EVOLUTION OF QUARTZ AND CALCITE
MICROSTRUCTURES EXHUMED FROM DEEP BRITTLE-
DUCTILE SHEAR ZONES IN THE SOUTHERN ALPS
OF NEW ZEALAND

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Frontispiece

The historic Chancellor Hut and the Fox Glacier from Chancellor Ridge looking out towards the West Coast in the South Island of New Zealand.

Abstract

Arrays of brittle-ductile shears exposed in the Southern Alps of New Zealand, have provided a superb natural laboratory for insight into the microstructural evolution of lower crustal shear zones during exhumation. Shears are exposed in the central section of the Southern Alps at Sam Peak, Chancellor Ridge, and Baumann Glacier in a zone ~2 km wide that is located 6–8 km structurally above the Alpine Fault. An array of systematically spaced shear zones that formed by embrittlement and faulting of quartzofeldspathic schist took place at the same time as ductile shearing of quartz-carbonate veins embedded within the schist. This study has used field-based structural mapping along with optical microscopy and universal stage measurements of crystallographic preferred orientations (CPO) to resolve the shear zone kinematics and rheology. On the basis of these data, the strain path can be reconstructed for the sheared veins during their progressive deformation. This began with their incidence as backshears at the base of the Alpine Fault ramp and ended with their subsequent recrystallisation, uplift, and exhumation.

The near-vertical shear planes have mean orientation of $221 @ 89 \text{ NW} \pm 1^\circ$ ($n = 780$). They are inferred to have formed as backshears accommodating uplift of the Pacific Plate as it was translated onto the oblique footwall ramp of the Alpine Fault during late Cenozoic oblique convergence. Detailed fault offset transect surveys across the shears at Chancellor Ridge and Baumann Glacier reveal a mean spacing between the shear zones of $25 \pm 5 \text{ cm}$ ($n = 410$). Quartz-carbonate marker veins are displaced in a dextral west-side-up shear sense. Fault offset geometry and a consistent arrangement of mineral fibre lineations that decorate fault surfaces, indicate that the mean displacement vector pitches 35° SW in the shear plane (trend and plunge of: $262, 35 \pm 7^\circ$). Ductilely deformed marker veins have been subject to a mean displacement of $9.9 \pm 1.4 \text{ cm}$ ($n = 344$) and a mean finite ductile shear strain of 4.8 ± 0.3 ($n = 219$). A strain-rate for the ductile deformation of the veins is estimated at $3 \times 10^{-11} \text{ sec}^{-1}$ based on the observed finite ductile shear strain, an escalator kinematic model, and assumptions about the width of the deforming zone.

Five deformation phases have affected the sheared veins during their transport up the fault ramp: 1) initial brittle faulting and ductile shearing; 2) grain boundary sliding of mylonitic quartz in response to a post-ramping differential stress drop; 3) recrystallisation and grain growth; 4) renewed late-stage dislocation creep; and 5) semibrittle deformation and exhumation.

In the schist, the shears initiated as planar brittle faults at lower crustal depths of ~21 km at a temperature of $450 \pm 50^\circ\text{C}$. They developed in a zone of transiently high shear strain-rates near the base of the Alpine Fault ramp. Dislocation creep caused a CPO of quartz and calcite to develop in sheared veins. Using the flow law of Hirth et al. (2001) and the estimated strain-rate, a differential stress of ~165 MPa is inferred for ductile deformation of the veins. Near-lithostatic ($\lambda = 0.85$) fluid pressures would have caused the rocks to undergo brittle failure, a situation that is confirmed by a late component of brittle deformation that over prints the ductilely sheared veins. Syntectonic quartz-calcite veins infill the shear fractures, and these themselves have been sheared. The deformation of the veins was not a simple shear process but one with triclinic flow symmetry. This is inferred from discordance between the shear direction and the near-vertical principle extension direction that is revealed by the pattern and symmetry of quartz and calcite CPO fabrics.

After the shears move away from the ramp-step, grain boundary sliding (GBS) accommodated by solid-state diffusion creep is inferred to have affected quartz veins. This deformation mechanism takes place because of 1) the small 8 μm grain size inherited from Phase 1; 2) the presence of fluid in the shear zone; and 3) a stress drop to ~22 MPa that followed the initial up-ramping. Quartz CPO fabrics in the sheared veins are remarkably weak considering their large shear strains. GBS is inferred to have been a chief deformation mechanism that caused the weakening of quartz CPO fabrics in the highly sheared sections of deformed veins. Calcite has also affected the quartz fabric strength as those veins containing >5% calcite have very weak quartz CPO fabrics. In contrast to quartz, the CPO fabrics for the co-existing calcite remained strong and continued to develop by dislocation creep.

The third phase of deformation, a process that may have contributed to subsequent weakening of quartz CPO fabrics, was recrystallisation and grain growth to 126 μm and an equigranular-polygonal grain shape fabric. This fabric was overprinted by late-stage dislocation creep microstructures in the fourth deformation phase in response increased differential stress encountered by the rocks at lower temperatures in the upper crust. The final phase of deformation to affect the sheared veins was semibrittle deformation at differential stresses of <189 MPa and temperatures of 200–280°C as the rocks passed through the steady-state brittle-ductile transition zone at depths of 8–10 km before being exhumed at the surface.

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CHAPTER 1: Introduction

Microstructures and the crystallographic preferred orientation (CPO) of rocks which have undergone ductile deformation have been used to determine many different aspects of the rheology of naturally deformed rocks. For example, combined with sound structural mapping, microstructural and CPO studies can be used to determine the kinematics of ductile deformation in exhumed crustal rocks. Quartz and calcite are among the most useful minerals for these fabric studies as they are abundant in crustal rocks and easily deform in the solid state by plastic intracrystalline deformation. In many studies it is possible to reconstruct aspects of the three-dimensional flow kinematics and deformation mechanisms of a rock from microstructures and crystallographic orientation fabrics generated from this plastic deformation. This is especially useful in transpressive tectonic regimes where complex three-dimensional flow fields are known to occur and where complex strain histories are to be expected. This study examines the conditions and deformation mechanisms that occurred during shearing of quartz-carbonate veins in the lower crust of the Southern Alps and the subsequent fabric evolution in these veins during their exhumation to the surface. The investigation of natural deformation processes in the crust, especially neotectonically deforming regions, is essential for understanding orogenic processes and for the calibration of experimental and field descriptions of crustal rheology.

The natural laboratory from which this study is based is located on the exhumed hanging wall of the Pacific Plate in the South Island of New Zealand. Uplift and exhumation of Pacific Plate rocks is occurring east of the plate boundary expressed on the surface as the Alpine Fault trace (Fig. 1.1). The Pacific Plate east of this boundary is undergoing oblique collision with the Australian Plate to the west and experiencing uplift and transpression as it is displaced in a dextral reverse sense up the southeast dipping Alpine Fault. Three main field sites have been selected for this research: Sam Peak, Chancellor Ridge and Baumann Glacier, located in the central part of the Southern Alps in the South Island, New Zealand (Fig. 1.1). These sites are situated 6-8 km structurally above the Alpine Fault in a zone where brittle-ductile shearing of Pacific Plate rocks, including quartz-carbonate veins, has occurred deep in the crust during the late Cenozoic. At these field sites glaciated platforms of schist provide superb exposure of exhumed arrays of shear zones.

Fig. 1.1. Southern Alps and field area location map. Digital elevation model map of the central Southern Alps of New Zealand generated from the LINZ digital 1:50,000 data set. Map grid (metres) are in New Zealand map grid coordinates. Red markers are the three main research field sites in this study; Sam Peak, Chancellor Ridge and Baumann Glacier. Green labelled markers are major glaciers, peaks, rivers and lakes. The Alpine Fault trace is marked for reference and is from Norris and Cooper (1995). Inset map of New Zealand shows the location of this figure in the South Island of New Zealand.

Fig. 1.2. Photograph of brittle-ductile shear zones in the Alpine Schist. The host schist has been displaced by brittle faults and quartz-carbonate vein has been deformed by ductile shearing. The vein has crossed three shear zones with ductile deformation in the lower two and brittle-ductile deformation in the upper shear. Photograph was taken on a flat glaciated exposure above Baumann Glacier and preferentially shows the strike-slip component of slip on a near vertically dipping vein.

Quartz-carbonate veins within the host schist rocks are found deformed in these shear zones and have undergone aspects of both brittle and ductile deformation (Fig. 1.2) at lower-crustal depths before their exhumation and subsequent exposure at the surface (Little et al., 2002b; Wightman, 2005). These shear zones provide a rare opportunity to study the natural ductile deformation of quartz and calcite in the crust in a young deforming orogen where the tectonic kinematics are well known.

This study builds on the initial recognition of these exhumed shear zones by Little et al. (2002a), and takes advantage of the opportunity to study processes of deep embrittlement and ductile deformation in naturally deformed crustal rocks. There are few case studies in the existing literature of the deformation of crustal material, such as quartz veins, where the kinematics and geodynamics is independently well constrained on an almost neotectonic time scale. Because of the superb exposure of the shear zones, their context in a modern orogen, the simplicity of their offset and measurable nature of their finite strain, we are able to estimate strain-rates and deformation mechanisms active during deformation and evaluated experimental flow laws. This study provides rare comparisons between the rheology of natural rocks and those deformed in laboratory experiments. Research from this study is able to directly contribute to the knowledge about the brittle-ductile deformation which may be active today several kilometres below the Southern Alps of New Zealand near a major continental plate boundary.

In this study I will analyse deformation processes affecting the quartz-carbonate veins deformed in the shear zones by a combination of detailed structural surveying, optical microscopy and crystallographic studies with a universal stage microscope. These results are discussed in terms the kinematics and deformation mechanisms affecting the Pacific Plate during its ramping and uplift on the Alpine Fault. The techniques employed in this research enable me to study aspects of the shear zone deformation from a broad tectonic scale of the deforming plate down to the crystallographic scale. Broad structural mapping has been undertaken across the ~2 km wide field areas as well as detailed structural surveys along 30-50 m long transects of the shear zone array. With this mapping we hope to quantify magnitudes and rates of both brittle and ductile bulk deformation, to calculate the shear displacement, shear strain and (maximum) strain-rate in the individual shear zones.

