New Zealand Journal of Geology & Geophysics, 2002, Vol. 45: 537–547
0028–8306/02/4504–0537 $7.00/0 © The Royal Society of New Zealand 2002

Tectonic significance of Cretaceous bivergent extensional shear zones in the Torlesse accretionary wedge, central Otago Schist, New Zealand

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Abstract We describe two shear zones in the Otago Schist of the Torlesse accretionary wedge, South Island, New Zealand: the north-dipping Rise-and-Shine Shear Zone (RSSZ) and the south-dipping Cromwell Gorge Shear Zone (CGSZ). Kinematic indicators (shear bands and asymmetric folds) indicate top-north movement for the RSSZ and top-south transport for the CGSZ. Back rotation of the shear zones into their Late Cretaceous orientation and consideration of the relationship of the shear zones to arching of the Otago Schist show that both shear zones are extensional. Offset of textural zones suggests up to 15 km of dip-slip displacement on the RSSZ and probably a similar amount of slip for the CGSZ. We speculate that the gold-mineralised RSSZ may be the western continuation of the late Mesozoic gold-bearing Hyde-Macraes Shear Zone in eastern Otago, forming a c. 100 km long extensional shear zone on the northern flank of the Otago Schist. Age constraints suggest that shear zone formation took place between 135 and 105 Ma. The shear zones aided the final exhumation of the deeper parts of the Otago Schist. We discuss whether normal shearing is related to syn-orogenic supercritical tapering of the Torlesse wedge, or due to post-orogenic New Zealand-wide Albian rifting.

Keywords normal fault; accretionary wedge; rifting; Torlesse Terrane; Dunstan Range; Otago Schist; New Zealand

INTRODUCTION

The role of syn-orogenic normal faulting in ancient and modern accretionary wedges related to ocean-continent subduction remains a controversial topic. The Hikurangi subduction zone in the North Island of New Zealand is an example where orogen-parallel extensional faults occur in the forearc (Pettinga 1982; Walcott 1987). However, the magnitude of extension accommodated by the listric normal faults is only 1–5% (Cashman & Kelsey 1990). Syn-orogenic normal faulting has also been proposed along the so-called Coast Range fault of the Franciscan subduction complex (Platt 1986; Harms et al. 1992). The tectonic juxtaposition of low-grade rocks above higher grade rocks was used as the major evidence for normal faulting. But subsequent work by Wheeler & Butler (1994), Ring & Brandon (1994), and Ring (1995) showed that this evidence is not conclusive, and Ring & Brandon (1994, 1999) and Bolhar & Ring (2001) showed that the Coast Range fault is an out-of-sequence thrust. Other well-studied accretionary wedges, such as the Olympic subduction complex at the North American west coast, also show no evidence for normal faulting (Brandon et al. 1998).

Frontal accretion and erosion both tend to promote horizontal contraction across an orogen. This case is well illustrated by the strain calculations in Dahlen & Suppe (1988). Horizontal extension may occur in the rear part of an accretionary wedge thickened by underplating (Platt 1986). But horizontal extension need not necessarily be expressed by normal faulting in the upper rear part of the wedge; it may also be accommodated by vertical ductile thinning related to a subhorizontal foliation. Thus, a large amount of vertical ductile thinning tends to suppress normal faulting. Flow fields that give rise to horizontal extension in the rear of accretionary wedges develop when the rate of frontal accretion and erosion at the rear of the wedge are small, and when the rate of underplating is dominantly controlling the flow field in the wedge (Platt 1986, 1993; Brandon & Fletcher 1998).

Before c. 105 Ma, the New Zealand part of the south Gondwana margin was a subduction zone along which continental growth took place by terrane accretion and arc-related magmatism (Mortimer et al. 1999) (Fig. 1A). The older Torlesse (Rakaia) Terrane and the Caples Terrane comprise greywacke of Permian–Triassic stratigraphic age and are thought to have been deformed in a Jurassic–Cretaceous accretionary wedge (MacKinnon 1983; Korsch & Wellman 1988). Albian (c. 105 Ma) graben development (Ballance 1993; Laird 1993) is related to the separation of New Zealand from Australia and Antarctica. This post-subduction rifting phase culminated in seafloor spreading in the Tasman Sea at c. 85 Ma (e.g., Korsch & Wellman 1988).

In this paper we present new field and petrographic data from the Rise-and-Shine and Cromwell Gorge Shear Zones (RSSZ, CGSZ) in the Torlesse accretionary wedge of central Otago. The RSSZ and also the Hyde-Macraes Shear Zone of eastern Otago (Fig. 1B) have previously been regarded as late subduction-related thrusts (e.g., Teagle et al. 1990; Winsor 1991). Nonetheless, our data show that the RSSZ and the CGSZ are net normal-sense shear zones. The age of shear zone formation is not well constrained, which makes it speculative to relate normal shearing to either late-accretionary destabilisation of the Torlesse wedge during ongoing convergence or to post-accretionary rifting.

