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Strain localisation within ductile shear zones beneath active faults: The Alpine Fault contrasted with the adjacent Otago fault system, New Zealand

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The Alpine Fault accommodates around 60–70% of the 37 mm/yr oblique motion between the Australian and Pacific plates in the South Island of New Zealand. Uplift on the fault over the past 5 Ma has led to the exhumation of the deep-seated mylonite zone alongside the present surface trace. Shear strain estimates in the mylonites reach 200–300 in the most highly strained rocks, and provide an integrated displacement across the zone of 60–120 km. This is consistent with the amount of displacement during the last 5 Ma, suggesting that displacement on the fault is localised within a 1–2 km wide ductile shear zone to depths of 25–30 km. Existing geodetic data, together with Late Quaternary slip rate and paleoseismic data, are consistent with the steady build-up and release of elastic strain in the upper crust driven by ductile creep within a narrow mylonite zone at depth. Faults of the Otago Fault System form a parallel array east of the Alpine Fault and accommodate c. 2 mm/yr contraction. Long periods of quiescence on individual structures suggest episodic, or "intermittently characteristic", behaviour. This is more consistent with failure on faults within an elastico-frictional upper crust above a ductile lower crust. Localisation of crustal deformation may be initiated by inherited weaknesses in the upper crust, with downward propagation of slip causing strain weakening within the ductile zone immediately beneath. Inherited structures of great length focus a greater amount of displacement and hence more rapidly develop underlying zones of ductile shear.

Key words: Strain localisation, faults, mylonites, neotectonics, Alpine Fault, New Zealand.

1. Introduction

Mylonite zones exposed in old rocks at the Earth's surface by uplift and erosion are generally considered to represent the deep portions of once active faults (e.g. Sibson, 1977; Hanmer, 1988). The rocks exhibit deformation by ductile creep processes under elevated conditions of pressure and temperature corresponding to depths of c. 10–30 km. A model of a crustal fault zone consisting of an upper elastico-frictional part which ruptures periodically in earthquakes and a lower ductile portion in which strain accumulates by viscous creep is commonly adopted (e.g. Sibson, 1977, 1983; Hanmer, 1988). Localisation of creep strain within the underlying mylonite zone is therefore significant in localising elastic strain around the brittle seismogenic fault. A problem is that deep portions of currently active faults, for which surface structure, slip rate, seismic activity, etc., are known, are difficult to investigate or even image seismically (Stern and McBride, 1998). Ancient exposed mylonite zones, on the other hand, have usually lost the corresponding upper brittle portion.

In some cases, GPS measurements (e.g. Alpine Fault, Beavan *et al.*, 1999) and satellite radar interferometry (e.g. North Anatolian Fault, Wright *et al.*, 2001) indicate focussed strain around a locked surface fault, suggesting localised creep below some depth along a downward extension of the fault. In other cases, it has been argued that no such localised creep occurs (e.g. Bourne *et al.*, 1998). Important questions include: (1) How much of the slip on the brittle structure is accommodated by localised creep within a narrow mylonite zone beneath? (2) How do zones of high creep rate form below brittle faults and are they a precursor or a successor to localisation of displacement within the brittle crust? (3) Do all active faults have downward extensions of narrow creeping mylonite zones?

In this paper, I use geological and geophysical data from the Alpine Fault to argue for a deeply penetrating crustal mylonite zone beneath the surface fault, and draw a comparison with the behaviour of a suite of parallel faults in eastern South Island that lack evidence for deep creeping mylonite zones. I conclude from these data that a possible model for the development of mylonite zones is the downward propagation into the lower crust of a strain-weakened ductile shear zone localised by the reactivation of a pre-existing upper crustal weakness.