Optical microscopic techniques in this study will be used to document deformation microstructures and to decipher the deformation mechanisms that accommodated the ductile strain. Observations of the microstructures in the sheared sections of quartz-carbonate veins, the sections of the vein external to the shear zone and the host schist will be compared and contrasted to determine key temperature and spatial relationships between fabrics and to determine the strain and deformation paths. Specific methods such as grain size piezometry, subgrain orientation and calcite twin density will be used to constrain the approximate pressure and temperature conditions at which the deformation occurred. Grain shape analysis will be used to identify the sense of shear from oblique fabrics in the sheared sections of deformed veins and shed insight into the final increments of strain prior to the freezing in of microstructures. These last increments will be compared with the field-based observations of finite ductile shear strain in the deformed veins.

CPO fabrics imprinted during ductile deformation are useful in determining the flow sense of sheared rock (e.g. Lister, 1977; Schmid and Casey, 1986; Law, 1990; Bestmann et al., 2000). This study has measured quartz and calcite c-axis crystallographic fabrics for over 100 sample sections using a universal stage on a polarising microscope. The crystallographic fabrics defined by these c-axis pole measurements are used to constrain the nature of the three-dimensional deformation, and as a tool to compare natural with experimental crystallographic studies of deformed quartz veins. In this study, the crystallographic fabrics will shed new insight into the deformation mechanisms active during the shearing and subsequent ductile deformation. The CPO fabrics will be used to determine the slip systems that the crystals were using to accommodate the intracrystalline plastic deformation and these inferences will add / support to the deformation temperature approximations made from the microstructural observations. This field to crystallographic scale geological research will aid in the understanding of complex transpressional tectonics and provide a sound dataset that will allow conclusions to be drawn about the applicability of experimental flow laws to natural crustal deformation.

Experimental determination of flow laws that describe the deformation of quartz and calcite (e.g. Rutter and Brodie, 2004a; Schmid et al., 1977) are found to extrapolate poorly from experimental high temperatures and fast strain-rates to natural geological conditions (Stipp et al., 2002a). This study aims to deduce the

deformation mechanisms active at calculated strain-rates and temperatures during natural deformation in the mid-crust to assist in better correlation of experimental results to natural conditions in wet polymineralic rocks. It has been shown that the alignment of crystallographic axes during ductile deformation of quartz and calcite is associated with the last increment of strain (e.g. Brunel, 1980). This study aims to determine if the last increment of strain during exhumation has overprinted older shearing-related crystallographic fabrics or whether there is still a remnant of the CPO in the shear zone that may represent earlier deformation increments that occurred at deep crustal levels. The ductile shear direction in the shear zones has been assumed to be coincident with the fault surface lineations on the brittle-ductile shears and has not been resolved because of poor microstructural preservation and very weak or randomised crystallographic fabrics (e.g. Little et al., 2002b; Little, 2004; Wightman, 2005). This study aims to use extensive CPO measurements from large sample sets to ascertain the ductile extension and shear directions during deformation in the shear zone and the microstructural evolution of fabrics during uplift.

This thesis is comprised of seven chapters which cover the tectonic and geological setting in the Southern Alps of New Zealand, the field-based structural mapping, optical microscopy and crystallographic orientation studies. Detailed appendices are found in the back of this thesis and document the structural field measurements, structural survey data, mineralogical and microstructural observations and a complete archive of all stereographic plots made for the crystallographic measurements obtained for this study.

CHAPTER 2: Tectonic setting and geology of the Southern Alps of New Zealand

2.1. Tectonics of the South Island of New Zealand

New Zealand straddles the plate boundary between the Australian (AUS) and the Pacific (PAC) plates (Fig. 2.1a). The plate boundary changes southward from a west dipping subduction zone beneath which oceanic lithosphere of the Pacific Plate is subducted off the east coast of the North Island, to an oblique collision zone between continental parts of both plates in the central South Island. This oblique collision zone is most obviously expressed on the surface by the Alpine Fault. Farther south, west of Fiordland, oceanic lithosphere of the Australian Plate is subducted beneath continental rocks of the Pacific Plate (Walcott, 1998; Sutherland et al., 2000; Barnes et al., 2005). Deformation across the plate boundary initiated at ca. 45 Ma in the South Island when PAC-AUS deformation was diffusely distributed and transtensional (Sutherland, 1995; Sutherland et al., 2000). An increase in strike-slip along the plate boundary took place at ~25 Ma (Sutherland, 1995). After this time the Alpine Fault has played a major role in accommodation of plate motion, today accommodating as much as 70% of the margin parallel component of motion (Cooper and Norris, 1994; Beavan et al., 1999; Sutherland, 1999a). The remaining 30% of the current motion distributed over a ~200 km wide zone to the east of the Alpine Fault (Walcott, 1979; Norris et al., 1990; Beavan et al., 1999). Since ~6.4 Ma the Alpine Fault has become an oblique-slip structure due to increased convergence across the PAC-AUS boundary (Walcott, 1998; Vry et al., 2004). Reverse slip on this fault allows uplift of the Southern Alps mountain range to the west of the southeast dipping Alpine Fault.

The contemporary plate motion direction of PAC relative to AUS is $071 \pm 2^\circ$ near Fox Glacier (NUVEL-1A solution of DeMets et al., 1994; Fig. 2.1b). This vector's velocity of 37 mm/yr can be divided into a 35.5 mm/yr component parallel to the Alpine Fault and 10.2 mm/yr component normal to that fault. Uplift rates in the central section of the Southern Alps determined from lacustrine sedimentation, uplifted marine terraces and direct geodetic measurements from GPS stations are as high as 8-10 mm/yr (Wellman, 1979; Bull and Cooper, 1986; Beavan et al., 2002) and are higher than other parts of the Southern Alps (Little et al., 2005). South of

Fig. 2.1. a. Large scale tectonic overview of New Zealand. Pacific and Australian plates shown for reference with northern and southern subduction zones. Traces of major faults in the South Island of New Zealand shown for reference. b. Terrane map of the South Island of New Zealand (after Sutherland et al., 2000) with the Alpine Fault and other major faults in the Marlborough Fault Zone. Major basement terranes of New Zealand are indicated and the three domains of schist found in the South Island including the Alpine Schist sampled in this study. Study area (area of Fig. 2.2) shown for reference as well as the central section of the Alpine Fault. Plate motion vector (DeMets et al., 1994) relative to fixed Australian Plate for position at Fox and Franz Josef glaciers.

Haast, in the southern section of the Southern Alps, uplift rates of the PAC plate rocks on the Alpine Fault are as low as 0.1-1.4 mm/yr (Sutherland and Norris, 1995; Sutherland et al., 1995). The topography of the Main Divide of the Southern Alps near the central section of the plate boundary reflects the high uplift rate and is where New Zealand's only peaks higher than 3000 m are located.

The Main Divide in the central part of the Southern Alps separates the Tasman Glacier from the Fox and Franz Josef glacier névés and includes the highest mountains in the South Island such as Aoraki / Mt Cook, Mt Tasman and Douglas Peak (Fig. 1.1). These mountains all exceed 3 km in height and are just 15 km from the Alpine Fault whereas the Main Divide outside this section is as far as 25 km from the fault (Little et al., 2005). The central Southern Alps may be uplifting more rapidly than other parts of the range to the north and south because the Alpine Fault is slightly more steeply dipping there on average (Little et al., 2005). High local uplift rates in the central Southern Alps are causing a rapid exhumation of crust because this uplift is balanced by an equally high erosion rate (Wellman, 1979). A result of this rapid exhumation on the east side of the Alpine Fault is a locally high geothermal gradient, perhaps as high as 60°/km in the upper crust (Allis and Shi, 1995), a situation that is reflected by an unusually shallow seismogenic zone of 10-12 km (Leitner et al., 2001).

2.2. The Alpine Fault

The Alpine Fault (Fig. 2.1b) is located west of the Southern Alps mountain range and is continuous for ~850 km across the South Island (Barnes et al., 2005) and has had up to 460 km of dextral strike-slip displacement since 45 Ma (Sutherland et al., 2000). The fault is expressed both as a fault trace offsetting Quaternary deposits (e.g. Cooper and Norris, 1994; Sutherland, 1994; Norris and Cooper, 1995; Norris and Cooper, 1997) and as a major boundary offsetting basement rocks of the Maitai and Caples terranes and the Haast Schist (Sutherland, 1999a; Fig 2.1b). The Alpine Fault plane has a mean strike of 055 (Norris and Cooper, 1995) and dips southeast at 30-50° (Sibson et al., 1981; Norris et al., 1990; Kleffmann et al., 1998). The Australian Plate footwall block is considered to be a relatively rigid indenter for the Pacific Plate. The base of the Pacific Plate hanging wall of the Alpine Fault consists of amphibolite grade schist and fault related mylonite rocks that have been

exhumed from depths of 22-25 km (Grapes, 1995; Walcott, 1998). To the east and structurally above these lower crustal metamorphic rocks are biotite grade schists that grade further eastwards into the protolith sedimentary Torlesse Terrane.