G01024; published 6 December 2002
Received 1 August 2001; accepted 8 July 2002

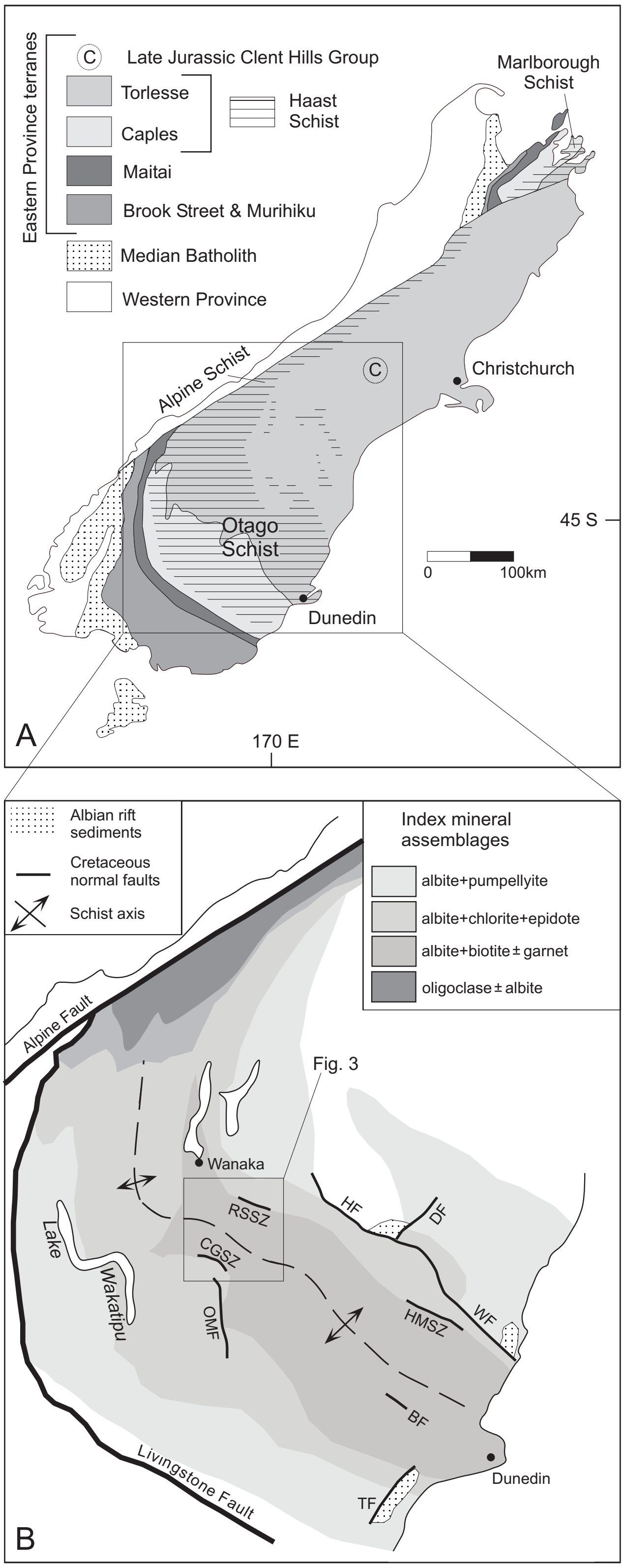


Fig. 1 **A**, Simplified geological map of pre-Late Cretaceous basement, South Island, New Zealand (after Mortimer et al. 1999). Haast Schist Belt is subdivided into Marlborough, Alpine, and Otago Schist. **B**, Map of the Otago Schist showing metamorphic grade, Cretaceous normal faults and shear zones, and Albian graben sediments (after Mutch & Wilson 1952; Bishop & Laird 1976; Mortimer 1993, 2000). HF, Hawkdun Fault; DF, Dansey Pass Fault; WF, Waihemo Fault; BF, Barewood Fault System; TF, Titri Fault; OMF, Old-Man Fault; HMSZ, Hyde-Macraes Shear Zone; CGSZ, Cromwell Gorge Shear Zone; RSSZ, Rise-and-Shine Shear Zone.

GEOLOGICAL SETTING

The terranes of the South Island of New Zealand can be divided into two major provinces (Fig. 1A). (1) The Western Province, consisting of Cambrian–Devonian terranes with local Permian–Triassic sedimentary cover, are considered to have been part of Gondwana since the mid Paleozoic (Mortimer & Campbell 1996). (2) The Eastern Province, consisting of Carboniferous–Cretaceous terranes, is interpreted to have been accreted to the Gondwana margin from the Triassic through the Cretaceous (e.g., MacKinnon 1983; Korsch & Wellman 1988; Mortimer & Campbell 1996). The two provinces are separated by the Median Batholith (Mortimer et al. 1999; Turnbull 2000), a Cordilleran-type magmatic arc that represents the major locus of Carboniferous to Early Cretaceous magmatism in New Zealand. Magmatic pulses in the Median Batholith can be related to subduction of the oceanic Pacific plate underneath southern Gondwana (Mortimer et al. 1999).

The Haast Schist in New Zealand's South Island is subdivided into the Otago, Alpine, and Marlborough Schist (Fig. 1A). The Otago Schist is a moderately high pressure metamorphic belt (Yardley 1982; Mortimer 2000), which formed by amalgamation of the Eastern Province Caples and Torlesse Terranes during the "Rangitata I" Orogeny in the Early–Middle Jurassic (Bradshaw et al. 1981; Adams & Robinson 1993; Little et al. 1999). The Otago Schist provides a view into the deeper part of the Torlesse accretionary wedge and forms a c. 150 km wide, two-sided arch. Metamorphism increases from prehnite-pumpellyite facies in the non-schistose rocks at the periphery of the arch to greenschist facies with peak metamorphic temperatures and pressures of 350–400°C and 8–10 kbar near the culmination axis in the deepest level of present exposure (Mortimer 2000) (Fig. 1B). Accompanying increasing metamorphism, there is an increase in deformation towards the centre of the Otago Schist as defined by the progressive development of fold generations and foliation transposition. Hutton & Turner (1936), Bishop (1972), Turnbull (2000), Forsyth (2001), and Turnbull et al. (2001) used meso- and microscale textural changes in the schist to define up to six different textural zones (TZs), which parallel the metamorphic and deformational changes across the Otago culmination. Textural zone discontinuities are the best indicators of postmetamorphic faults in the otherwise monotonous rocks of the Otago Schist (Craw 1998).

Exhumation of the Otago Schist either occurred very slowly and continuously at a rate of c. 0.2 km/m.y. from 190 to 110 Ma (Adams et al. 1985; Adams & Robinson 1993) or was punctuated by a phase of more rapid exhumation at rates of 0.6–1.0 km/m.y. after 135 Ma (Little et al. 1999). Deeply buried rocks in the Torlesse wedge reached the surface at c. 105 Ma during the initial rifting phase. This is indicated by the first appearance of schist fragments in the Kyeburn Formation (Korsch & Wellman 1988; Adams & Raine 1988). The Kyeburn Formation, together with the Horse Range Formation and the Henley Breccia, was deposited in Albian rift-related graben on the Otago Schist (Fig. 1B); similar graben are found throughout the New Zealand terranes (Ballance 1993; Laird 1993). Rifting is manifested as half graben in the Eastern Province terranes and magmatism and metamorphic core complex development in the Western Province (Tulloch & Kimbrough 1989).