2. Alpine Fault, New Zealand

2.1 Regional setting and current activity

The Alpine Fault is the main manifestation of the Australian-Pacific plate boundary within the South Island of New Zealand (Fig. 1; Norris *et al.*, 1990). Estimates of Late Quaternary slip rates (Norris and Cooper, 2001) and contemporary strain accumulation measured by GPS surveys (Beavan *et al.*, 1999) indicate that the Alpine Fault accommodates around two-thirds to three-quarters of the 37±2 mm/yr of plate motion calculated from the Nuvel 1A global plate model (DeMets *et al.*, 1994). The interplate

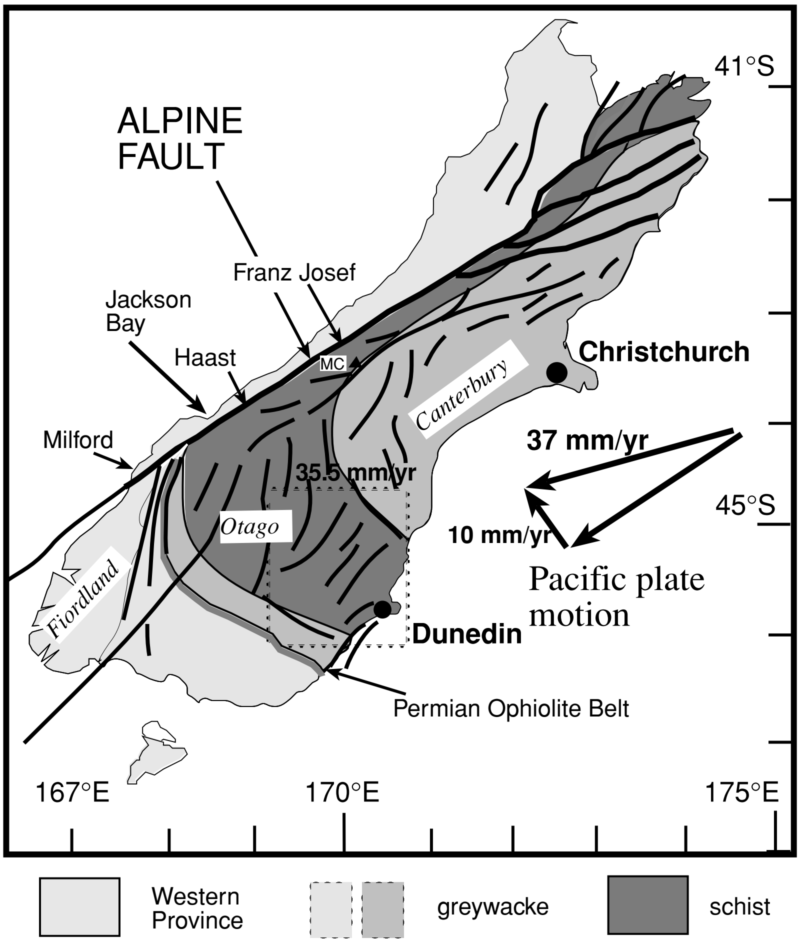

Fig. 1. Map of South Island showing Alpine Fault, distribution of major Late Quaternary faults (somewhat generalised) and current plate vector (after DeMets *et al.*, 1994). Rectangle indicates area shown in Fig. 6.

slip vector is oriented approximately 20° to the trace of the fault, resulting in components of 35.5 mm/yr parallel and 10 mm/yr perpendicular to the Alpine Fault. Motion on the fault within its central portion is approximately parallel to the interplate vector with components of both strike-slip and dip-slip. The dip-slip component reduces in the northeast and southwest of the South Island, and falls to zero on the far southwestern part of the fault south of Jackson Bay (Fig. 1; Norris and Cooper, 2001). Estimates of rates of strike-slip on the fault are consistent with a constant rate along its length of 27±6 mm/yr (Norris and Cooper, 2001; revised estimates by Sutherland, Berryman and Norris (unpublished ms) of 23.2±1.6 mm/yr at the southern end of the fault may provide a more accurate rate). Reconstruction of plate motions through the late Cenozoic indicates a total convergence across the South Island of some 70–90 km (Walcott, 1998).

The depth to the Moho approximately doubles from c. 20 km off the east coast to 40 km under the Southern Alps (Davey *et al.*, 1998; Van Avendonk *et al.*, 2004). Part of the total convergence has been accommodated by crustal thickening forming a deep root. Walcott (1978) argued that geodetically measured strain is accommodated by ductile distributed creep within a broad zone across the South Island. The Late Quaternary slip data on the Alpine Fault (i.e. at least 23 mm/yr) indicate that this can only be true near surface for, at most, the remaining 14 mm/yr, or c. 35% of the predicted plate motion. Based on mantle anisotropy, Molnar *et al.* (1999) and Stern *et al.* (2000) have suggested that New Zealand overlies a broad zone of shear some 200 km wide and localisation onto faults only occurs in the brittle crust.