Offset Quaternary markers indicate a strike-slip rate of 26-28 mm/yr in the southern section of the Alpine Fault, a place where dip-slip displacement is as low as 0-2.5 mm/yr (Sutherland et al., 1995; Sutherland and Norris, 1995; Norris and Cooper, 2001). The central section of the Alpine Fault has similarly high late Quaternary strike-slip rates of 22-27 mm/yr (Cooper and Norris, 1994; Norris and Cooper, 1997) but has a dip-slip rate of 8-12 mm/yr that is much higher than those to the north and south (Norris and Cooper, 2001). The slip direction on the oblique-reverse Alpine Fault pitches northeast at 14-35° as inferred from striations on the fault surface (e.g. Norris and Cooper, 1997). This direction is essentially parallel to the predicted slip direction (10° pitch to the northeast) calculated from the PAC plate motion resolved onto the mean fault plane. Stretching directions from lineations in the mylonite exhumed along the Alpine Fault however are more scattered pitching ~30-70° in the fault plane (Sibson et al., 1981; Wightman, 2000; Little et al., 2002b; this study Appendix F).

No fault creep at the surface has occurred on the Alpine Fault during the past 25 years and no earthquakes have ruptured that structure historically in the last 170 years suggesting that the Alpine Fault fails in large or great earthquakes (Sutherland, 1994; Beavan et al., 1999; Wells, 1999). Although the upper crust is accumulating elastic strain today (Sutherland, 1994; Beavan et al., 1999, 2002), dislocation modelling from GPS data suggests that ongoing slip could be accommodated by aseismic ductile creep processes on the down dip extension of the Alpine Fault ramp at depths greater than 5-8 km (Beavan et al., 1999). Although the PAC-AUS plates in map view are obliquely converging, the three dimensional deformation of the Pacific Plate is likely to be transpressive and deviate from simple shear by including a component of pure shear shortening perpendicular to the plate boundary (Sibson et al., 1979; Koons et al., 1998; Beavan et al., 1999; Jiang et al., 2001; Wightman 2000; Little et al., 2002a; Little, 2004; Norris and Cooper, 2003).

2.3. Geology of the central Southern Alps

The crust exhumed on the Alpine Fault ramp is a segment of metamorphic rock that represents a vertical section through the crust after tilting and uplift on the Alpine Fault ramp (Grapes and Watanabe, 1992). This exhumed section shows a complete progressive prograde metamorphic sequence from the protolith sedimentary rocks in the southeast through to garnet-oligoclase amphibolite facies Alpine Schist in the northwest adjacent to the Alpine Fault (Grapes, 1995; Fig. 2.2). The predominant quartzofeldspathic Alpine Schist has been metamorphosed from a protolith Torlesse Terrane greywacke; however in structurally deeper sections of the Alpine Schist, the rocks are dominantly pelitic with metabasite and metachert horizons, interpreted to have originated from the Aspiring Terrane (Craw, 1984; Norris and Craw, 1987; Grapes et al., 1998). The Alpine Schist was subject to a period of sustained deep burial and ductile deformation during its residence in the lower crust of the Pacific Plate and during its late Cenozoic passage through the PAC-AUS deformation zone east of the Alpine Fault. The ductile fabrics in the Alpine Schist become progressively more ductile and complex from southeast to northwest with increasing metamorphic grade, and were initially imprinted into these rocks in the Mesozoic before the modern phase of oblique convergence and uplift. Within 1-2 km to the east of the Alpine Fault the hanging wall consists of mylonitic and protomylonitic (“curly schist”) rocks (Fig 2.2) formed from the changes related to late Cenozoic shearing along the Alpine Fault structure. These mylonite rocks over thrust the late Quaternary outwash and glacial sediments found on the western side of the Alpine Fault (e.g. Cooper and Norris, 1994; Norris and Cooper, 1997).

The Alpine Schist in the Southern Alps has undergone four deformational events (D_1 to D_4 from Little et al., 2002a) with D_4 being the last event during the late Cenozoic and related to Southern Alps deformation and related ramping and uplift on the Alpine Fault. Field observations of the Alpine Schist in this study largely concern the foliations generated during the D_2 and D_3 events as well as the mylonitic foliation generated during the D_4 event. The subvertical S_3 or “Alpine” foliation is a crenulation or cleavage foliation generated from the folding of the older S_2 fabric during the D_3 deformation event in the late Cretaceous (ca. 86 Ma). These Alpine fabrics were later reactivated and strengthened during the late Cenozoic D_4 transpression (Little et al., 2002a; Little, 2004; Vry et al., 2004). During the D_2 and

Fig. 2.2. Map of the central Southern Alps of New Zealand and locations of main research sites Sam Peak, Chancellor Ridge and Baumann Glacier. Inset map for reference location of this Figure within New Zealand. Coordinates are in NZ Map Grid (m) with the Alpine Fault trace from Norris and Cooper (1995), isograds from this study and QMap unpublished data (courtesy Simon Cox IGNS), Alpine Fault mylonite zone from Little et al. (2002a) and brittle-ductile shear zone from Wightman (2005) and this study. Reference locations for Crawford Knob (CK), Waiho River (WR) and Hare Mare Creek (HM) are also shown. Permanent ice and snow shaded dark grey and only the major rivers have been plotted. Stereographic, equal area, lower hemisphere projections of the mean Alpine Fault plane and the mean brittle-ductile shear plane are inset.

D₃ events quartz-carbonate veins were emplaced in the Alpine Schist. The veins have been variably deformed during the subsequent D₃ and D₄ events by folding, boudinage and (importantly here) brittle-ductile shearing. The S₂ and S₃ foliations generally lie at an angle to each other with folding of the older fabric (S₂) folded by the steep axial planar S₃. Little et al. (2002a) have shown that on the steep or overturned limbs of large Alpine (F₃) folds, termed the planar fabric zones, the two foliations are near parallel and difficult to distinguish in the field.

Arrays of brittle-ductile shears in the Alpine Schist (Fig. 1.2) have been mapped 6-8 km southeast of the Alpine Fault (Little et al., 2002a; Little et al., 2002b; Little 2004; Little et al., 2005; Wightman, 2005; Fig. 2.2). These shears crosscut and displace the quartzofeldspathic Alpine Schist brittlely, but displace quartz veins embedded in this quartzofeldspathic schist in a variably ductile to brittle manner. This shearing is the youngest ductile deformation to have affected the non-mylonitic Alpine Schist (Little et al., 2002a). The brittle-ductile shears are found in a ~2 km wide brittle-ductile shear zone (BDSZ) that lies in biotite grade Alpine Schist (Fig. 2.2). This schist is mostly psammitic, but includes pelitic interbeds, with a phyllitic cleavage in the central and upper sections of the zone. Deeper parts of the zone to the west have a distinct schistosity (S₃). The brittle-ductile shears are not found in garnet grade schist or are they well developed in the pelitic dominated Alpine Schist from the Aspiring Terrane protolith. The BDSZ has been traced along strike, sub-parallel to the Alpine Fault (Fig. 2.2) from the most northern known occurrence at Gunn River (Fig. 1.1) to Sam Peak in the south (Fig. 2.2; Wightman, 2005). These shears have been interpreted as forming during a short-lived period of deep embrittlement in the otherwise ductilely deforming lower crust during upward bending of the Pacific Plate onto the Alpine Fault ramp in the last 3-4 Ma (Little et al., 2004; Wightman, 2005). In this study, the brittle-ductile shears themselves are referred to in abbreviated form as “S₄” (equivalent of S_{bds} in Little et al., 2002a) because of their discrete cleavage-like appearance, regular systematic spacing and their development during the D₄ deformation.

2.4. The Alpine Fault ramp

The collision of the Australian and Pacific plates has exhumed deformed mid-crustal rock from the Pacific Plate up the Alpine Fault to expose amphibolite schist

adjacent to the Alpine Fault mylonites (Grapes, 1995; Walcott, 1998). This exhumation of crustal rock that does not include any deeper lower crustal material has been used as evidence for a possible décollement in the Pacific Plate between the middle and lower crust (Grapes, 1995). Geophysical reflection, seismic velocity and gravity studies (e.g. Woodward, 1979; Davey et al., 1998; Kleffmann et al., 1998; Stern et al., 2001) support the basic model of a décollement at depth. They also delineate Moho depths of ~25 km to the southeast of the Southern Alps outside of the deforming orogen, and 40 to 50 km in the root zone below the Southern Alps (Fig. 2.3). Modelled seismic velocity contrasts within the crust (Davey et al., 1998) confirm this crust thickening under the Southern Alps, with the lower crust forming a crustal root while the middle and upper crust velocity contours are deflected upwards onto the Alpine Fault (Fig. 2.3). This geophysical evidence supports the earlier hypothesis of Wellman (1979) who noted that the need for a décollement in the mid-crust and the accommodation of the lower crust by thickening and formation of a crustal root.

The down-dip projection of Alpine Fault is imaged as a reflection that dips southeast at $40 \pm 5^\circ$ (Davey et al., 1995; Davey et al., 1998; Kleffmann et al., 1998) from seismic velocity contrasts (Davey et al., 1998; Stern et al., 2001). The Alpine Fault zone (Davey et al., 1995; Fig. 2.3) is inferred from seismic reflections located at depths of 25-35 km to intercept the crustal Pacific Plate décollement at depths of 30-40 km (Kleffmann et al., 1998). Above the downward projections of the Alpine Fault at depths of 10-35 km a low seismic velocity zone of 5.5-5.8 km/s (Fig. 2.3) has been imaged (Davey et al., 1998) as well as a zone of decreased resistivity (Wannamaker et al., 2002). These two features have both been interpreted as reflected a interconnected body fluid under lithostatic pressure which could reduce the work required for deformation in the lower crust (Stern et al., 2001).

Due to the fast exhumation rates in the central Southern Alps, high geothermal gradients and a shallow brittle-ductile transition zone have been inferred (Holm et al., 1989; Shi et al., 1996). A high near surface geothermal gradient of ~60°C/km has been calculated from heat flow data from a single drill hole in the Waima River (Fig. 1.1) and from thermal modelling of the central Southern Alps (Allis and Shi, 1995). Isotherms that have been advected upward on the inboard

Fig. 2.3. Cross section through the Southern Alps with wave speed (km/s) contours from Davey et al. (1998) and Stern et al. (2001), Alpine Fault seismic reflectors from Stern et al. (2001), decollement seismic reflectors from Kleffmann et al. (1998) and the seismogenic zone (after Leitner et al., 2001). Modelled isotherms from Batt and Braun (1999). Seismically defined brittle-ductile transition zone (s-BDTZ) illustrated at base of seismogenic zone at 10-12 km depth.