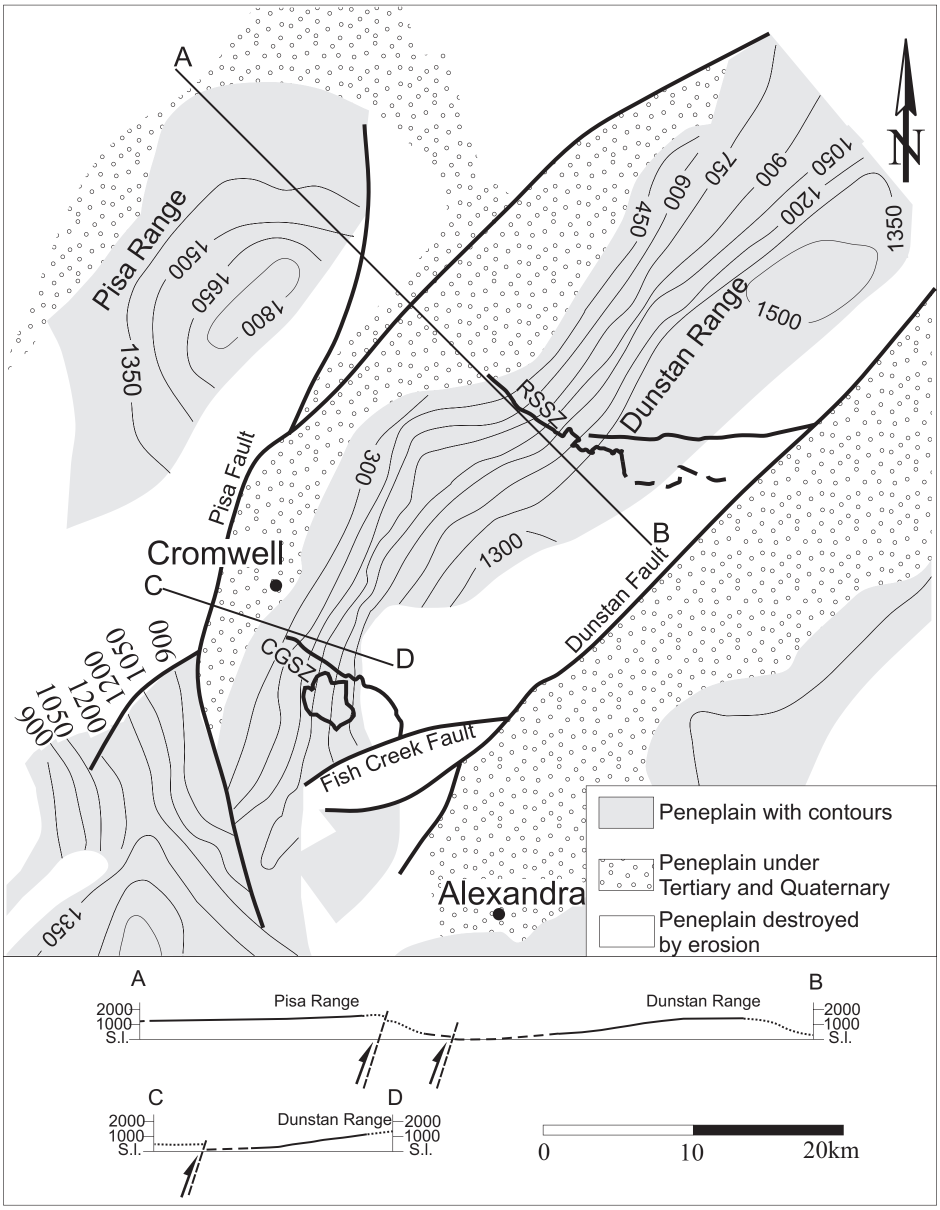


Fig. 2 Map showing the Otago peneplain with contours in Dunstan Mountains (modified after Bishop 1994 and Turnbull 2000). Cross-sections show Neogene deformation of the peneplain.

This deformation has been referred to as "Rangitata II" Orogeny (Bradshaw et al. 1981) and arguably is the oldest geological event common to all New Zealand basement terranes.

Widespread erosion of the Otago Schist and also the Albian graben sediments resulted in peneplanation of much of the southern South Island. The Waipounamu Erosion Surface is probably composite and time transgressive (Bishop 1994; LeMasurier & Landis 1996). A prominent unconformity at the base of Haumurian (c. 85 Ma) sediments in northern and offshore South Island is thought to be a lateral equivalent of the Waipounamu Erosion Surface (Crampton et al. 1999), and can be used to date the initial formation of the erosion surface between 105 and 85 Ma. Miocene–Recent deformation related to formation of the Alpine Fault folded the Waipounamu Erosion Surface and gave central and east Otago its present basin-and-range topography (Cotton 1917; Bishop 1994; Jackson et al. 1996; Turnbull 2000; Forsyth 2001) (Fig. 2).

POSTMETAMORPHIC SHEAR ZONES IN THE OTAGO SCHIST

Postmetamorphic shear zones in the Otago Schist are of interest for two main reasons: (1) as hosts of gold mineralisation (e.g., Winsor 1991); (2) as structures that might shed light on the exhumation history of the Torlesse accretionary wedge. The best studied low-angle shear zone in the schist is the northeast-dipping, gold-mineralised Hyde-Macraes Shear Zone in east Otago (Fig. 1B) (Teagle et al. 1990; Winsor 1991; Craw et al. 1999; De Ronde et al. 2000; Forsyth 2001). Kinematic studies of the shear zone have shown that late- to postmetamorphic thrusting was followed by a period of normal faulting (Teagle et al. 1990; Angus 1992). The gold mineralisation in the Hyde-Macraes Shear Zone took place between 132 and 158 Ma (Adams & Graham 1997).

The large-scale structure of the Otago Schist in the southern Dunstan Range (Fig. 3, 4) is dominated by a