On a short CDP reflection line east of the Alpine Fault, Davey *et al.* (1995) recognised reflections dipping at 40–50° in line with the surface trace of the Alpine Fault and extending to a depth of over 25 km. These were interpreted as the extension of the Alpine Fault zone into the lower crust.

Rocks from over 20 km depth have been exhumed within the last few million years within the hangingwall due to the component of convergence across the Alpine Fault (Cooper, 1980; Adams, 1981; Holm *et al.*, 1989). East of the surface trace, a zone up to 1 km wide of mylonite and protomylonite is exposed (Reed, 1964; Sibson *et al.*, 1979; Norris and Cooper, 2003). Mylonitisation increases inhomogeneously westwards across the zone from amphibolite facies schist protolith in the east, to protomylonite, mylonite, and ultramylonite adjacent to the active fault trace. Mineral assemblages in the mylonites indicate deformation under amphibolite facies conditions at depths of 20–30 km (Holm *et al.*, 1989; Grapes and Watanabe, 1994; Vry *et al.*, 2004). We can definitely say that a narrow zone of faulting with a slip

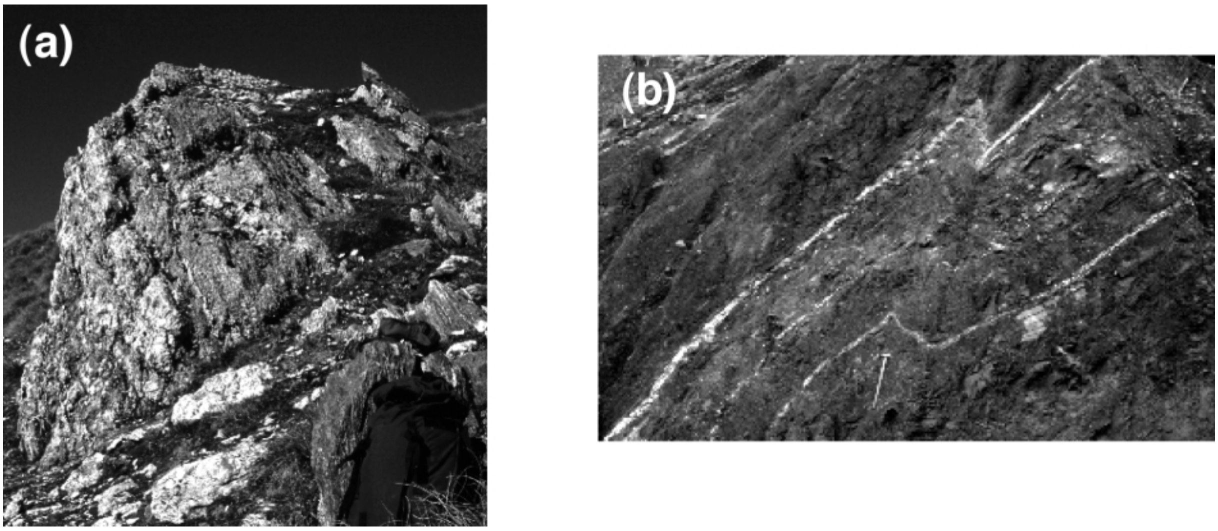

Fig. 2. (a) Non-mylonitised pegmatite in hangingwall schist near Haast; (b) highly attenuated pegmatite veins in ultramylonites near Franz Josef.

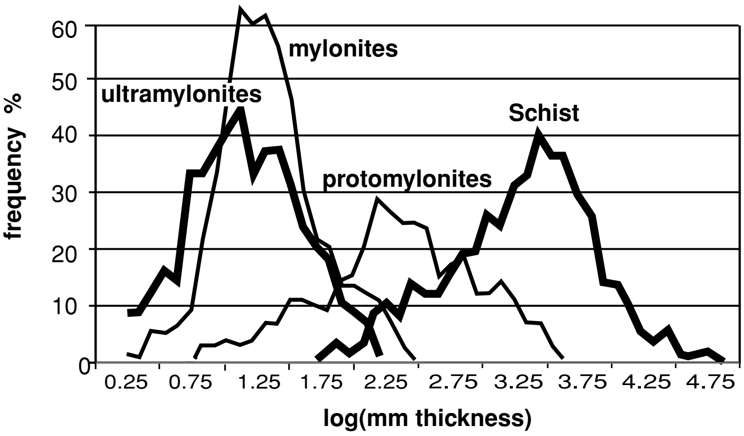

Fig. 3. Plot of smoothed frequency distributions of thickness of pegmatite veins in different parts of the mylonite zone (after Norris and Cooper, 2003).

rate of around 25 mm/yr at the surface overlies a mylonite zone 1–2 km wide originally developed at a depth of 20–30 km. The Alpine Fault, therefore, presents a rare opportunity to study the deep-seated part of a currently active fault whose surface dimensions and structure we already know and whose slip rate and slip direction we can determine.