Fig. 2.4. Schematic cross sections through the Southern Alps of New Zealand. a. Cartoon simplification of backshearing model of Little et al. (2002b) showing the transient brittle-ductile transition zone (t-BDTZ) and the exhumed brittle-ductile shear zone (BDSZ). b. Cartoon illustration of backshearing model after Sanderson (1982) and Little et al. (2002b) with labels for two-sided orogen model used in Koons (1990) and location of backshearing zone. c. Cartoon model of flexural bending after Sanderson (1982).

wedge during convergence have been modelled using the finite element method for two-sided orogens like the Southern Alps by Batt and Braun (1999). This advection of the isotherms (Fig. 2.3) is due to the inability of the rapidly exhumed hanging wall of the Alpine Fault to dissipate heat as it is uplifted and is inferred to thermally weaken the hanging wall block (Koons, 1987; Batt and Braun, 1999). Crustal temperatures within 2 km of the surface are inferred to range between 140° and 350°C and are consistent with hot springs found in the central Southern Alps and the mixing between meteoric and metamorphic fluid within this shallow depth range (Allis et al., 1979). A brittle-ductile transition zone 6-8 km below the surface found from modelling of fluid inclusion analyses was suggested by Holm et al. (1989) and a transition at 10-12 km was inferred from a shallow seismogenic zone by Leitner et al. (2001). This depth is shallower than other brittle-ductile transitions in the continental crust, which commonly occur at depths of 10-15 km (Stöckhert et al., 1999).

The uplift and exhumation of the Pacific Plate can be described in the context of a two-sided orogen, for example Koons (1990). An outboard wedge (the Pacific Plate) transported west across a basal décollement. Ultimately, the Pacific Plate rocks collide with a less deformable or “rigid” indenter (the Australian Plate and Alpine Fault foot wall), which causes the outboard wedge to ramp upward as the inboard wedge. This ramped crust forms the western flank of the resultant Southern Alps mountain range and undergoes rapid erosion due to the prevailing westerly airflow and its associated orographic climate regime.

The work of Little et al., (2002a) on the brittle-ductile shears indicate that structural deformation of the Pacific Plate in the central Southern Alps during its uplift onto the Alpine Fault ramp is best described by a backshearing process (Fig. 2.4a; e.g. Sanderson, 1982; Bonini et al., 2000). Pacific Plate rocks that encounter the Alpine Fault ramp are cut by a zone of shearing that is up-to-the-west and which tilts material up onto the dipping fault ramp (Fig. 2.4b; e.g. Beaumont et al., 1996; Batt and Braun, 1999; Little et al., 2002b; Little, 2004). Today these backshears are exposed at the surface as brittle-ductile shears in the BDSZ's, 6-8 km structurally above the Alpine Fault. These exhumed shear zones have near vertical shear planes and a dextral, west-side-up sense of shear that is antithetic to dip-slip on the Alpine Fault (Little et al., 2002a). Little et al. (2002b) have argued that these arrays of shear

zones have been produced from a sequential activation of shears required for rock particles to move across the step at the base of the ramp. Once a shear has accomplished the tilting on the fault ramp it is translated away from the base of the ramp it, and eventually abandoned in favour of formation of a new shear at the base of the ramp. The inactive shears are passively translated up the Alpine Fault ramp where they are eventually exposed at the surface (Fig. 2.4a). Little et al. (2005) have argued that the slightly steeper dip of the Alpine Fault in the central Southern Alps causes backshearing to occur as the accommodation mechanism for deformation at the fault ramp bend rather than flexural bending processes that might accommodate a more gentle change in dip at the base of the ramp (Fig. 2.4c).

One can define two different types of brittle-ductile transition zones (BDTZ's) in the Southern Alps. The first is the contemporary seismically defined BDTZ (s-BDTZ) as expressed by the base of the seismogenic zone at 10-12 km (Leitner et al., 2001). Presumably this marks the base of brittle deformation in the crust at the prevailing strain-rates and temperature structure. The s-BDTZ is to a large degree thermally controlled and fixed relative to the topographic surface. Rock particles flux through the s-BDTZ as they are transported upward along the Alpine Fault (Holm et al., 1989).

A second type of BDTZ can be defined in the Southern Alps, a palaeo-BDTZ. This BDTZ coincides with the BDSZ in the biotite zone Alpine Schist. Wightman (2005) has shown that these shears were formed during a transient deep embrittlement of the mid-crust at 21 ± 5 km beneath the Southern Alps, during shearing of the Pacific Plate rocks as they negotiated the step onto the Alpine Fault ramp (Fig. 2.4a). This palaeo-BDTZ in the mid-crust formed due to transiently elevated strain-rates and fluid pressures associated with the ramp bend that allowed deep embrittlement of crust that otherwise would be deforming ductilely. We refer to this transient palaeo-BDTZ, which is represented by specific structures in the rocks, as the t-BDTZ.

Some predictions have been made about the conditions during deformation in t-BDSZ of this study from experimental modelling, mineral thermometry and thermochronology. High strain-rates and differential stresses have been modelled at the base of indentor fault ramps from thermally coupled modelling and numerical

mechanical models (e.g. Batt and Braun, 1999; Erickson et al., 2001). These models can explain the formation of a deep t-BDSZ as rock particles move through the backshearing zone. There, conditions of high differential stress and strain-rate are inferred to occur above the base of the ramp. These conditions, as well as high pore fluid pressures (Wightman, 2005), triggered transient brittle deformation of the Pacific Plate crust in the t-BDTZ significantly deeper than the modern s-BDTZ. Wightman (2005) has estimated deformation temperatures in this t-BDTZ from stable oxygen isotope thermometry and chlorite thermometry of quartz-calcite veins that infill the brittle-ductile shear and from $^{40}\text{Ar} - ^{39}\text{Ar}$ thermochronology of muscovite in schist surrounding the BDSZ. These analyses indicate temperatures and of shear zone deformation of $450 \pm 50^\circ\text{C}$ and at depths of 21 ± 5 km. Because the brittle-ductile shears formed at greater depths and higher temperatures than the s-BDTZ they may have undergone further ductile deformation as they were translated upwards through the mid to upper crust, presumably under slower strain-rate conditions than the fast transient strain-rates that initiated deep embrittlement and formation of the brittle-ductile shears.

CHAPTER 3: Field based structural geology of the brittle-ductile shear zones

Field studies involving collection of detailed structural data and sampling of brittle-ductile shears has been undertaken at Sam Peak, Chancellor Ridge and Baumann Glacier (Fig. 1.1). These field areas all have superb exposures of Alpine Schist on smooth glaciated outcrops that provide excellent continuous outcrop for more than 100 m in some locations. The field areas are situated 6-8 km structurally above the Alpine Fault and are in biotite zone schist (Fig. 2.2). Field studies of the exposed brittle-ductile shear zones in these areas included mapping, sampling, measurement of structural data and detailed structural surveys of spacing and slip of individual shears within the exposed brittle-ductile shear zones (BDSZ's). This field work aimed to define the structural extent of the BDSZ, to quantify the amount brittle-ductile slip across the shear zones, and to calculate the finite strain accumulated in deformed veins offset by individual shear zones.

Structural mapping techniques were used to measure the attitude of foliation planes, lineation directions and offset veins in the BDSZ. The orientation of S_2 and S_3 foliation planes were measured as well as shear planes (S_4) and displaced marker veins within the individual shear zones. $L_{2 \times 3}$ intersection lineations were calculated from the intersection of the two foliations (S_2 and S_3) and also measured directly as crenulation lineations. The intersection lineations and the changing vergence between the two foliations were used to map the position and attitude of large kilometre-scale F_3 fold structures in the Alpine Schist. Detailed measurements were made on individual S_4 shear zones of the orientation of the shear planes, fabric elements in the Alpine Schist, and the displaced quartz vein markers. In addition, separations of the veins across the shears were recorded and the pitch of any fault surface lineations. Detailed structural surveys were conducted at four sites within the BDSZ to quantify the amount of offset and deformation accommodated across the array; three surveys were undertaken on Chancellor Ridge and one at Baumann Glacier. This chapter discusses the results from the structural mapping and detailed shear zone surveys and proposes a deformation sequence to explain the brittle-ductile deformation observed in the shear zones.

3.1. Structural mapping of the field sites

3.1.1. Sam Peak

Sam Peak is located to the southwest of Fox Glacier, ~8 km southeast of the Alpine Fault, and was the southern-most field area examined in this study. The 3 km-wide field area (Fig. 3.1) can be divided into two sections: the western section consists of patchy outcrop of dominantly pelitic schist; and the eastern section where a ~1 km-wide shear array is superbly exposed on glaciated rock platforms in dominantly psammitic schist. The schist in the western section is comprised of F_3 -crenulated sections of psammite within >100 m thick dark grey pelitic schist sequences (e.g. Figs. 3.2a and 3.2b). This schist has been identified as part of the Aspiring Terrane based on this dominantly pelitic composition. In the eastern section thick-bedded sequences of psammitic schist with a phyllitic cleavage are found with only minor 1-10 m sequences of pelite. This section has been identified as part of the Torlesse Terrane (Fig. 3.1a) based on the absence of thick pelitic schist sequences. Textural zone (TZ) boundaries, defined after Turnbull et al. (2001), have been mapped from field observations of the rock textures and by optical microscopy. The eastern section contains TZ's 2b and 3 and the western section contains TZ's 3 and 4. The location of the boundaries between these TZ's is shown in Fig. 3.1a.