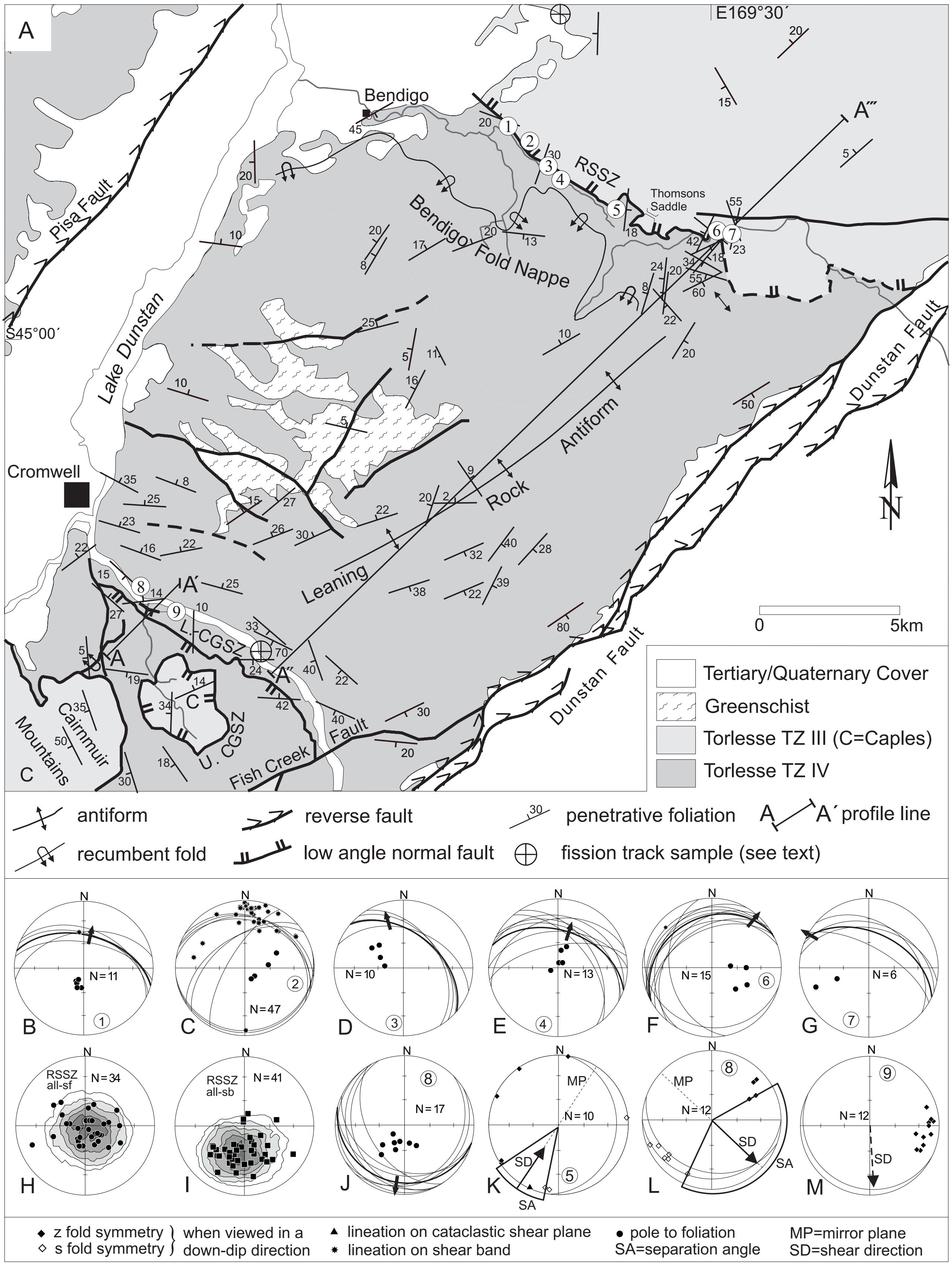


Fig. 3 Penetrative foliation, shear bands, and asymmetric folds along the Cromwell Gorge and Rise-and-Shine Shear Zones (CGSZ and RSSZ). **A**, Geological map of the Dunstan Range area showing the Cretaceous–Neogene fault pattern and textural zones (modified after Turnbull 1987, 2000; Mortimer 1993) and zircon and apatite fission track samples (Tippett & Kamp 1993). **B–G, J**, Stereograms showing shear bands (great circles), foliation (dots), the calculated mean direction of all shear bands measured in an outcrop (bold great circles) and the calculated mean displacement direction of the hanging wall (arrows) (equal area, lower hemisphere projections, corresponding to localities 1–4 and 6–8 on map). **H, I**, Contouring (Kamb method) of foliations and shear bands at the RSSZ. **K–M**, Stereographic projection of fold axes from asymmetric folds along the RSSZ and CGSZ (localities 5, 8, 9); great circles represent measured fault planes.

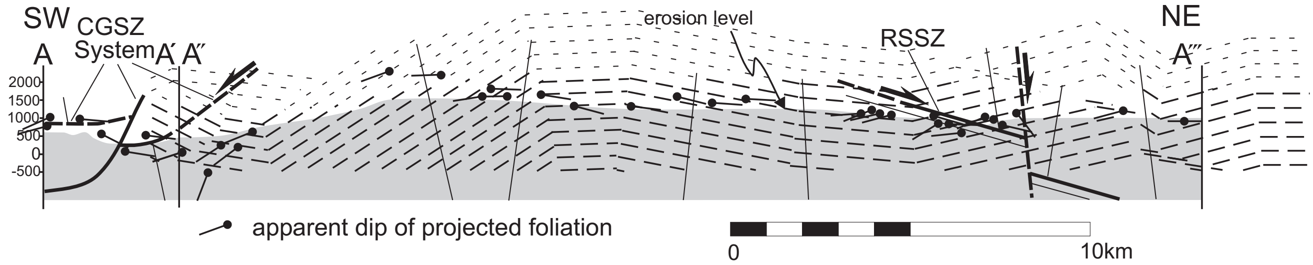


Fig. 4 Cross-section through the Dunstan Range along the Leaning Rock Antiform, based on a kink band model using foliation planes shown in Fig. 3A (only data near the section line were used). All used foliation planes were projected onto the section plane except the foliations from the Caples klippe in the south. Thin solid lines represent axial-plane orientations which separate different dip domains; dashed lines show projected trace of foliation above erosion level. Change of dip direction directly in the footwall of the RSSZ is due to drag of foliation into the shear zone.

subhorizontal regional foliation which is folded about the c. north–south trending, broad, open, doubly plunging Miocene–Recent Leaning Rock Antiform (Turnbull 1987, 2000; Mortimer 1993). Before the development of the Leaning Rock Antiform, the regional foliation was folded by the Bendigo fold nappe and minor related folds that are regionally classified as F3 (Craw 1985). The gold-bearing brittle-ductile RSSZ in the northern part of the Dunstan Range in central Otago is c. 10–50 m in thickness and was previously mapped in detail by Corner (1988) and Grieve (1997), and at 1:250 000 scale by Turnbull (2000). The brittle-ductile CGSZ in the Cairnmuir Mountains is a southwest-dipping, >400 m wide system of faults on the southern side of Cromwell Gorge (Fig. 3, 4) (Turnbull 1987). The CGSZ and RSSZ are strongly localised features in the Otago Schist and crosscut older ductile F3 folds and the regional foliation. Thus, the two shear zones are not related to the general strain field in the Otago Schist, which is characterised by strong vertical shortening and the development of the subhorizontal foliation. Relative finite-strain work in conglomerate, sandstone, and mudstone indicates up to 70% of vertical shortening in the Otago Schist resulting in a generally oblate strain symmetry (Norris & Bishop 1990; Maxelon et al. 1998; Deckert et al. 2002).

Our structure contour data for the RSSZ indicate an average shear zone orientation of 025/15 (dip direction and dip) (Fig. 4). The constant orientation of the RSSZ across the projection of the Leaning Rock Antiform suggests a planar geometry. The shallowly south dipping foliation in the immediate footwall of the RSSZ might be explained by an antithetic rotation of the foliation.

