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Tectonic rotation about the termination of a major strike-slip fault, Marlborough fault system, New Zealand

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Abstract. The Marlborough fault system comprises a series of major right-lateral strike-slip faults that link the Alpine fault to the Hikurangi subduction zone in the Pacific/Australia plate boundary zone in New Zealand. All of the major active faults of the Marlborough fault system have continuous traces except for the Clarence fault which terminates abruptly near the Ward syncline. Paleomagnetic data from upper Miocene and lower Pliocene sedimentary rocks between the Marlborough faults indicate a consistent post-early Pliocene regional clockwise rotation of about 20°. An additional rotation of about 10° is evident at many localities near the termination of the Clarence fault. It is proposed that the additional rotation, relative to the rest of the region, is caused by a velocity gradient that likely exists between the active Awatere fault and the termination of the Clarence fault. The existence of such a velocity gradient is consistent with inferences from geodetic strain data which suggest that one-third of the displacement in the Marlborough fault system occurs between the Awatere and Clarence faults. The kinematics of rotation can be modelled by treating the area as a rigid block that pivots about the termination of the Clarence fault. The block rotation model satisfies field constraints on the styles of deformation observed at the boundaries of the block and is consistent with available paleomagnetic and geodetic data.

Introduction

The Marlborough fault system of northeastern South Island, New Zealand, is one of the world's major strike-slip fault systems. The major faults of the Marlborough fault system include the Wairau, Awatere, Clarence, Kekerengu and Hope faults. These faults link the Alpine fault, which has a right-lateral displacement in excess of 500 km, to the Hikurangi subduction zone in the Pacific/Australia plate boundary zone (Fig. 1a). Relative plate motion is distributed across the Marlborough fault system, as indicated by fault displacements, crustal shortening and vertical axis rotations [*Walcott*, 1978].

Paleomagnetic data provide a means for investigating vertical axis rotations in zones of active continental deformation. Several models have been proposed to account for rotational deformation in the Marlborough fault system [e.g., *Merzer and Freund*, 1974; *Ron et al.*, 1984; *Lamb*, 1988; *Lamb and Bibby*, 1989]. However, these models were largely constructed prior to the acquisition of a significant paleomagnetic data set for the Marlborough region. Paleomagnetic data from this important strike-slip fault system are interpreted herein and a kinematic model that accounts for the rotational deformation is proposed.

Paleomagnetic data

Paleomagnetic data were obtained by *Roberts* [1992] from upper Miocene and lower Pliocene siliciclastic marine sedimentary rocks of the Awatere Group in an investigation of vertical axis rotations within the Marlborough fault system (Fig. 1; Table 1). At least six sites were sampled from each locality, over stratigraphic intervals of at least 50 kyr, to average secular variation of the geomagnetic field. At least three samples from each site were subjected to full stepwise thermal demagnetization and only samples with straightforward linear characteristic remanence components were used for determination of vertical axis rotations. Details of the sampling strategy and paleomagnetic analysis are given by *Roberts* [1992]. The stratigraphy and age of the sampled units are described by *Roberts and Wilson* [1992]. Age estimates of strata are based on foraminiferal biostratigraphic zonations which are partially constrained by magnetostratigraphic studies of the Awatere Group [*Roberts et al.*, 1994], as well as by correlation with the New Zealand biostratigraphic zonation of *Hornibrook et al.* [1989] which has been calibrated elsewhere by magnetostratigraphy. High rates of uplift in the plate boundary zone, and erosion of Cenozoic sedimentary rocks, severely restrict the distribution and number of localities from which useful data can be obtained (Fig. 1b,c).

The Marlborough fault system is contiguous with the Pacific plate and vertical axis rotations are reported with respect to the Pacific plate. Cenozoic paleomagnetic poles from the Pacific plate in the New Zealand region show no apparent polar wander [*Grindley et al.*, 1977], indicating no significant rotation relative to true north since 35 Ma. The rotation of a rock unit younger than 35 Ma in the Marlborough fault system is therefore equal to the mean paleomagnetic declination minus the axial dipole declination. Paleomagnetic declinations divergent from those expected from the stable Pacific plate are referred to as "declination anomalies" on Table 1 and are interpreted as rotations about a vertical axis. The average inclinations on Table 1 are generally indistinguishable from those expected for an axially geocentric dipole field, indicating that the effects of secular variation have been sufficiently averaged by the adopted sampling strategy [*Roberts*, 1992].