The Alpine Schist exposed in the Sam Peak area contains both the S_2 and S_3 foliations. The mean orientation of S_3 is $200@89\text{ NW} \pm 7^\circ$ (95% elliptical confidence cone about the planes pole), with variable S_2 orientations due to F_3 folding. The changing vergence between these two foliation planes indicates an F_3 antiform in the middle of the western section with a fold hinge orientation of $211, 26^\circ$ (Figs. 3.1a and 3.1b). This large km-scale folding was accompanied by cm-scale crenulation of the S_2 foliation with S_3 seen parallel to the axial plane of these crenulations (Fig. 3.2a). Where S_3 was observed as a crenulation foliation, the intersection of the two foliation planes (Fig. 3.2b) defines a fold hinge lineation, L_{2-3} (Fig 3.2c). The mean L_{2-3} lineation measured in the field of $215, 27^\circ \pm 3^\circ$ (95% elliptical confidence cone) matches well with the pole to the S_2 π -girdle (Fig. 3.1c). Extensional features in the schist such as necked and boudinaged quartz veins were also observed near the F_3 fold hinge (Fig. 3.2b). Quartz veins, found commonly

Fig. 3.1. Structural geology of Sam Peak in the Southern Alps of New Zealand. a. Structural map of the Sam Peak field area with mapped mineral isograds, textural zones (after Turnbull et al., 2001), terrane boundaries and brittle ductile shear zone (BDSZ) boundaries. Alpine Schist foliations of S₂ and S₃, brittle-ductile shear planes (S₄) and major F₃ folds are plotted. Altitude contours are spaced at 100 m intervals, taken from the LINZ 1:50,000 topographic digital data set. Projected grid system is New Zealand Map Grid with units in metres. b. Cross section through line A-A' at the same scale as (a) with schematic formlines of major structures and foliations. c. Stereographic, lower hemisphere, equal area projections of mean foliation planes and lineations calculated from measured structural field data. Full stereographic scatter plots available in Fig. 3.6 with data listed in Appendix A. Uncertainties represent a 95% confidence ellipse about the line or pole to the plane.

Fig. 3.2. Alpine Schist in the Sam Peak field area. a. Pelitic schist with crenulated S_2 foliation with S_3 foliation visible as axial planes to the folding. b. Pelitic schist with S_2 and S_3 foliations visible and a necked quartz-carbonate vein. c. Crenulated psammitic schist with crenulated lineation clearly visible. All photographs taken with 58 mm lens cap for scale. d. Glaciated platform covered with some snow near Crozet Peak with Sam Peak and Craig Peak silhouetted by the cloud in the distance to the west.

throughout the field area, are often discordant to the S_3 foliation in the Alpine Schist and have been folded by F_3 about axial planes parallel to S_3 .

Brittle-ductile shears occur in the eastern section of the Sam Peak field area (Fig. 3.1a). The brittle-ductile shears are located in a zone ~1 km-wide but are not found in the adjacent Aspiring Terrane schist to the west. The base of the BDSZ must therefore lie to the west of the mapped S_4 shears but east of the terrane boundary (Fig. 3.1a and 3.1b), but was not actually observed in outcrop. BDSZ boundary in the west is defined passed on where the S_4 shears are no longer present. The flat glaciated surfaces in this eastern section of Sam Peak (Fig. 3.2d) provide excellent exposure for the detailed study of these features. The brittle-ductile shears crosscut both foliations in the Alpine Schist and have displaced quartz-carbonate veins in the schist that act as markers of brittle-ductile deformation with variable components of ductile shearing and brittle slip. The shear planes (S_4) have a mean orientation of $210 @ 66 \text{ NW} \pm 4^\circ$. Mineral fibre lineations were observed on the surface of some 1-10 mm-thick quartz-carbonate veins that infill brittle fractures along the shear zone. These lineations are defined by aligned fibrous calcite or chlorite grains and have a mean orientation of $226, 21^\circ \pm 25^\circ$. They are referred to here as L_4 . Markers of brittle-ductile deformation include quartz-carbonate veins in the schist as well as the foliation and other and layering (e.g. bedding) all indicating a consistent west-side-up sense of dip-slip and dextral sense of strike-slip motions along the shears. Structural data for the Sam Peak field area is documented in Appendix A.

Open cavity veins that infilling the brittle fractures were also found in the Sam Peak area and had a distinctly different texture to the thinner, fibrous veins that commonly infill the brittle-ductile shears. The thick open cavity veins were up to 100 mm wide, consisting of large (some greater than 5 mm in diameter) quartz and calcite crystals, that are often euhedral in form, are texturally distinct from the more typically fine-grained and commonly fibrous veins that infill the shears. Similar open-cavity veins have been described by Craw et al. (1987) and Teagle et al. (1998) from the Callery River headwaters and Almer Ridge in the central Southern Alps, and interpreted as hydrothermally deposited veins. These open cavity veins also occur at Chancellor Ridge and Baumann Glacier field areas but are not as abundant

as at Sam Peak field. These veins, where they infill the brittle-ductile shears, probably represent shallow subsurface reactivation of the S_4 shears, resulting in precipitation of the coarse grained hydrothermal veins at a much later time than the brittle-ductile deformation that initiated the shear zones (Wightman, 2005).

3.1.2. Chancellor Ridge

Chancellor Ridge is located next to Fox Glacier, ~7 km east of the Alpine Fault (Fig. 1.1). This field site has been divided into three sections based on the textural grade of the schist. The eastern section is comprised of psammitic schist classified as TZ 2b (Fig. 3.3a) with a phyllitic cleavage (Fig. 3.4a). This section is comprised of biotite zone schist that is psammite-dominated in composition and is here attributed to a Torlesse Terrane protolith. The middle section consists of TZ 3 Alpine Schist (Fig. 3.3a). This section has the same composition psammitic Alpine Schist as in the eastern section however the foliation is more developed and is defined by the macroscopically visible biotite and muscovite minerals. The western section is structurally deeper than the other two and closest to the Alpine Fault (Fig. 3.3b) and is comprised of TZ 4 psammitic schist (Fig. 3.4b) attributed to the Torlesse Terrane and pelitic schist attributed to the Aspiring Terrane. The Torlesse Terrane schist is biotite grade like the other two sections, but has a visibly layered schistosity defined by mica and quartzite domains. The transition to Aspiring Terrane schist is defined by a sharp contact between TZ 4 psammitic schist and pelitic schist with metabasite and metachert units 10–20 m thick.

The Alpine Schist exposed throughout the Chancellor Ridge field area includes both the S_2 and S_3 foliations. In the western section the two foliations are typically at an angle of $\sim 15^\circ$ to each other (Fig. 3.4b) and define a vergence direction which indicates an antiform to the northwest (Fig. 3.3b). In the central section the S_3 foliation is near parallel to the weakly crenulated S_2 foliation, but in the eastern section only a single phyllitic S_2 cleavage is present (Fig. 3.4a). The mean orientation of the S_2 and S_3 foliations is $036@71$ SE $\pm 17^\circ$ and $033@77$ SE $\pm 3^\circ$ respectively (Fig. 3.3c). Intersection and crenulation lineations (L_{2-3}) measured in the field area have a mean direction of $214, 29^\circ \pm 7^\circ$ (Fig. 3.3c). Quartz-carbonate veins that are 5–20 mm were found in the Alpine Schist where they are folded and

Fig. 3.3. Structural geology of Chancellor Ridge in the Southern Alps of New Zealand. a. Structural map of the Chancellor Ridge area with mapped, textural zones (after Turnbull et al., 2001), terrane boundaries and brittle ductile shear zone (BDSZ) boundaries. Alpine Schist foliations S₂ and S₃, and brittle-ductile shear planes (S₄) are plotted. Altitude contours are spaced at 100 m intervals, taken from the LINZ 1:50,000 topographic digital data set. Projected grid system is New Zealand Map Grid with units in metres. b. Cross section through line A-A' with formlines for major structures, foliations and Chancellor Hut for reference. c. Stereographic, lower hemisphere, equal area projections of mean planes calculated from measured structural field data. Full stereographic scatter plots available in Fig. 3.6 with data listed in Appendices A and B. Uncertainties represent a 95% confidence ellipse about the line or pole to the plane.

Fig. 3.4. Alpine Schist on Chancellor Ridge and structural surveys on Chancellor Ridge and Sam Peak. a. Psammitic schist in textural zone 2b with a millimeter scale phyllitic cleavage. S₂ foliation is visible with quartz-carbonate vein that infills a brittle shear (S₄) that has a mineral fibre lineation on the surface (marked with arrow). b. Alpine Schist from textural zone 4 with well defined S₂ schistosity. Schistosity is folded with S₃ cleavage visible parallel to the fold hinges. Quartz-carbonate vein is displaced by brittle-ductile shear (S₄) that crosscuts all foliations. Glaciated platform with geologists R. H. Wightman and K. J. Wilson working on structural survey CH03 on Chancellor Ridge. d. Glaciated platform at Baumann Glacier with geologist A/ Prof. T. A. Little working on structural survey BM01.

crenulated across folds that are axial planar to the S_3 foliation. These veins are typically <5 m in length.

Brittle-ductile shears were observed in all three sections on Chancellor Ridge with the best exposures of the arrays occurring in the eastern section on glacially eroded platforms (Fig. 3.4c). The shear arrays in the central and western sections crop out between tussock fields and in incised river channels leading down toward Fox Glacier. The eastern BDSZ boundary was not seen in the field because of excessive seasonal snow and ice, but can be approximately located using aerial photographs (see section 3.2.1). The western structurally lower BDSZ boundary was located in the western section along the margin of Fox Glacier where brittle-ductile deformation was no longer seen in the Alpine Schist on distinct shear planes.