The CGSZ is mainly characterised by a c. 10 km long fault (lower CGSZ), which changes dip from subhorizontal in the east to c. 60° south dipping in the western part. A listric shape of the CGSZ is suggested by the fact that if the eastern part of the CGSZ is a non-listric fault it should reappear in the higher Dunstan Mountains to the north of the Cromwell Gorge due to its planar geometry. However, this is not the case (Fig. 3). The lower CGSZ cuts a subhorizontal subsidiary shear zone in its footwall, which also belongs to the CGSZ system. In this subsidiary shear zone, kinematic indicators such as asymmetric folds and shear bands were mapped (Fig. 3).

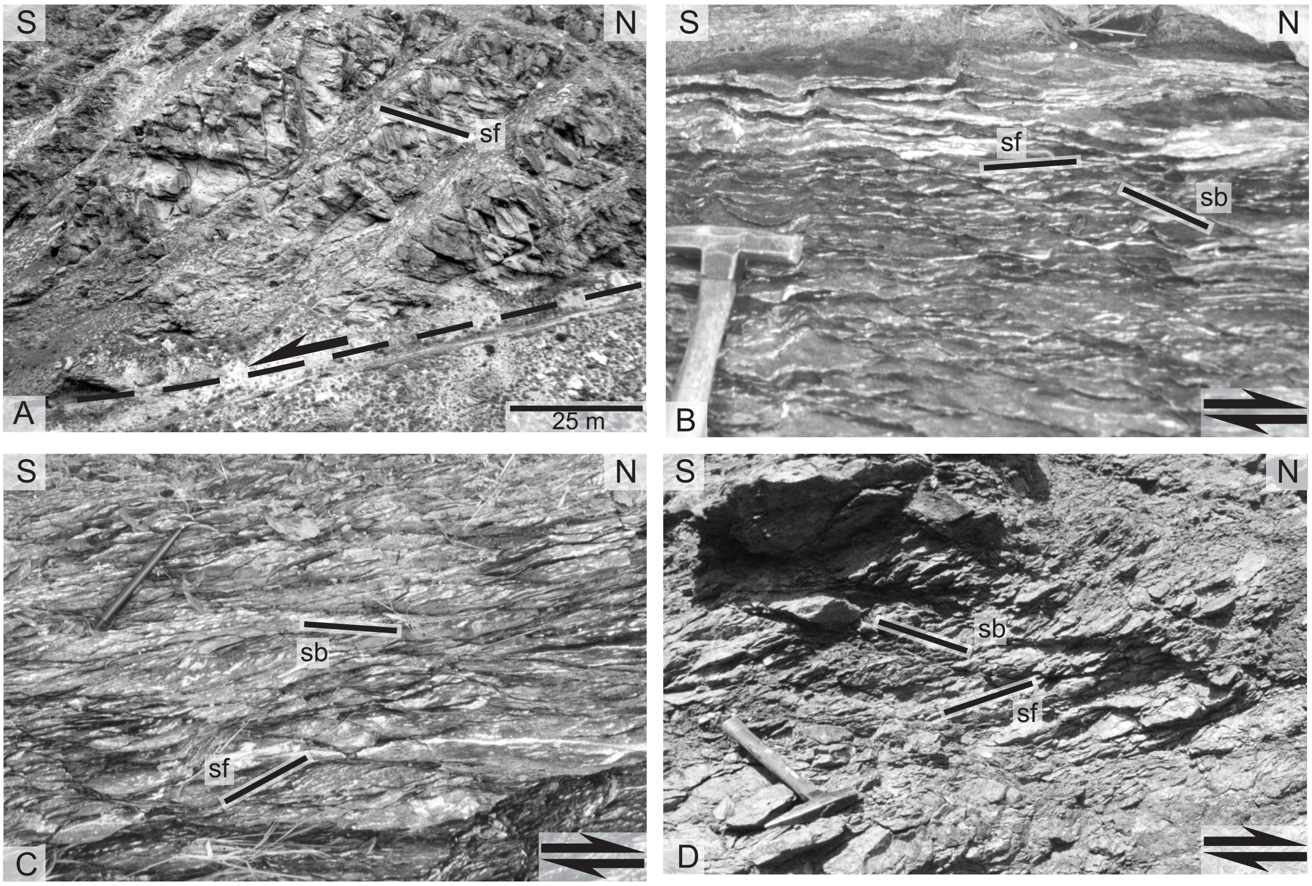
The foliation within the CGSZ system dips shallowly to the north (Fig. 4). Steeply south dipping synthetic branch faults are responsible for the antithetic rotation of the foliation to the north (Fig. 5A). About 400 m above the lower CGSZ there is the flat-lying upper CGSZ fault that underlies a klippe of Caples Terrane schist. We suggest that the whole CGSZ system comprises a set of several listric normal faults (Fig. 4).

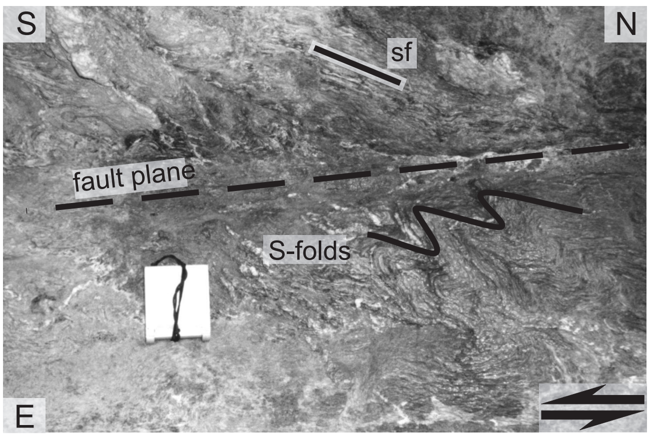
The lack of suitable marker horizons has hindered an estimation of the displacement across intraschist faults. Mortimer (2000) suggested that the RSSZ, CGSZ, and Hyde-Macraes Shear Zone could all be significant metamorphic discontinuities, with garnet-biotite-albite-zone rocks in their footwalls and chlorite-zone rocks in their hanging walls (Fig. 1B).