Consistent amounts of tectonic rotation are observed from upper Miocene and lower Pliocene sediments between the Wairau and Kekerengu faults (Fig. 1b). A zone of substantial active faulting and folding, comprising a number of fault-bounded blocks < 5 km across, exists immediately southeast of the Kekerengu fault [*Lamb and Bibby*, 1989]. Because of the small size of the fault-bounded blocks, it is unlikely that paleomagnetic data from this area are regionally significant. No rotation is evident further to the southeast from sites on the relatively less deformed Pacific plate, outside the Marlborough fault system (Fig. 1b). Paleomagnetic data from within the Marlborough fault system indicate a consistent regional clockwise rotation of ~ 20° relative to the Pacific plate (Fig. 2; Table 1). The same amount of rotation is indicated from 8 Ma and younger strata, implying that regional rotation post-

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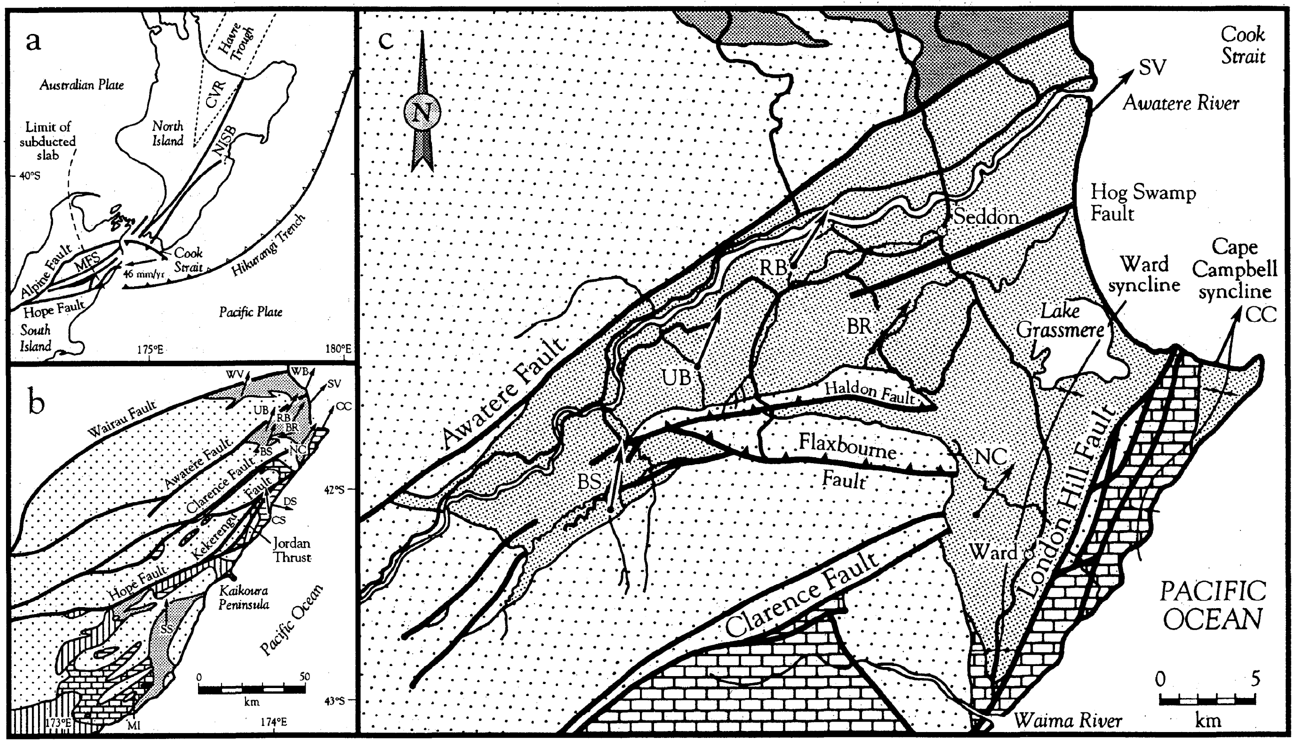