The shear planes (S_4) at Chancellor Ridge have a mean orientation of $217 @ 87 \text{ NW} \pm 1^\circ$ with mean spacing between the shears varying from ~2 m in the western section to ~10 mm in the eastern section. Like the shear arrays found at Sam Peak, the Chancellor Ridge shear arrays offset quartz-carbonate veins in the host rocks and the Alpine Schist foliation by a variable combination of ductile shearing and brittle slip. Displaced veins and foliations consistently indicate west-side-up dip-slip and dextral strike-slip shear senses throughout the BDSZ. The shear planes are commonly filled with quartz-carbonate veins 1-10 mm thick preserve a mineral fibre lineation (L_4) defined by fibrous calcite and chlorite on the vein margin, that has a mean orientation of $222, 28^\circ \pm 10^\circ$. All structural data for the Chancellor Ridge field area is listed in Appendix A.

3.1.3. Baumann Glacier

The Baumann Glacier field area is located around the Baumann, Fritz and Andermatten Glaciers (Fig. 3.5a) and is the northernmost field area in this study, situated 1.5 km south of Franz Josef Glacier (Fig. 1.1). This field area is located ~6 km east of the Alpine Fault and field mapping was limited to outcrops exposed through unseasonably extensive snow and ice. There the Alpine Schist is biotite grade and consists dominantly of psammite with an inferred Torlesse Terrane protolith. Outcrops of Aspiring Terrane metabasites were seen to the northwest from a distance across the Baumann Glacier. There green and red coloured outcrops occur near the boundary between TZ 4 and TZ 3 outcropping on the steep southeast slope

Fig. 3.5. Structural geology of the Baumann Glacier region in the Southern Alps of New Zealand. a. Structural map of the Baumann Glacier area with mapped textural zones (after Turnbull et al., 2001), terrane boundaries and brittle ductile shear zone (BDSZ) boundaries. Alpine Schist foliations, S_2 and S_3 , brittle-ductile shear planes (S_4), and major F_3 folds are plotted. Altitude contours are spaced at 100 m intervals, taken from the LINZ 1:50,000 topographic digital data set. Projected grid system is New Zealand Map Grid with units in metres. b. Cross section through line A-A' at the same scale as (a) shows schematic formlines for major structures and foliations. Area of unmapped BDSZ has structure interpreted from aerial photographs. c. Stereographic, lower hemisphere, equal area projections of mean planes calculated from measured structural field data. Full stereographic scatter plots available in Fig. 3.6 with data listed in Appendices A and B. Uncertainties represent a 95% confidence ellipse about the line or pole to the plane.

of Mt Moltke (Fig. 1.1) to the northwest of Baumann Glacier. This approximate location of the Torlesse-Aspiring terrane boundary (Fig. 3.5a) matches unpublished maps of T. A. Little and B. R. Ilg who identified a fault which juxtaposes the Torlesse and Aspiring terrane lithologies. Two TZ boundaries are identified in this field area (Fig. 3.5a). The TZ 2b to TZ 3 boundary was mapped based on field observations from this study and from unpublished maps of T. A. Little and B. R. Ilg. The TZ 3 to TZ 4 boundary was located based on field textural observations of the schistosity at the northwest extent of the outcrops observed in this study.

Most outcrops of Alpine Schist throughout the Baumann Glacier area have the S_2 and S_3 foliations. The mean orientation of S_3 is $043@80\text{ SE} \pm 5^\circ$ with the orientation of S_2 varying throughout the field area (Fig. 3.5c). The location of F_3 fold structures (three antiforms and two associated synforms) were mapped (Figs. 3.5a and 3.5b) on the basis of the changing vergence between these two foliations. Hinges of the F_3 folds have a mean orientation of $215, 31^\circ$. This large kilometre-scale folding is accompanied by centimetre-scale crenulation of the S_2 foliation with S_3 axially planar to these crenulation folds. Intersection and crenulation lineations are parallel to the fold hinges with a mean orientation of $215, 27^\circ \pm 3^\circ$. Quartz-carbonate veins in the Alpine Schist are generally <5 m long. Some outcrops contained 30 cm-long gash veins in arrays of 10 veins or more, spaced ~ 20 cm apart. These gash veins are folded and crenulated with axial planes parallel to the S_3 foliation. Extensive ice and snow cover during the field season prevented study of the region to the northwest of the TZ 3 to TZ 4 boundary.

Arrays of brittle-ductile shears have been mapped from the southeast cirque walls of the Andermatten Glacier to the northwest side of the Baumann Glacier and both the upper and lower boundaries of the BDSZ can be approximately located (Fig. 3.5a). Brittle-ductile shears occur as discrete fault-like planes that are spaced ~ 15 cm apart. They offset quartz-carbonate veins and the Alpine Schist foliations by variable components of ductile shearing and brittle slip. Shear planes (S_4) exposed on glaciated surfaces (Fig. 3.4d) have a mean orientation of $046@82\text{ SE} \pm 2^\circ$ (Fig. 3.5c) and consistent west-side-up dip-slip and dextral strike-slip shear senses. Shears were not seen in the snow-covered northwest section of the field area, however, aerial photographs confirm their presence in these regions (see section 3.2.1). As at

Sam Peak and Chancellor Ridge, some shear planes are filled by quartz-carbonate veins that are 1-10 mm thick. These infilling veins have mineral fibre lineations (L_4) composed of calcite and chlorite visible on the surface of the veins, with a mean orientation of $228, 42^\circ \pm 9^\circ$; however, some infilling veins had more than one orientation of lineation on their surface or had a lineation which curved from a steep to shallow pitch within the same shear plane. All structural data collected from the Baumann Glacier field area in this study can be found in Appendix A.

3.1.4. Variation in foliation and lineation orientations between the field areas

The structural attitudes of the shear planes, schist foliations, and lineations are plotted in Fig. 3.6 and illustrate the changing orientation of the shear planes and the foliations from Sam Peak in the south to Baumann Glacier in the north. The Alpine folded S_2 foliation at Sam Peak (Fig. 3.6a) and Baumann Glacier (Fig. 3.6c) has a mean northeast strike and varies in dip from near horizontal to near vertical. The S_2 foliations at Chancellor Ridge are consistently steeply dipping to the southeast with a northeast strike (Fig. 3.6b). The southwest plunging pole to the π -girdle is similar at both Sam Peak and Baumann Glacier, and matches well with the measured intersection lineations (L_{2-3}) and the plotted intersection of the S_2 and S_3 foliations in all three field areas (Fig. 3.6). The attitude of S_3 is similar across all the field areas with a common northeast strike and dip that is within 15° of vertical. Mean structural attitudes for the field areas can be found in Table 3.1.

The brittle-ductile shear planes change their strike from NNE in the south at Sam Peak to NE strike in the north at Baumann Glacier (Fig. 3.6; Table 3.1; Fig. 3.7). This clockwise rotation of strike continues further north at Crawford Knob (Fig. 1.1; Table 3.1) where an ENE strike was measured by Wightman (2005). The average dip of 66° northwest for the Sam Peak shear planes to the south is shallower than the Chancellor Ridge and Baumann Glacier shear planes that, on average, dip within 10° of vertical (Fig. 3.7). This changing attitude of the shear planes has been related to the changing dip of the Alpine Fault ramp at depth by Little et al. (2005). The mineral fibre lineations found on quartz-carbonate veins infilling the shear zones vary in pitch from 80° to 7° southwest (Fig. 3.7). They have a mean trend and plunge of $226, 35^\circ \pm 6.9^\circ$ as calculated for the combined data from Sam Peak, Baumann Glacier and Chancellor Ridge (Table 3.1). The lineations (L_4) appear to be slightly

Fig. 3.6. Stereographic, lower hemisphere, equal area projections of foliation and shear planes and lineation lines for Sam Peak (a), Chancellor Ridge (b) and Baumann Glacier (c). Orientations are listed in Table 3.1 with data used to generate plots in Appendices A and B.

Plane / Line	Chancellor Ridge			Sam Peak			Baumann Glacier			Combined		
	mean	±	n	mean	±	n	mean	±	n	mean	±	n
S ₄	217@87 NW	0.8	459	210@66 NW	4	59	049@82 SE	1.5	262	221@89 NW	1.1	780
L ₄	222, 28°	10.3	7	226, 21°	25.4	4	228, 42°	8.9	14	226, 35°	6.9	25
S ₃	033@77 SE	2.9	49	207@82 NW	6.7	35	043@80 SE	4.7	35	034@84 SE	3.4	119
S ₂	036@71 SE	17.3	3	196@62 NW	9.4	21	049@68 SE	9.4	49	045@73 SE	13.3	73
Pole to S ₂ girdle	213, 08°	7.9	3	216, 33°	6.9	21	215, 31°	6.9	49	214, 31°	7.5	73
L ₂₋₃	214, 29°	7.2	5	216, 31°	6.4	16	215, 27°	3.7	27	216, 28°	2.8	48

[Crawford Knob: S₄: 240@89 NW (n=1074) and L₄: 241,39° (n=81)]

Table 3.1. Mean values for planes and poles plotted in Fig. 3.6 calculated from data in Appendices A and B. Uncertainties in degrees for 95% elliptical confidence cone about a mean line or pole to plane. Crawford Knob data courtesy of Wightman (2005). Combined column represents an augmented data set from Chancellor Ridge, Sam Peak and Baumann Glacier data sets for measured planes and poles.

Fig. 3.7. Mean orientation of brittle-ductile shear planes from the main field areas and Crawford Knob. a. Stereographic, lower hemisphere, equal area projection of mean brittle-ductile shear planes and mineral fibre lineations for the main field areas. b. 3-dimensional block diagrams of the shear planes with the mean orientation listed with strike values all for the northeast end of the plane.

steeper plunging in the northern field areas than the southern ones (Fig. 3.7a), but these differences are not statistically significant.