Displacement estimates

We studied the RSSZ for 15 km along strike. Our observations indicate that there is a textural zone break from TZIII to TZIV across the RSSZ (Turnbull 2001; for photomicrographs see Mortimer 2001, fig. 3). Three TZIII rocks collected from the hanging wall have an average white-mica grain thickness of c. 20 µm, pelitic schist segregation thickness of c. 1 mm, and a psammite-pelite layering still visible as sharply bounded grey and black bands. In contrast, three footwall rocks along the RSSZ are TZIV with an average white-mica grain thickness of c. 40 µm, a pelitic schist segregation thickness of 5–10 mm, and psammite-pelite differences blurred into gradational massive and layered schist. A recent review and revision of textural zones in Otago by Turnbull et al. (2001) has emphasised the progressive, irreversible five-fold increase in white-mica grain size between TZIIA and TZIV schist. Mortimer (2001) has provisionally correlated the grain-size increase with a relative structural depth parameter in the Otago Schist. Based on this relationship, and assuming horizontal isotects in the Dunstan Mountains (Mortimer 1993), the observed differences of 20 µm in white mica grain size (textural grade) suggest net excision of at least c. 2 km and possibly up to c. 4 km of schist section across the RSSZ. Dip-slip movement on a 15°-dipping fault (Fig. 4, see below) yields a total net displacement of c. 8–15 km for the RSSZ.

A textural zone break from TZIII to TZIV was also mapped across the upper CGSZ by Turnbull (1987). Therefore, we suggest a similar excision for the CGSZ as for the RSSZ, but because of the different dips of the individual CGSZ structures, the net displacement across the whole shear zone cannot be estimated.





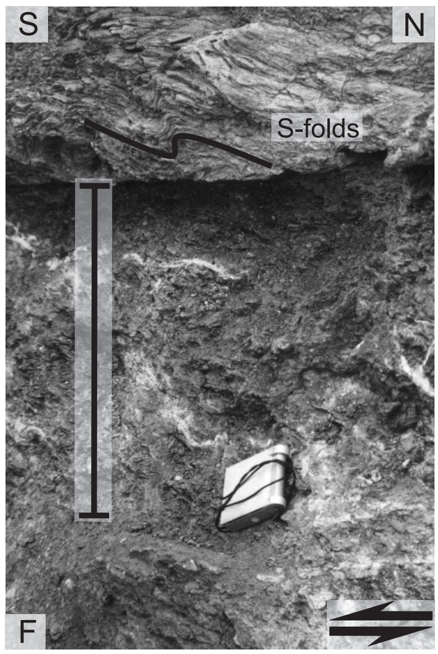


Fig. 5 Structures documenting opposite shear sense along the RSSZ and CGSZ. **A**, Shallowly dipping brittle shear zone in the CGSZ with top-to-south shear sense and c. 45° south-dipping synthetic branch faults (from upper right to lower left) curving into the major fault. Foliation is dipping towards the north due to antithetic rotation during faulting; photograph has been taken at locality 9 in Fig. 3. **B–D**, Mesoscale shear bands in pelitic and psammitic outcrops in the RSSZ, foliation (sf) curves into the shear bands (sb) indicating top-north displacement; photographs in B and C have been taken at locality 6 and the photograph in D at locality 2 in Fig. 3. **E, F**, Cataclastic shear zones in the CGSZ; asymmetric folds (here S-shaped) show top-south shear; photographs have been taken at localities 2 and 8, respectively; bar in F marks a c. 50 cm thick gouge layer.

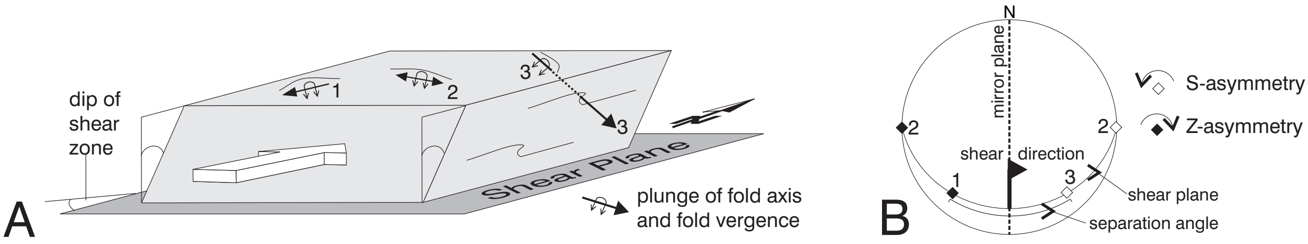


Fig. 6 Diagram illustrating relationship between asymmetric folds and shear direction (after Cowan & Brandon 1994). **A**, Material deformed in a ductile shear zone under progressive simple shear. Hinge lines of asymmetric folds are generally parallel to the shear plane, but may have different orientation within that plane. **B**, Hinge lines 1–3 from Fig. 6A are plotted in a lower hemisphere stereogram. The sense of asymmetry is assigned on the form of a fold when viewed in a down-plunge direction. Fold axes lie on a great circle that parallels the shear plane. Fold axes plot as two distinct groups, with Z-folds in one group and S-folds in the other. The separation angle is defined by the gap between these groups. The shear direction lies within the separation angle. See text for further information.

KINEMATICS OF THE SHEAR ZONES

Shear bands

We use the term shear band in the sense of C´-type shear bands of Berthé et al. (1979) and extensional crenulation cleavage according to Platt & Vissers (1980). In contrast to C-type shear bands, which are parallel to the shear zone, C´-type shear bands enclose an angle of 15–35° to the shear zone boundaries (Passchier & Trouw 1996). Shear-band orientations were collected from six outcrops of strongly foliated TZIV metapelites and psammites in the footwall of the RSSZ (Fig. 3A). One outcrop was studied in the CGSZ. The shear bands only occur in the shear zones and crosscut the foliation at relatively steep angles of 30–40° (Fig. 5B–D). At each locality, we measured the orientation of shear bands and foliations. If possible, the lineation on a shear band, which is assumed to trace the slip direction, was also recorded. The lineation measured in the outcrops is defined by stretched pre-existing grains. In pelitic layers no lineations were found. This can be explained by the initial fine grain-size of the parent rocks that hinders the development of stretching lineations during deformation (Piazolo & Passchier 2002). In this case the shear direction was assumed to be the intersection lineation between the great circle of the shear band and a constructed great circle that is defined by the pole of the shear band and the pole of the regional foliation. The sense of shear was deduced by the offset across the shear bands.

We can rule out significant later rotation and reorientation of shear bands and foliation in the studied shear zones because all post-shear-zone deformation resulted in strongly localised brittle faulting at the range fronts and large-scale warping of the Otago Schist.