2.2 Alpine Fault mylonite zone

Strain within the mylonites, as indicated by the intensity of development of a mylonitic foliation and degree of grainsize reduction, increases towards the present surface trace of the Alpine Fault. Large strains in the more deformed mylonites are indicated by the parallelism of all features with the foliation and the destruction of most of the original schist fabric. Shear sense indicators on both mesoscopic and microscopic scales consistently record oblique dextral-reverse shear in accordance with the recent slip on the fault (Prior, 1988; Little *et al*., 2002). A strong convergent component developed on the fault around 5–6 Ma (Sutherland, 1995), since when there has been at least 70 km of convergence across the whole plate boundary (Walcott, 1998). It is likely, therefore, that the mylonites currently exposed formed within this period of convergence.

Norris and Cooper (2003) addressed the question of what proportion of the surface fault displacement can be accommodated by ductile creep within the mylonites. They measured the thicknesses of pegmatite veins within a 65 Ma swarm that is progressively sheared across the mylonite zone and compared the thickness distributions of the deformed veins with that of their un-mylonitised counterparts to calculate a finite shear strain within different parts of the mylonites (Figs. 2, 3). Depending on assumptions, shear strains ranged from 12–22 in the protomylonites, 120–200 in the main mylonites and 180–300 in the ultramylonites. By fitting an exponential function to these strains across the exposed zone, an integrated displacement of 55–60 km may be calculated (Norris and Cooper, 2003; Fig. 4). This is also consistent with the pegmatites extending through the mylonite zone over a distance of at least 60 km parallel to strike.

In 5 Ma at an average slip rate of 25 mm/yr, some 125 km of displacement is predicted. Earthquakes in the vicinity of the Alpine Fault are restricted to the top 10 km of crust (Leitner *et al*., 2001), indicating that the ductile strains accumulated below this depth—i.e. between 30 and 10 km depth, The strain recorded in the mylonites, therefore, would represent only two-thirds of the total surface

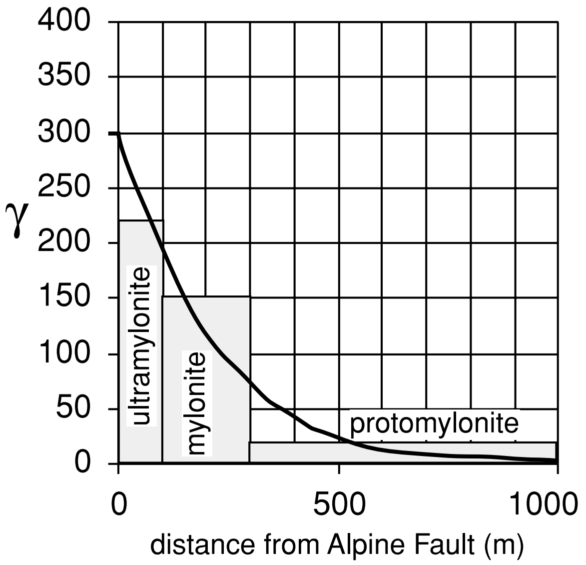

Fig. 4. Strain profile across the mylonite zone. Boxes are estimated strains for the three subzones. The smooth curve is an exponential fit (after Norris and Cooper, 2003).