Figure 1. Maps showing: (a) geodynamic setting of New Zealand. NISB is the North Island Shear Belt; CVR is the Central Volcanic region and MFS is the Marlborough fault system. Arrow indicates direction and rate of convergence of the Pacific plate with respect to the Australian plate in the study area. (b) The major faults of the Marlborough fault system, sampling localities and amounts of vertical axis rotation relative to the Pacific plate (*cf.* Table 1; *Roberts*, 1992). Vertical lines: Quaternary alluvium; shading: upper Miocene and Pliocene siliciclastic sediments; block pattern: undifferentiated upper Cretaceous - Oligocene sediments; open stippled pattern: basement outcrop of the Torlesse Supergroup southeast of the Wairau fault; simplified after *Lensen* [1962] and *Gregg* [1964]. (c) The Lower Awatere Valley, modified after *Lensen* [1962]. Open stippled pattern: Jurassic Torlesse Supergroup basement; block pattern: undifferentiated upper Cretaceous - Oligocene sediments; light shading: upper Miocene - Pliocene Awatere Group sediments; dark shading: upper Miocene - Pliocene freshwater rocks of the Lower Wairau Valley. Arrows indicate vertical axis rotations. WB = White Bluffs; WV = Waihopai Valley; SV = Sea View; RB = Richmond Brook; UB = Upton Brook; BR = Blind River; CC = Cape Campbell; BS = Boundary Stream; NC = Needles Creek; DS = Deadman Stream; CS = Camp Stream; SS = Swamp Stream; MI = Motunau Island.

dates the early Pliocene (Fig. 2). Similarity in amounts of tectonic rotation in the area between the Wairau and Kekerengu faults (i.e., at Waihopai Valley, White Bluffs, Upton Brook, Boundary Stream and Cape Campbell; Figs 1b,c & 2) suggests that the area is rotating as a large rigid block, or at least as a series of crustal slivers with comparable amounts of rotation. The rigid block rotation model of *Ron et al.* [1984] has been adapted by *Lamb* [1988] and accounts reasonably well for the kinematics of the Marlborough fault system. However, the area east of the Awatere fault, and around the termination of the Clarence fault, appears to have been subjected to additional rotation of ~ 10°, as evident at Sea View, Richmond Brook, Needles Creek and Blind River (Figs 1c & 2). A second mechanism may therefore be responsible for rotations, in addition to the observed regional rotation.

Tectonic rotation about the termination of the Clarence fault

Offset late Quaternary topographic features and continuous fault surface traces indicate that all of the major faults of the Marlborough fault system are active. Seismic reflection profiles in Cook Strait (Fig. 1a) indicate that the Wairau and Awatere faults have detectable traces offshore, whereas the Hope fault does not [*Carter et al.*, 1988], even though it has a lateral slip rate of 20 mm/yr on segments of its onshore trace [*Van*

Table 1 Paleomagnetically determined tectonic rotation data from within the Marlborough fault system

Locality	Latitude, Longitude (°S, °E)	D[1] (°)	I[1] (°)	n/N[2]	κ[3]	α95 (°)	D Anomaly[4] D±δ (°)	Age (Ma)
Data from *Roberts* [1992]								
White Bluffs	41.54, 174.13	204.2	67.0	8/29	58.1	3.6	24±7	3.9±0.8
Waihopai Valley	41.63, 173.41	199.6	60.6	8/42	84.6	2.4	20±4	8±1
Sea View	41.63, 174.15	223.5	58.7	9/33	67.1	3.1	44±5	3.9±0.8
Richmond Brook	41.67, 173.99	211.6	61.8	11/25	56.5	3.9	32±7	4.2±0.6
Blind River	41.72, 174.03	212.6	59.5	32/132	37.5	2.0	33±3	4.8±0.2
Upton Brook	41.75, 173.88	201.3	59.0	28/132	48.2	1.8	21±3	4.8±0.2
Needles Creek	41.75, 174.10	215.4	59.8	7/31	61.1	3.5	35±6	5.4±0.6
Boundary Stream	41.83, 173.85	196.6	63.3	14/14	29.6	7.4	17±13	8±1
Data from *Walcott et al.* [1981]								
Cape Campbell	41.75, 174.25	024.4	-60.5	-	56.2	5.4	24±9	8±1

1. D and I are corrected for stratal tilt [*cf. Roberts*, 1992]; 2. n = number of sites, N = number of samples with stable demagnetization behavior; 3. Fisher's precision parameter; 4. Standard errors on declination anomalies are calculated after *Demarest* [1983].

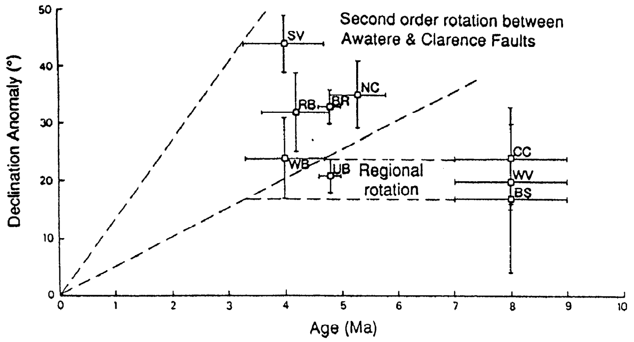


Figure 2. Rotational history of the area between the Wairau and Kekerengu faults, with respect to the Pacific plate. The same amount of rotation is indicated from 8 Ma and younger strata, implying that regional rotation post-dates the early Pliocene. Additional rotation is evident at localities between the Awatere and Clarence faults (SV, RB, BR, NC). Names of sampling localities are the same as in Figure 1.