Almost all measured shear bands along the north-dipping RSSZ dip at c. 45° to the north. The shear directions vary from 300 to 040° and indicate a top-north movement at the RSSZ (Fig. 3B–G). The contouring of all data at the RSSZ shows that the modal foliation is subhorizontal and the shear-band mode dips at 45° to the north (Fig. 3H, I).

In the studied outcrop of the south-dipping CGSZ, all shear bands are shallowly south dipping (Fig. 3J). The shear bands again have an angle of c. 45° to the moderately north dipping regional foliation. The geometric relationship between foliation and shear-band orientations suggests a top-south shear sense, which is opposite to that of the RSSZ.

Asymmetric folds

Both shear zones contain several zones of fault gouge up to 50 cm thick. Within a distance of up to 1 m from the gouge layers, the schist is folded into asymmetric tight to semi-open folds with amplitudes ranging from a few centimetres to a few decimetres (Fig. 5E, F). The angular profiles of the folds and their spatial relationship to the shear zones distinguish them from the rounded F3 folds outside the shear zones. The shear zones and related fault gouges cut F3 folds and therefore provide robust crosscutting relationships.

The method of Hansen (1971) (or internal-rotation-axis method of Cowan & Brandon 1994) was used to deduce the average direction and sense of shear from the asymmetric shear zone related folds. The method is based on the fact that layers in sheared rocks may form asymmetric folds, which reflect the sense of shear during deformation (Fig. 6A). The sense of asymmetry is used to distinguish between clockwise and anticlockwise asymmetry, or a Z and S shape of the fold, when viewed in the down-plunge direction of the fold axis. The axes of the S- and Z-folds are expected to lie on a great circle representing the shear plane in which they formed, and are distributed in two groups, separated from each other by the separation angle and a related mirror plane (Fig. 6B). The shear direction can be determined from the intersection of the shear plane (average girdle of S and Z axes) and the mirror plane. An important assumption is that the final deformation fabric has a monoclinic symmetry, defined by the mirror plane (Cowan & Brandon 1994). The slip vector is interpreted to indicate the average direction and sense of tectonic transport of the hanging wall relative to a fixed footwall (Cowan & Brandon 1994).

In the RSSZ, one outcrop with shear zone related S- and Z-folds with subhorizontal axes was analysed (Fig. 3K). The separation angle lies between 190 and 235°, which is supported by one measurement of a stretching lineation at this locality. Fold asymmetries indicate a top-north shear.

In the CGSZ, two outcrops were analysed (Fig. 3L, M). At locality 8 (in Fig. 3A), northeast-plunging axes of Z-folds and southwest-plunging axes of S-folds define a shear plane which parallels the shear-zone boundaries and supply a top-southeast sense of shear. At locality 9 (in Fig. 3A), only Z-folds are present. Therefore, a determination of the shear direction is not possible. If a 90° angle between the fold axes and the transport direction is assumed, top-south shear would be implied. It is possible that the fold axes are somewhat rotated into the shear direction, which would imply a more southeasterly shear direction, as has been deduced at locality 8.

DISCUSSION

Thrusting versus normal faulting

The structural data show a consistent top-north shear sense for the north-dipping RSSZ and a top-south/southeast shear sense for the south-dipping CGSZ. However, to attribute the data to thrusting or normal faulting, the orientation of the shear zones and the related shear bands relative to the Earth's surface at the time of shearing has to be established (cf. Wheeler & Butler 1994).

It is not clear if the shear zones formed before, during, or after folding of the Otago Schist into the 150 km wide regional arch. A pre- to syn-arching formation implies a modification of the dip of the shear zones by arching. Foliation thickness isopachs (Mortimer 2001) can be used as markers of folding. Their unfolding along the east–west-trending anticlinorium axis that lies between the RSSZ and the CGSZ suggests a rotation of the shear zones of c. 5° to the north in the northern part, and to the south in the southern part of the Dunstan Mountains. Back rotation does not change the dip direction of the RSSZ, that is, it remains a normal fault. The subhorizontal eastern part of the CGSZ would be slightly tilted (≤5°) to the north, resulting in a top-south thrust geometry. However, thrust faulting is in contrast to the observed synthetic high-angle normal faults that merge into the CGSZ (Fig. 3, 5A).

Thus, we favour post-arching formation of the shear zones. If so, the shear zones cut across arched isotects and isograds. This would render our assumption of horizontal isotects (see section on displacement estimates) wrong. However, as shown above, arching caused only c. 5° of rotation and in the Dunstan Range, therefore our estimates are not significantly affected by this small rotation. Nonetheless, later rotation caused by Cenozoic deformation must be taken into account. The Waipounamu Erosion Surface can be used as a proxy for pre-Miocene (and possibly pre-Cenozoic) paleohorizontal. The dip of the peneplain is c. 7° to the WNW in the Dunstan Range (Turnbull 2000; Fig. 2). Rotation of the shear zones and related shear bands by 7° about a NNE-trending axis does not change their orientations significantly and shows that both the RSSZ and CGSZ remain low-angle normal faults rather than tilted thrust faults. This is compatible with the observed map pattern of texturally and metamorphically low-grade rocks structurally above higher grade rocks. We found no unequivocal evidence for an earlier thrusting event along the two studied shear zones as has been postulated for the Hyde-Macraes Shear Zone.

Correlation of extensional shear zones in the Otago Schist

Current kinematic interpretations of the Hyde-Macraes Shear Zone emphasise thrusting (Teagle et al. 1990; Winsor 1991) and a later normal sense reactivation of the fault (Angus 1992). These 20th century studies did not take differences in metamorphic and textural grade of the hanging wall and footwall into account. We note that the dip and the brittle-ductile deformation style of the Hyde-Macraes Shear Zone and the RSSZ are similar. Both shear zones are mineralised, and coincide with a textural and metamorphic break separating TZIII chlorite-zone rocks in the hanging wall from TZIV garnet-biotite-albite-zone rocks in the footwall (Turnbull 2000; Mortimer 2000; Forsyth 2001). As with the RSSZ, a rotation of the Hyde-Macraes Shear Zone to its pre-Waipounamu Erosion Surface orientation shows no significant tilting of its present dip direction. According to the displacement-length relationships for faults longer than 10 km (Cowie & Scholz 1992), a minimum strike length for the RSSZ of 80–150 km is suggested. Even if the method of Cowie & Scholz (1992) gives only a crude estimate of fault length, the calculation shows that the trace of the RSSZ has to be much longer than mapped in the Dunstan Range. A minimum length of c. 80 km suggests that the RSSZ could connect with the Hyde-Macraes Shear Zone. Therefore, we speculate that both shear zones belong to one single top-north net-normal sense shear zone in the Otago Schist. The extensional shear zone correlation does not invalidate interpretations of early contractional deformation on the Hyde-Macraes Shear Zone (Teagle et al. 1990; Winsor 1991; Angus 1992). In this regard, we note that the CGSZ is approximately along-strike from, and may merge into, the Old Man Fault (Turnbull 2000). A pre-Miocene graben structure mapped SSW of Cromwell (Turnbull et al. 1993) may also be related to the CGSZ.

