukumara domain suggests that the trend of the underlying subducted slab has not changed relative to the Australian plate in the last 20 Ma, while the 4 Ma reconstruction suggests that the plate-boundary zone further south has rotated *ca* 15° clockwise relative to the Australian plate (*ca* 20° clockwise relative to the Pacific plate) in the last 4 Ma (Fig. 16).

The rotation in the Wairoa domain (*ca* 20 clockwise relative to the Australian plate in the last 4 Ma) may partially record the rotation of the trend of a segment of the subducted slab south of the Raukumara domain.

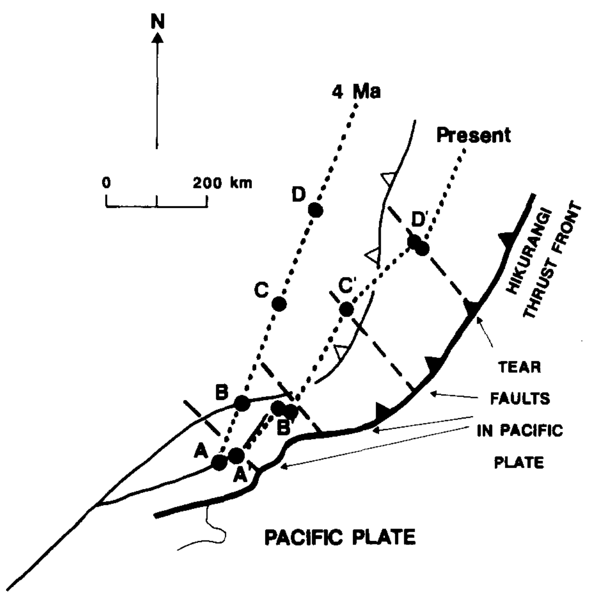

Fig. 16. Diagram showing the position of the Hikurangi thrust front at *ca* 4 Ma relative to its present position. Also shown is the deformation of a straight line ABCD at 4 Ma to become A'B'C'D' today, illustrating the different behaviour of the various domains. The rotation of AD to A'D' may represent the rotation of the trend of the plate boundary zone and trend of the subducted slab. Note that the proposed tear faults (Reyners 1983, Ansell & Adams 1986, Robinson 1986, Kuge & Satake 1987) more-or-less coincide with the present ends of the various line segments (boundaries to rotation domains), but not with those at 4 Ma.

However, the failure of back-arc spreading to propagate further south, perhaps due to the strength of the overlying plate or the buoyancy of the subducted slab, appears to have only allowed a limited part of the overlying plate in the vicinity of the Wairoa Syncline to rotate with the trend of the subducted slab (Fig. 16). Further south, in the vicinity of the Wairarapa domain, the strength of the Australian plate, at the back of the overlying crustal wedge, may have prevented the rotation of crustal blocks (Fig. 16). However, the Hikurangi thrust front may have migrated further east into more of the Pacific plate sedimentary cover, accommodating the rotation of the trend of the subducted slab by a widening of the plate-boundary zone on the Pacific side.

The boundaries to the various rotation domains approximately coincide with tear faults in the subducted slab, as might be expected if the rotations of the domains coincide with rotations of the trend of the subducted slab. However, the boundaries to the domains appear to have moved relative to the tear faults in the last 4 Ma (Fig. 16).

Deformation in the overlying plate

If the overlying plate deforms internally, then there may not be a simple relation between the rotation of the trend of the subducted slab and the rotation of crustal blocks. The rotation of the trend of the subducted slab and leading edge of the overlying crustal wedge may be better described as the rotation of a passive marker line, while palaeomagnetism gives information on rigid-body rotation. Small crustal blocks, such as those near the Kekerengu Fault in the northern Marlborough domain, may be floating and rotating as a consequence of shear in a continuously deforming and underlying crust. These rotations need not be the same as those of passive marker lines.

The relative motion of the bounding plates may induce shear stresses on the sides and base of large crustal blocks. Shear stresses exerted by the subducted Pacific plate on the base of the overlying crust may cause the commonly observed partitioning of the deformation in the overlying plate (Fitch 1972, Walcott 1978b, Bibby 1981, Lamb & Vella 1987) so that slip on the subducted slab interface is minimized. Thus, in obliquely convergent subduction systems the component of plate motion normal to the plate-boundary zone occurs in the crust resting on the subducted slab, while the component of plate motion parallel to the plate-boundary zone occurs on subvertical faults elsewhere. If large strong elongate crustal blocks straddle the plate-boundary zone and rest on the subducted slab, as in the northern Marlborough domain, then the requirement for partitioning of the slip on the subducted interface may cause the blocks to pivot round so that the frontal parts move normal to the plate-boundary zone and the back parts parallel to it (Fig. 17). However if elongate crustal blocks are aligned parallel to the plate-boundary zone, perhaps due to earlier deformation, as may be the case in the Wairarapa domain, then this partitioning will not cause rotation