3.1.5. Waiho River and Hare Mare Creek

The Waiho River and Hare Mare Creek locations (Fig. 2.2) were chosen in order to compare the CPO behaviour of quartz in the higher grade non-mylonitic and mylonitic schist with the deformed veins in the BDSZ. These two field sites are located structurally below the BDSZ, closer to the Alpine Fault. The Waiho River site is located ~4.5 km east of the Alpine Fault in the garnet zone non-mylonitic schist and Hare Mare Creek site is located ~100 m east of the Alpine Fault in amphibolite facies mylonitic rocks (Fig. 2.2). The Waiho River sample site occurs on the overturned limb of a large F_3 antiform, referred to as a planar zone by Little et al., (2002a). There, S_2 and S_3 are a single parallel cleavage and lineations plunge moderately southwest and include crenulation lineations, intersection lineations and stretching lineations. Foliation and lineation data are listed in Appendix A and have mean orientations of $040@79\text{ SE} \pm 2.1^\circ$ and $206, 50^\circ \pm 5.2^\circ$ respectively.

The Hare Mare Creek sample site is located in the Alpine Fault mylonite zone (Fig. 2.2) and is comprised of fine-grained micaceous mylonitic fault rocks which are well foliated and laminated into cleavage and microlithon domains. These domains are <5 mm thick and defined by mica-dominated layers and quartzofeldspathic dominated layers. Locally, 5-15 mm chert bands lie parallel to this mylonitic foliation. S-C' shears, necked quartz bands, boudinaged hornblende porphyroblasts and rotated garnet porphyroblasts are observed in hand sample as well a northeast plunging mineral stretching lineation defined by the elongated quartz and hornblende porphyroclasts. Orientation for the mylonitic foliation (S_m) and the mineral stretching lineation (L_m) are in Appendix A and Appendix F. This foliation and lineation have mean orientations of $048@30\text{ SE} \pm 3^\circ$ and $105, 28^\circ \pm 7^\circ$ respectively.

3.2. Observations of deformation in the BDSZ's

3.2.1. Brittle-ductile shear arrays

Brittle-ductile shear arrays have been observed in aerial photographs in each of the three main field areas (not including the Waiho River and Hare Mare Creek sample sites), as well as in ~100 m high cliff outcrops and directly on flat glaciated

platforms at the scale of an individual shear zones spaced at 20 cm. Aerial photographs of Chancellor Ridge and Baumann Glacier in Fig. 3.8 show the entire 2 km-wide BDSZ and some of the individual shear zones. These shear zones are seen as distinct lineaments parallel to the strike of the brittle-ductile shears (S_4) and have allowed the upper and lower boundaries of the BDSZ to be mapped beyond the areas where foot access was possible. The lineaments seen on the aerial photographs are defined by the S_4 fault planes in the schist along which differential erosion has caused the rock to weather and partition into slabs in preference to the more NNE striking Alpine Schist foliation. Wightman (2005) mapped the upper and lower boundaries from aerial photographs to define a 1-2 km wide zone of brittle-ductile shear arrays, located 6-8 km southeast of the Alpine Fault, that extend along strike from Sam Peak in the south to the Price Range above the Gunn River in the north (Fig. 2.2).

Distant views of cliff outcrops, in some cases greater than 100 m high, have been used to obtain a better understanding of the three-dimensional extent of the shear zones and their orientation with respect to the Alpine Foliation (Fig. 3.9). These exposures clearly revealed the brittle-ductile shear planes (S_4) cross cutting both the S_2 and S_3 foliations at an acute angle (Fig. 3.9a). The shears are more steeply dipping than S_3 at Chancellor Ridge (Fig. 3.9b) but shallower in dip than S_3 at Sam Peak (Fig. 3.9c). An approximately consistent <10 m spacing and orientation of shear planes can be seen throughout all of these cliff exposures.

Outcrops of brittle-ductile shear arrays on glaciated surfaces of the Alpine Schist (Fig. 3.10) have been studied in detail with respect to their spacing, shear sense and separation or offset of displaced marker veins. Fig. 3.10a illustrates the superb glaciated exposure of Alpine Schist and the parallel fractures that represent shear zones with brittle-ductile offset. The fractures are spaced ~20 cm apart (Figs. 3.10b and 3.10c) and offset markers such as quartz-carbonate veins in the schist in both a dextral (Fig. 3.10d) and a west-side-up (3.10e) shear sense. These quartz-carbonate veins are commonly serially displaced across a series of adjacent shear zones (Fig. 3.10d), and make excellent markers for analysis of shear-related deformation caused by repeated slip across faults in the array.

Fig. 3.8. Aerial photographs of Chancellor Ridge and Baumann Glacier field areas. a. Chancellor Ridge and Fox Glacier aerial photograph with shear planes visible as discrete lineaments and fractures in the Alpine Schist. Arrows indicate and are parallel to some selected fracture locations. b. Baumann Glacier and Fritz Glacier aerial photograph with shear planes visible as discrete lineaments and fractures as at Chancellor Ridge. Arrows indicated shears as in Chancellor Ridge photograph in Fig. 3.8a.

Fig. 3.9. Vertical cliff outcrops at the three main field areas with brittle-ductile shears visible. a. SW side of Andermatten Glacier (from the Baumann Glacier field area); NW-SE striking glacially eroded exposure showing steep SE-dipping S_4 shears, S_3 foliation, S_2 foliation and F_3 fold. Geologists for scale on rock, circled, bottom, centre. b. Chancellor Ridge; exposure of steep NW-dipping S_4 shears and S_3 foliation. c. Sam Peak; exposure of moderate NW-dipping S_4 shears. Sam Peak photograph by T. A. Little. Author for scale in bottom left corner (circled).

Fig. 3.10. Arrays of brittle-ductile shears on Chancellor Ridge and Baumann Glacier. a. Glaciated platform on Chancellor Ridge with discrete crack features running horizontally across the exposed Alpine Schist. b. Vertical section of brittle-ductile shears seen as cracks crosscutting the Alpine Schist at Baumann Glacier (author for scale). c. Arrays of brittle-ductile shears with west-side-up sense of shear at Chancellor Ridge. Shear planes arrowed. d. Horizontal surface outcrop showing displaced quartz-carbonate vein in Alpine Schist at Chancellor Ridge separated by multiple shear planes showing dextral shear sense. e. Vertical outcrop surface at Chancellor Ridge showing west-side-up sense of shear and brittle-ductile deformation of quartz-carbonate veins. Shear infilling vein 2-3 mm thick also seen precipitated along central shear plane. Cold chisel for scale is 150 mm long.

3.2.2. Brittle-ductile sheared veins

Deformation within individual shear zones is accommodated by brittle offset of the quartzofeldspathic Alpine Schist with contemporaneous ductile deformation of quartz-carbonate veins embedded within that schist (Fig. 3.11). These veins are observed to have variably undergone ductile, brittle-ductile or totally brittle deformation. Veins that have undergone ductile shearing only (e.g. Fig. 3.11a) have the same displacement as markers in the schist that are offset by brittle fracturing, however, the brittle cracks in those cases terminated into the ductilely deformed vein and did not propagate through across it. Brittle faults displace the quartzofeldspathic schist as far as the margins of the vein where they are blunted into the edge of the vein, and later potentially propagate along the margin of the already ductilely sheared vein.

Some sheared veins have undergone both brittle and ductile deformation (e.g. Fig. 3.11b). In these veins ductile shearing accommodated a proportion of the offset and brittle slip accommodated the rest. Younger, shear-parallel, veins infill some of the brittle fractures cross-cutting the quartzofeldspathic schist. These syntectonic shear infilling veins are found in the shear zone where the quartz-carbonate marker veins have deformed by brittle offset (e.g. Fig. 3.11c). Some quartz-carbonate veins have undergone solely brittle offset in the shear zone and the faults are seen to displace the veins without any accompanying ductile shearing (e.g. Fig. 3.11d).

Deformation in a series of individual shear zones and across different marker veins is variably brittle to ductile with inconsistent marker separations, largely because of the different dips of these veins. The proportion of brittle to ductile shear strain in a given vein is rarely the same as an adjacent offset on the same or an adjoining shear. It is not uncommon for deformation of a single vein to be accommodated by different proportions of brittle and ductile styles where it is intersected by a series of shears (Fig. 3.11d). Marker offsets are rarely exactly the same between adjacent shears because of changing vein attitude and outcrop orientations. Most outcrop separations are in the range of 25-100 mm (e.g. Fig. 3.11d and Fig. 3.11e) with the largest separation measured at 720 mm.

The Alpine Schist foliation (S_3) is cut at an acute angle by the younger shear planes (Fig. 3.11e). Where the schist is pelitic, shear planes commonly either

crosscut or merge into parallelism with the Alpine foliation. Such merging does not occur in the psammitic schist which is crosscut everywhere by the shears at an acute angle. Between the shears, folding and buckling of the deformed veins accompanied development of the older foliations and has generated a cleavage parallel to S_3 in some veins (e.g. Fig. 3.11a). The mean orientation of the marker veins measured in this study was $029@77\text{ SE} \pm 4^\circ$ ($n=425$). Where markers for the shear zone deformation were folded, the enveloping surface was measured as the mean marker orientation. Some shear planes did not crosscut quartz-carbonate veins and alternative features such as the S_2 or S_3 foliation layering defined by graphitic or pelitic rich layers were used as offset markers (Fig. 3.11f).

The veins infilling the brittle fractures in the shear zone vary from 1-20 mm in thickness and often have a mineral fibre lineation (L_4) on the vein surface (Fig. 3.11g). Occurring in calcite and chlorite selvages on the outside of the vein wall, the mineral fibre lineations give the vein surface a grooved texture and striate the fault plane. Chlorite books and single crystals observed on the vein surface in the field (Fig. 3.11h) are dimensionally aligned to define a surface lineation on the vein surface. The lineations plunge moderately to the southwest at a mean pitch of $35^\circ \pm 7$ ($n=25$) with a range from $8-80^\circ$. Lineations are typically well preserved in shear zones with infilling veins but are found on some shear planes as a thin mineral layer on the fault surface.