Timing of shear-zone movement

The Waipoumanu Erosion Surface is not offset by the RSSZ and CGSZ (Fig. 2). Although the Waipounamu Erosion Surface is of pre-85–105 Ma age in coastal and offshore Otago (LeMasurier & Landis 1996; Crampton et al. 1999), the oldest sedimentary rocks resting on the Waipounamu Erosion Surface in inland Otago (near the Dunstan Range) are Miocene, and there is some debate about the diachroneity of the erosion surface in inland Otago. Tippett & Kamp (1993) reported apatite and zircon fission track ages for two samples in the Cromwell Gorge and Bendigo areas (Fig. 3). The northern sample (zircon 76 ± 8 Ma, apatite 35 ± 16 Ma, 2 standard deviation errors) is in the hanging-wall block of the RSSZ, and the southern sample (zircon 90 ± 10 Ma, apatite 33 ± 8 Ma) is in the footwall block of the RSSZ and CGSZ. The permissibly similar thermochronological histories of these samples support a case for no significant differential movement across the shear zones since the Late Cretaceous. An older age limit on shear-zone movement is supplied by the fact that the RSSZ and related shear bands crosscut F3 folds (Winsor 1991). The F3 folds are generally considered to be post-peak metamorphic (Craw 1985), and consequently younger than c. 135 Ma (Little et al. 1999). Thus, activity of the RSSZ and CGSZ is broadly placed into the interval between 135 and 105 Ma. This is supported by new $^{40}Ar/^{39}Ar$ data, which suggest extensional exhumation and cooling of the metamorphic core of the Otago Schist from 109 to 100 Ma (Gray & Foster 2002). Further geochronological studies from the shear zones are needed to refine these estimates.

Syn-orogenic versus post-orogenic extension

We have crudely bracketed the timing of activity at the RSSZ and CGSZ between 135 and 105 Ma. An Early Cretaceous formation of the two normal-sense shear zones would fit into two possible tectonic scenarios:

(1) *Late-stage accretion in the convergent Torlesse accretionary wedge*. Little et al. (1999) speculated that the onset of enhanced cooling and exhumation in the Otago Schist at 135 Ma is related to a phase of crustal thickening as a result of accretion of the Otago Schist to the New Zealand margin along the Livingstone Fault (Fig. 1B). Crustal thickening by underplating may have destabilised the accretionary wedge leading to orogen-parallel normal faulting in the upper rear part of the wedge (cf. Platt 1986). Extensional basins are expected to form above these faults (Wallis et al. 1993). Examples for such basins that formed at convergent margins are the Recent forearc basins of the Hikurangi margin in the North Island of New Zealand (Walcott 1987; Cashman & Kelsey 1990). However, it is unlikely that pre-Albian deposits of this type would be preserved in the internal parts of the Otago Schist. In the Clent Hills Group north of the Otago Schist, weakly indurated Late Jurassic deltaic deposits rest on highly indurated Late Triassic Torlesse greywacke (Fig. 1A) (Oliver et al. 1982). These sediments are little studied in terms of their provenance and structure but are probably trench-slope rather than extensional basins.

Norris & Bishop (1990), Maxelon et al. (1998), and Deckert et al. (2002) showed that the Otago Schist was subjected to extreme vertical contraction of up to 70% in its internal parts. Great vertical contraction tends, like erosion, to drive a wedge in a subcritical configuration promoting shortening and not extension across the wedge. Thus, the large vertical contraction also makes a syn-accretionary formation of the extensional shear zones unlikely.

(2) *New Zealand-wide Albian rifting*. In this scenario, the two studied normal-sense shear zones together with the Hyde-Macraes Shear Zone, the Barewood Fault System (MacKenzie & Craw 1993), and faults bounding the Albian graben (Fig. 1B) would belong to a distributed regional array of Early Cretaceous normal faults. The aforementioned ^{40}Ar/^{39}Ar data of Gray & Foster (2002) also suggest that the RSSZ and CGSZ formed in the Albian. The Albian normal faults aided final exhumation of the Otago Schist during early rifting stages. Support for exhumation at c. 105 Ma is provided by the composition of breccia clasts in the Albian graben sediments of the Kyeburn and Henley Formations. The basal parts of the graben fills are dominated by non-foliated greywacke, whereas clasts in the upper parts are high-grade schist (Mutch & Wilson 1952; Bishop & Laird 1976). This sedimentological evidence suggests that not much of the deeper part of the Otago Schist was eroded and exhumed before rifting. Thus, we postulate that well-known normal faults bounding the Albian graben (Fig. 1B) may represent the structurally higher (and possibly younger) equivalents of extensional shear zones in the inner part of the Otago Schist (e.g., RSSZ, CGSZ, Hyde-Macraes Shear Zone), which were progressively exhumed by erosion and normal faulting.

CONCLUSIONS

The main contribution of this study is the recognition of bivergent Early Cretaceous net-normal faulting at the Rise-and-Shine Shear Zone and Cromwell Gorge Shear Zone in the central Otago Schist. This result is based on a kinematic analysis of the shear zones, their relation to paleohorizontal in the Cretaceous, and on breaks in textural and metamorphic grade across the shear zones. Our work contrasts with earlier studies in which low-angle intra-schist shear zones have been described as thrusts. Syn-convergent formation of both shear zones due to destabilisation of the accretionary wedge must be considered, but we favour a relationship of the shear zones to New Zealand-wide extension starting in the Albian. The major problem of distinguishing between syn- and post-accretionary formation of the shear zones lies in the poor timing constraints of the Cretaceous shear zones. Future dating will shed light on this controversial issue.

ACKNOWLEDGMENTS

We thank the journal reviewers Richard Norris and Michelle Markley for their comments, Rob Lynch for editorial handling, Neville Orr for thin sections and Mark Brandon, Ian Turnbull, and Jane Forsyth for discussions. Comments on an earlier version of the manuscript by Dave Craw and John Platt helped improve the content. Deckert and Ring's funding was provided by the Deutsche Forschungsgemeinschaft (grant Ri538/12-1); Mortimer's funding was provided by the New Zealand Public Good Science Fund. Institute of Geological & Nuclear Sciences contribution number 2394.

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