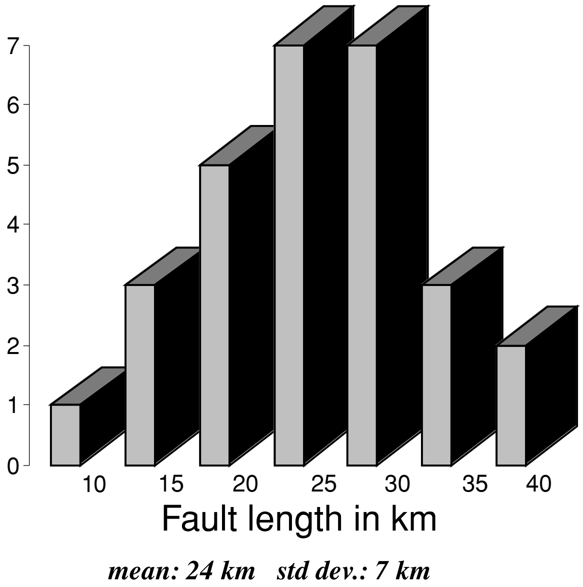

Fig. 5. Histograms of lengths of Late Quaternary fault traces east of the Alpine Fault.

slip accumulated during their uplift—i.e. c. 85 km. The highest strained mylonites are immediately adjacent to the present brittle fault, suggesting that a portion of the mylonite zone lies at depth within the footwall. If the original ductile zone were symmetric, it would have been twice the width of the exposed zone, although a highly asymmetric zone is also possible. Therefore total displacement across the mylonite zone would lie between 60 and 120 km (Norris and Cooper, 2003). This value is compatible with all the required displacement on the fault being accommodated by ductile shear within a 1–2 km wide mylonite zone within the lower crust.

2.3 Displacement rate and seismic behaviour of the Alpine Fault

Estimates of Late Quaternary (last 50 ka) rates of slip on the Alpine Fault of 27±6 mm/yr (Norris and Cooper, 2001) are consistent with the long-term estimate of Sutherland (1994) of 26 mm/yr since the mid Pliocene. We can conclude from these results that the rate of strike-slip displacement on the fault has been reasonably constant over a long period of time.

Results of repeated GPS surveys across the South Island (Beavan *et al.*, 1999) show high strains accumulating within a zone about 30 km wide east of the Alpine Fault. Velocities relative to the Pacific plate show a rapid decrease eastwards within 15 km of the surface trace. In order to explain these observations, Beavan *et al.* (1999) use various dislocation models. A combination of localised ductile shear on an eastward dipping extension of the Alpine Fault below 8 km locking depth combined with slip on a deeper, westward dipping structure (or a more distributed deformation) best fit the data. The data require around 60% of interplate slip to be concentrated as ductile creep within an extension to the Alpine Fault below c. 8 km and extending to at least 15 km and probably 30 km depth. The balance may be distributed on a number of possible structures, including a broader thickening of the crust. Above 8 km, strain is considered elastic and no evidence for aseismic creep on the fault is present. Thus the geodetic data is consistent with the structural results in supporting a creeping mid-lower crustal extension of the fault.

There have been no ground ruptures on the Alpine Fault since written records began in the early 19th century. Paleoseismic studies, however, have provided evidence of substantial surface breaks along large sections of the fault (Cooper and Norris, 1990; Sutherland and Norris, 1995; Bull, 1996; Yetton *et al.*, 1998; Wells *et al.*, 1999; Norris *et al.*, 2001; Rhoades and van Dissen, 2003) every 200–350 years since 900 AD. The last surface break is dated by dendrochronology as occurring in 1717 AD (Wells *et al.*, 1999) and probably broke most of the 400 km surface trace. Single displacements range from 5 to 8 m dextral. Vertical offsets range from 0 to 2 m although no single offset data are available in the central part of the fault where the long-term average rate of vertical offset is greatest. At 25 mm/yr, 5 m–8 m breaks would be expected every 200–320 yrs, so that the paleoseismic record and the long-term average slip rates are in general agreement.

All the above data indicate a fault that shows a more or less constant long-term average slip rate and a cyclical build-up and release of elastic strain in the seismogenic crust. Coupled with the geodetic data, this behaviour is compatible with a fault in which localised creep within a deep extension to the brittle fault is occurring at a more or less constant rate and is partly instrumental in focussing the build-up of elastic strain around the surface trace.