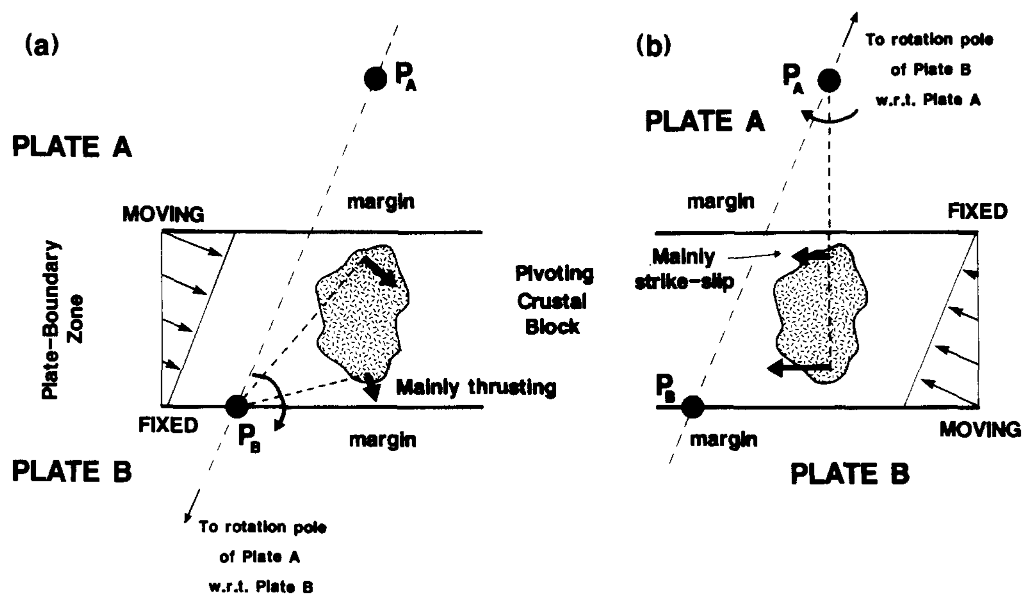

Fig. 17. Diagrams illustrating how rotation of a large crustal block, straddling the plate-boundary zone, can accommodate partitioning of the deformation into normal compression in the frontal parts and strike-slip at the back of the crustal wedge overlying the subducted slab. (a) Crustal block lies within plate-boundary zone between Plates A and B. The motion of Plate A relative to Plate B (fixed) is described by a translation resulting in deformation with components of dextral shear and compression within the plate-boundary zone (rotation about pole at infinity). The instantaneous motion of the crustal block, relative to Plate B, is described by a clockwise rotation about pole P_B, resulting in mainly thrusting between the crustal block and Plate B. (b) The instantaneous motion of the crustal block, relative to Plate A (fixed), is described by a clockwise rotation about pole P_A, resulting in mainly strike-slip between the crustal block and Plate A. Instantaneous rotation poles P_A, P_B and the relative plate rotation pole are co-linear.

and the blocks will move only perpendicular or parallel to the trend of the subducted plate.

CONCLUSION

Walcott (1984b, 1987) has suggested that the long-term history (last 20 Ma) of crustal rotations in the New Zealand plate-boundary zone can be explained by the uniform rotation of the trend of the underlying plate, and can be predicted from the finite plate motions. However, in the short-term during the last *ca* 4 Ma, the pattern of crustal rotations in the northern part of the New Zealand plate boundary zone is complex. The rotation rate varies in space and time. It appears to be related to the dimensions of crustal blocks and the strength and structure of the crust and the presence of an underlying subducted slab. Large crustal blocks (tens of km across) rest on the subducted slab.

The large amount of shortening in the Southern Alps, the internal deformation in the northern Marlborough domain, and also the opening of the Havre Trough and associated back-arc basins, record a large shift in the instantaneous rotation pole of relative plate motion between the Pacific and Australian plates, with an increase in the component of plate motion perpendicular to the plate-boundary zone. This change in geometry of the plate-boundary zone may have initiated the complex pattern of rotations.

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APPENDIX I

Floating block model

Small crustal blocks within a wide zone of intense deformation are modelled as isolated rigid ellipsoidal floats (with principal dimensions a, b, c; and b horizontal) floating on a highly viscous fluid. Take axes (x, y, z) such that the origin is the centre of the ellipsoid and x, y are horizontal. If u, v, w are the components of velocity of the fluid parallel to the x, y, z axes, respectively (positive velocities in the positive x, y, z directions, respectively), and there are no velocity gradients parallel to the margins of the deforming zone, and w does not vary with x and y ($\partial u/\partial x = \partial v/\partial x = \partial w/\partial x = \partial w/\partial y =$ zero), and one of the principal axes of the ellipsoid is vertical (c axis parallel to z), then the instantane-

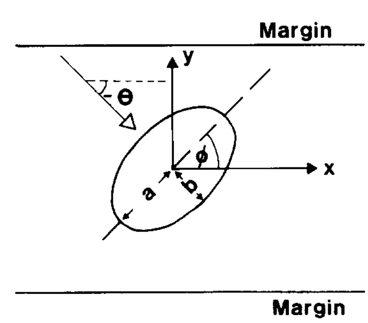

Fig. A1. Diagram illustrating the various parameters defined in Appendix I. The fixed axes have an origin in the centre of the elliptical float: x, y horizontal; z vertical. The orientation of the ellipse (principal dimensions a and b) is defined by ϕ, which is the angle between the long axis of the ellipse and the x axis. θ is the angle between the relative velocity vector and the margins (x axis). Negative θ (as shown) implies dextral shear and compression.

ous rotation rate about the z axis (clockwise is positive) can be described by the expression (Jeffery 1923, Lamb 1987):

$$d\phi/dt = -0.5(\partial u/\partial y)[((1 - k^2)/(1 + k^2)) \times (\cos 2\phi + \tan\theta \sin 2\phi) - 1], \quad \text{(A1)}$$

where $\partial u/\partial y$ is the vorticity vector (**w**) of the velocity field at a great distance from the ellipsoid, k is the horizontal aspect ratio of the crustal block (b/a, $a > b$), ϕ is the angle of the 'a' axis relative to the margins of the deforming zone, θ is the angle between the relative vector of motion and the margins of the deforming zone (Fig. A1). If $\theta = \pm 90°$, then the vorticity vector (**w**) is zero and equation (A1) becomes:

$$d\phi/dt = -0.5(\partial v/\partial y)\ ((1 - k^2)/(1 + k^2)) \sin 2\phi. \quad \text{(A2)}$$