Dissen and Yeats, 1991]. Instead, strike-slip displacement on the Hope fault is transferred to the more north-trending Jordan thrust (Fig. 1b), which has a lateral dip slip rate of 4 mm/yr [*Van Dissen and Yeats*, 1991]. The Clarence fault, however, which has a lateral slip rate of 4-8 mm/yr at places [*Van Dissen and Yeats*, 1991], terminates abruptly near the Ward syncline (Fig. 1c) where it fails to cut Neogene and Quaternary sediments [*Browne*, 1992].

The second-order rotation (Fig. 2) observed near the termination of the Clarence fault (Fig. 3a), can be accounted for by extending the rigid block model of *Lamb* [1988]. If right-lateral displacement of 4-8 mm/yr on the Clarence fault ceases near Needles Creek, but continues on the Awatere fault, then a velocity gradient will exist across the Lower Awatere Valley. Geodetic strain data, from repeated triangulation surveys over a period of one century, indicate that one third of the strain across the Marlborough fault system is accommodated between the Awatere and Clarence faults [*Bibby*, 1981]. It is proposed that this strain is due to a velocity gradient that results from significant displacement on the Awatere fault, relative to the termination of the Clarence fault. Furthermore, it is proposed that such a velocity gradient is responsible for differential rotation about the termination of the Clarence fault, relative to the rest of the region. The second-order rotation observed in the Lower Awatere Valley can be modelled by treating this area as either a zone of ductile simple shear or as a rigid block (Fig. 3b,c). The second-order rotation is observed in the Ward syncline (NC) but not in the Cape Campbell syncline (CC), thus the London Hill fault is inferred to be the eastern boundary of the area undergoing second-order rotation.

Ductile simple shear

If the Lower Awatere Valley is treated as a zone of ductile simple shear between the Awatere and London Hill faults (Fig. 3b), then it will be displaced a distance, s, relative to the London Hill fault. The shear strain, γ, is related to the angular shear strain, ψ, such that:

$$\gamma = \tan \psi, \tag{1}$$

$$s = z \tan \psi = z\gamma, \tag{2}$$

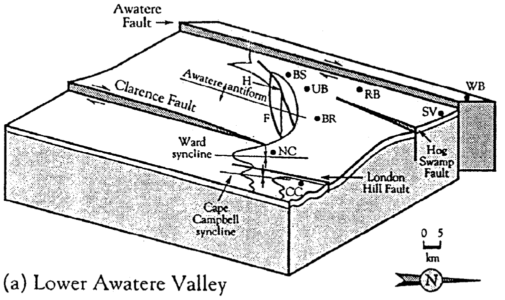
where z is the width of the shear zone [*Ramsay*, 1980]. The strain is a rotational strain, with the internal rotation, ω, given by:

$$\tan \omega = \gamma/2. \tag{3}$$

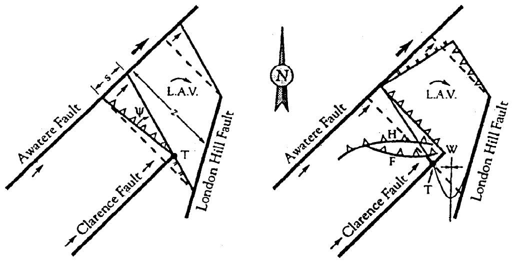
For a paleomagnetically determined internal rotation of ω = 10° and a shear zone width of z = 20 km, the angular shear strain will be ψ = 19° and the displacement of the Awatere fault relative to the London Hill fault will be s = 7 km. Lack of evidence of shear fabrics on an outcrop scale and lack of en echelon folds and other structures that would be expected for rocks that have experienced the calculated shear strains [*Ramsay*, 1980; *Sylvester*, 1988] suggest that penetrative simple shear is an unlikely mechanism for the observed differential rotations in the Lower Awatere Valley. Furthermore, the Esk Head Mélange, a Late Triassic to Early Jurassic marker unit, has been displaced by the Marlborough faults [*Siberling et al.*, 1988] and estimated offsets are about 16 km and 12 km, respectively, for the Awatere and Clarence faults. This provides further evidence against the ductile simple shear model and its predicted 7 km relative displacement between the Awatere and London Hill faults.