3. Otago Fault System

3.1 Faulting east of the Southern Alps

As noted above, only around 60–70% of the total interplate displacement is accommodated by slip on the Alpine Fault. The lack of much micro-seismic activity west of the fault (Leitner *et al.*, 2001) suggests the rest is distributed mainly to the east on a number of smaller faults and folds

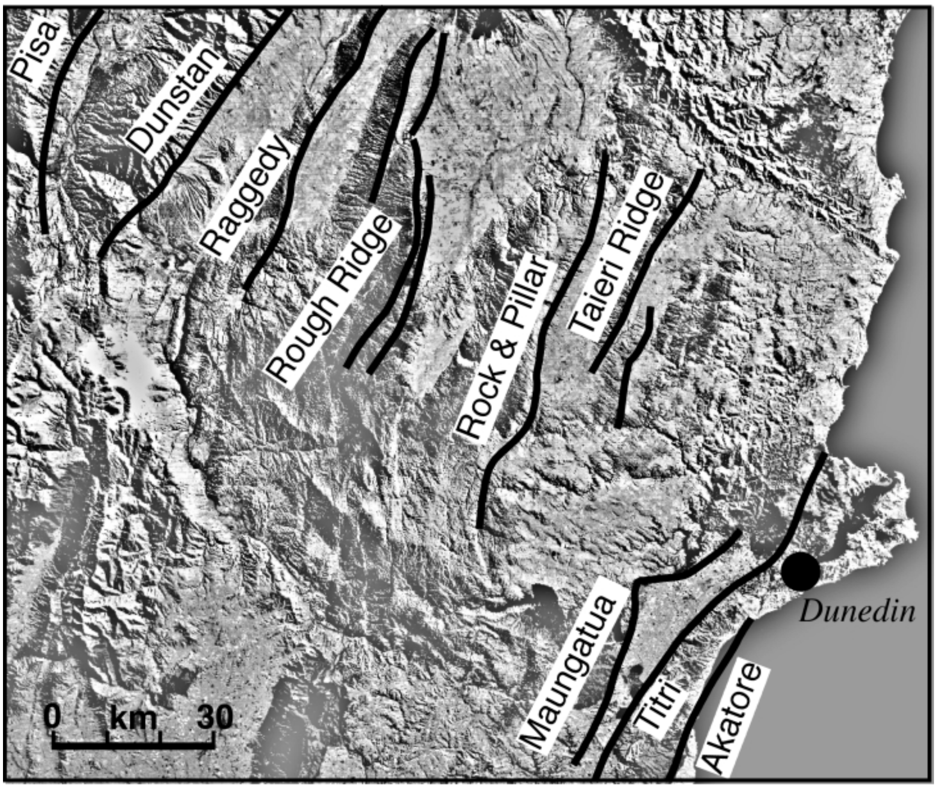

Fig. 6. Relief image of Otago (processed from Landsat images) showing NE-striking Late Quaternary faults and uplifted anticlinal ranges (note: only NE-striking faults referred to in text are shown; Cardrona Fault is just off the image to the NW; the Alpine Fault is not shown). Area of view is shown by box in Fig. 1.

(Norris and Cooper, 2001). Figure 5 is a histogram showing the lengths of Quaternary surface traces of faults east of the Alpine Fault, taken from regional maps (e.g. Officers of the Geological Survey, 1983). The average fault length is 24 km and typical surface displacements measured for a single event are 1–2 m. About 12 faults of this length would be needed to stretch the 300 km or so of the central Alpine Fault. If about 10 mm/yr of plate movement is being accommodated east of the Alpine Fault, we might expect around 12 faults of this size to rupture every 100–200 years, with earthquakes of around M6.5–7 (Wells and Coppersmith, 1994).

3.2 Otago fault system

In Otago, a series of NE-striking ranges extend across the province from the Southern Alps to the coast (Fig. 6). Mainly west-dipping reverse faults bound the ranges. These faults are predominantly blind thrust faults, with subdued surface expression, and border anticlinally folded ranges (Jackson *et al.*, 1996; Markley and Norris, 1999). Several of the faults are complex, with frontal splays and offset segments (Jackson *et al.*, 1996). Total vertical displacement across the ten faulted ranges may be estimated from the offset of a Cretaceous-early Tertiary erosion surface (Bishop, 1994; LeMasurier and Landis, 1996). Vertical displacements on individual structures range from c. 2000 m to 120 m, with an average of about 1000 m. Stratigraphic evidence indicates uplift of the ranges occurred during the Quaternary (Youngson *et al.*, 1998). By adding estimates of total displacements on all major structures, an average uplift rate across the whole system of 2–3 mm/yr is obtained. If the faults are assumed to dip at 45°, this is also equal to the average shortening rate across the province. This value is in reasonable agreement with preliminary GPS data (Norris and Nicolls, 2004), suggesting that rates of shortening across the whole system may be fairly constant.