Rigid block rotation

Differential rotation of ~ 10° is more readily explained by treating the Lower Awatere Valley as a rigid block that pivots about the termination of the Clarence fault. In this model, displacement on the Awatere fault, relative to the Clarence fault, causes the block between the faults to move northeastwards, resulting in rotation of the Lower Awatere Valley about T, the termination of the Clarence fault (Fig. 3c). The different styles of deformation expected at the boundaries of a rigid rotating block are evident in the Lower Awatere Valley (Fig. 3c). Shortening between the Awatere and Clarence faults is accommodated by the Haldon and Flaxbourne thrust faults.



(a) Lower Awatere Valley



(b) Simple Shear Model (c) Rigid Block Model

Figure 3. Simple mechanical models for second-order rotations between the Awatere and Clarence faults. (a) Block diagram with structural features of the Lower Awatere Valley (L.A.V.) and localities studied (F and H = Flaxbourne and Haldon thrust faults). Names of sampling localities are the same as in Figure 1. (b) Map view of model in which ductile simple shear across the L.A.V. gives rise to differential rotations. Arrows indicate overall kinematics of model. Teeth indicate shortening and short double lines indicate extension. ψ, s, and z indicate angular shear strain, displacement on the Awatere fault relative to the termination of the Clarence fault, and the width of the shear zone, respectively (see text). T = termination of Clarence fault. (c) Map view of model in which the L.A.V. rotates as a rigid block (see text). Symbols are the same as in (a) and (b).

These faults are buried in the Medway Valley area (where the additional rotation is not observed at Boundary Stream and Upton Brook; Fig. 1c), but they cut upper Miocene strata in the Haldon Hills area [*Lensen*, 1962; *Roberts and Wilson*, 1992], where they have a distinctly different orientation. These faults may therefore have been reactivated in the Pliocene to take up relative displacement between the Awatere and Clarence faults. Shortening would also be expected between the Clarence and London Hill faults, as observed in folded strata of the north-northeast trending Ward syncline. Reverse faulting on the northern part of the London Hill fault would also be consistent with such a pattern of deformation, although the sense of displacement on this fault is unknown. There is little structural control in the north of the Lower Awatere Valley, but extensive normal faulting has been observed by the author along the lower reaches of the Awatere River and along the coast, south of the Awatere fault. This observation is consistent with the deformation predicted by the rigid block rotation model (Fig. 3c), but no structural analysis of the normal faults is presently available. Additional differential rotation may have occurred between the Awatere and Hog Swamp faults, as evident in the highest rotation recorded in this study (44°±5°) at Sea View (i.e., ~ 20° differential rotation).

Discussion and conclusions

Lamb [1988] and *Lamb and Bibby* [1989] used geodetic data and fault slip rates to estimate the angular velocities of crustal blocks in the Marlborough fault system. If the geodetic data can be extended back in time, the calculated velocities indicate that a regional rotation of about 20° should have occurred in the last 4 Ma, and that north-south shortening on the Haldon and Flaxbourne thrust faults could give rise to additional rotation. Acquisition of paleomagnetic data by *Roberts* [1992] and the structural interpretation presented here confirm this model. The rigid block rotation model presented here is kinematically similar to that proposed for the whole of the Marlborough fault system by *Lamb and Bibby* [1989] and accounts well for the available paleomagnetic, geodetic and structural evidence. A similar model has been proposed to account for the rotational kinematics of blocks with dimensions of several tens of kilometers in zones of strike-slip faulting in California [*Nicholson et al.*, 1986].

Towards the termination of the Clarence fault, the slip rate of 4-8 mm/yr appears to be accommodated by uplift, folding and thrust faulting [*Browne*, 1992], large shear strains [*Bibby*, 1981] and block rotations [*Roberts*, 1992] as well as alternating styles of deformation, including transtension and transpression, along the edges of the rotating block. *Browne* [1992] suggested that the Clarence fault becomes a blind thrust towards its termination and that slip is taken up by folding in basement rocks: a mechanism consistent with the model proposed here. *Van Dissen and Yeats* [1991] suggested a mechanically similar model whereby transfer of right-lateral slip from the Hope fault gives rise to folding and uplift of the Seaward Kaikoura Range on the Jordan thrust fault.

Paleomagnetic data provide important insights into the kinematics of the observed deformation in the Marlborough fault system, additional to those obtained from structural and geodetic studies. Vertical axis tectonic rotation is clearly an important component of the deformation associated with termination of displacement on the Clarence fault.

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