Typical single displacements on the range fronts range from 1–3 m. If all 10 faults were moving at the same constant rate of 0.2 mm/yr, each would have a return period of 5–15 ka. Limited paleoseismic data on the Dunstan Fault (Beanland *et al.*, 1986) is compatible with this whereas recent movement on the Akatore Fault (Litchfield and Norris, 2000) is faster. What is remarkable is that all four faults investigated paleoseismically (Pisa Fault, Beanland and Berryman, 1989; Dunstan Fault, Beanland *et al.*, 1986; Titri Fault, Litchfield, 2001; Akatore Fault, Litchfield and Norris, 2000) show periods of quiescence of more than 100 ka, i.e. 10 times the average return period. This led Beanland and Berryman (1989) to suggest that movement on each fault was episodic, and switched between one fault and another (termed "intermittently characteristic" behaviour by Beanland and Berryman, 1989). Similar behaviour has been suggested for other systems of parallel faults (Wallace, 1987; Jackson and Leeder, 1994).

Such behaviour as outlined above indicates that the faults cannot have a constant rate of slip, nor do they produce ruptures at regular intervals. Each fault may be active for a period and then become quiescent while movement transfers to another structure. Such behaviour is more typical of faults within an elastic upper crust overlying a uniformly weak lower crust within which stress relaxation occurs by distributed creep (e.g. Ellis *et al.*, 2004; also see Ben-Zion *et al.*, 1999), rather than each fault having an individual creeping downward continuation into the lower crust.

4. Discussion

Geodetic data, geologic slip-rate data, and paleoseismic information are all consistent with the Alpine Fault within the seismogenic crust overlying a downward extension into the lower crust in which ductile creep strain is localised. This is compatible with the evidence from the exhumed mylonite zone alongside the present fault trace, that shows very large shear strains and intense strain localisation. Information on the Otago fault system on the other hand, while preliminary, is consistent with a set of faults within an elastico-frictional upper crust overlying a ductile lower crust and lacking zones of strongly localised creep beneath each fault.

Major differences between these fault systems are that the rate of slip on the Alpine Fault is much higher than on the Otago Faults, and its strike length is over an order of magnitude greater. Both fault systems appear to represent, at least in part, reactivated older structures within the crust (e.g. Sutherland *et al.*, 2000; Turnbull *et al.*, 1993). Molnar *et al.* (1999) have argued from seismic data that the mantle beneath the South Island is deforming by distributed shear without a zone of highly localised creep. If this is accepted, the localisation of deformation on the Alpine Fault is unlikely to derive directly from the mantle. Maggi *et al.* (2000) and Jackson (2002) have recently questioned the assumption of high strength upper mantle and have suggested that most of the continental lithospheric strength lies in the seismogenic crust. In this scenario, weak zones within the upper crust may localise brittle deformation along major faults, which in turn will cause cyclical high stresses and high strain-rates in the lower crust immediately below them (White, 1996; Ellis and Stöckhert, 2004). If strain weakening occurs due to the increase in strain (cf. Hobbs *et al.*, 2002), a zone of enhanced ductile creep will propagate downwards from the upper crustal fault and a positive feedback loop will lead eventually to a highly focussed fault zone through the crust. Associated with this, pronounced exhumation during localised uplift on the fault will also result in focussed thermal weakening (Ellis *et al.*, 2001; Koons *et al.*, 2003)

In the early history of the plate boundary, deformation was distributed across a broad region rather than focussed on the Alpine fault (Sutherland, 1999). The discontinuity that localised the Alpine Fault was the old passive margin along the Resolution Ridge (Sutherland *et al.*, 2000). This was a long linear feature, and so the localisation of deformation was pronounced. The Otago faults are reactivated from a set of Cretaceous normal faults and are too short to accumulate large amounts of displacement. Slip on individual structures is as yet too small to have generated deep zones of ductile creep beneath each one.

Long fault zones focus more deformation and high slip rates generate a strain-weakened ductile shear zone below that feeds back positively in localising deformation. Short multiple discontinuities have too low slip rates to develop deep zones of strain-weakened mylonites.

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