3.3. Calculated net-slip pitch

The pitch of the three-dimensional displacement vector (net-slip pitch) in the shear plane has been calculated from multiple non-parallel veins in cross section (Fig. 3.12). Measurements were made of the outcrop surface orientation, vein orientations, shear attitude, and the separation of the veins on the outcrop surface. The planar data are plotted on a stereographic projection to find the marker vein intersections on the fault surfaces and then a fault-parallel orthographic plot of these cut-offs and the outcrop trace was constructed. When the non-parallel traces of the sheared veins are plotted on the fault surface, piercing points in the shear plane can be determined from the two differently intersecting marker traces. Piercing points are identified from this orthographic projection and line connecting these points is the inferred pitch of the displacement vector (Fig. 3.12).

Fig. 3.12. Net-slip vector pitch calculations using the piercing point method for samples MHCH20 (a) and BM22 that contain multiple non-parallel marker veins (b). Photograph or cartoon of outcrop surface, stereographic projections of marker, shear and outcrop surface planes, and orthographic projection of the fault plane where the net-slip pitch and shear displacement (net-slip) are calculated. White labels in black circle are constant for the planes in the different diagrams for each sample and defined in text below stereographic projection. See text for further details.

More typically, the shear zones offset only one visible displaced marker visible on a given outcrop exposure or multiple markers that are sub-parallel in their orientation and calculation of the net-slip vector is not possible. However, two pairs of non-parallel marker vein offsets have been used to calculate the net-slip vector from a site at Chancellor Ridge (Fig. 3.12a) and another at Baumann Glacier (Fig. 3.12b). Shallow southwest net-slip pitches of 2° and 18° for these two sites have been calculated. Unfortunately neither of these samples had a mineral fibre lineation present on the shear plane for direct comparison to the calculated net-slip pitch. Given the uncertainties, in this calculation the resulting displacement vectors are similar to the observed mean mineral lineation pitches at these localities (Table 3.1) and confirm that the fault surface lineations are at least sub-parallel to the net-slip vector.

Fault offset analysis and numerical modelling by Wightman (2005) from data collected from a linear transect survey undertaken in the BDSZ at Crawford Knob (Fig. 2.2) has shown that a mean southwest net-slip pitch of $20\text{--}45^{\circ}$ is likely for the brittle-ductile shears. Wightman (2005) also concluded that the mineral fibre lineations, although having a broad range, represent the displacement vector at some point within the deformation phase and that the mineral fibres grew throughout the displacement. Results from this study agree well with these arguments and the displacement vector for the shears can therefore be inferred as a pitch of $\sim 30^{\circ}$ from the southwest.

The mineral lineation and calculated net-slip directions have a broad range of southwest pitches from 2° to 80° . During transpressive deformation, this range is not unusual and lineations may have a wide range of orientations (Robin and Cruden, 1994), or even rotate along strike or across the shear zone due to strain gradients (Tikoff and Greene, 1997). Mineral lineations that curve and have variable pitches are found on some exposed shear planes at Baumann Glacier. These variations are therefore most likely due to transpressive deformation in the shear zones.

3.4. Structural surveying of the BDSZ's

Detailed structural surveys were carried out within the BDSZ along linear transects at Chancellor Ridge and Baumann Glacier. Surveying was undertaken along a survey transect line approximately perpendicular to the strike of the Alpine

Fault on glaciated exposures of schist with continuous outcrop, along which we endeavoured to measure every shear zone offset. These surveys involved measuring structural data to calculate the shear displacement, shear spacing and finite ductile shear strain. These calculations made for the individual surveys (e.g. Figs. 3.13 and 3.14) have been used to approximate the bulk deformation and kinematics of the shear zone arrays as a whole.

3.4.1. Structural survey methods and field locations

The survey transects involved measuring the orientation of 1) the shear plane, 2) a separated marker plane, and 3) the outcrop surface in addition to the offset or separation of the marker on that surface. Each shear zone intercepted by the transect was allocated a node number for reference in the survey and the distance between the shears in the direction parallel to the transect line was noted. The computer software (in Microsoft Excel) from Little (1996) was used to calculate the shear normal spacing and the shear displacement from the data measured in the field for each node (Fig. 3.13). A three-dimensional slip vector for each offset observation (1 per node) was assigned. The mineral lineations were used as this slip direction for the six nodes (~1% of the surveyed nodes) where they were measured on the shear plane. For the remaining nodes where a lineation was not observed on a given shear a mean value was assigned instead. The assigned mean value has a southwest pitch of 30° in the shear plane and was based on an average of the mineral fibre lineations measured across the field areas and the calculated net-slip pitch from piercing point analyses (see section 3.3).

Surveys were made at different structural levels within the BDSZ on sections where continuous outcrop exposed more than fifty shear zones for measurement. Measurement of the ductile deformation width, the deformed vein thickness and the ductile separation of the marker was also made. This data will be used to compare the ductile deformation in the shear zones with shear spacing and Alpine Schist lithology at different structural levels within the BDSZ.

Structural transect data were collected on Chancellor Ridge at three survey locations; one at the structural base of the BDSZ, one in the middle, and one near the top of the BDSZ (see Fig. 3.3a for mapped locations). Survey Chancellor 01 (CH01) was made at a site of dominantly pelitic schist located ~220 m structurally above the

Fig. 3.13. Method of calculation for shear displacement (net-slip) from data in survey transects of fault offsets. Node 34 in survey BM01 (Appendix B) used as example. Black numbered circles represent planes measured and are consistent across all three sections of figure. a. 3-dimensional block diagram illustrating calculated net-slip from measured surface displacement and given SW net-slip pitch of 30°. Shear normal spacing (SNS) calculated as distance to structurally lower shear. Shear normal convergence (SNC) calculated from plate convergence vector (PCV) of 071° at 37 mm/yr and angle θ (PCV - shear plane strike). Surface (1') is a representative outcrop plane for this Fig. with the same shear intersection as the actual surface. Net-slip of 250 mm, net-slip SW pitch of 30°, and marker vein are scaled and oriented as in Figs. b and c. b. Lower hemisphere, equal area, stereographic projection of outcrop surface (1), shear plane (2), marker vein (3) and representative outcrop surface in Fig. a (1'). Pitch of intersections with shear plane are labeled. c. Calculated net-slip from displaced marker in projected view of the shear plane. Pitches of marker vein and outcrop surface from Fig. b. See Fig. 3.14a for displacement measurement.

b Calculated λ_d and ϵ_m

$$\gamma_d = \frac{(\text{netslip} \times DTR)}{DW} = \frac{337 \times 0.12}{20} = 2$$

where:

$$DTR = \frac{\text{ductile_sep.}}{\text{total_sep.}} = \frac{30}{250} = 0.12$$

$$\epsilon_m = \frac{\gamma_d}{\text{time}} = \frac{2}{2.45 \text{ yr}} = 2.6 \times 10^{-8} \text{ sec}^{-1}$$

where:

$$\text{time} = \frac{SNS}{SNC} = \frac{40}{16.2} = 2.45 \text{ yr}$$

$$SNC = \sin \theta \times PCV = \sin(26) \times 37 = 16.2 \text{ mm / yr}$$

Fig. 3.14. Calculation of finite ductile shear strain (γ_d) and maximum strain-rate (ϵ_m) from survey data. Node 34 in survey BM01 (Appendix 2) used as example. a. Cartoon shear zone illustrating the measured brittle and ductile separation and ductile deformation width (DW) of a displaced vein. Black labeled circles represent planes in Fig. 3.13. b. Formula used for calculating γ_d and ϵ_m for Node 34. Formula for shear normal convergence rate (SNC) using the plate convergence vector (PCV) (Fig. 3.13) and the time between sequential shear activation using the shear normal spacing (SNS) and the SNC. Ductile to total separation ratio (DTR). Angle between the shear plane and the PCV (θ).

western and basal BDSZ boundary. This transect consisted of 47 nodes measured along a 61.01 m long survey line. Survey Chancellor 02 (CH02) was made southeast of CH01 in psammitic schist located ~1150 m structurally above the western and basal BDSZ boundary. This transect consisted of 100 nodes measured along a 5.1 m survey line. Survey Chancellor 03 (CH03) was made southeast of CH02 in psammitic schist at a site located ~1420 m structurally above the western and basal BDSZ boundary (Fig. 3.4c). This transect consisted of 155 nodes along a 27.11 m survey line.

At Baumann Glacier, another transect was measured (see Fig. 3.5a for location) and individual shear array measurements collected across the field area were additionally compiled into a second data set that was not rigorously measured along a continuous transect. Survey Baumann 01 (BM01) was made in psammitic schist located ~515 m structurally above the western and basal BDSZ boundary (Fig. 3.4d). This transect consisted of 111 nodes measured along a 19.54 m survey line. The non-transect line survey (BM-f) consisted of 22 shear observations measured throughout the BDSZ near Baumann Glacier (mapped area of Fig. 3.5). The survey BM-f was compiled to test whether the small survey lines measured in the transect surveys (CH01, CH02, CH03 and BM01) are biased towards particular localised deformation conditions within the BDSZ or representative of the whole 2 km wide zone. Grid references, survey line bearing directions and data measured for all of the transect surveys in the Baumann Glacier and Chancellor Ridge field areas can be found in Appendix B.

Mean planar orientations of the shear planes and markers were calculated from the data compiled from the five surveys, including cut-offs of the marker veins against the shear planes (Figs. 3.15 and 3.16). The mean shear plane for the aggregated the Chancellor Ridge data (compiled from all three surveys) is steeply dipping to the northwest whereas the mean shear plane from the Baumann Glacier data has a steep southeast dip. The northeast strike of the shear planes in both survey areas is similar. The marker veins in the Baumann Glacier surveys have near vertical dips and strike close to the north whereas the Chancellor Ridge marker veins have a northeast strike and a moderate southeast dip. Unfortunately, this southeast-dipping mean vein orientation at Chancellor Ridge results in a southwest pitching cut off for these markers on the shear planes. Typically the southwest cut-off pitch of 17-26° is

Fig. 3.15. Orientations of shear planes and marker veins from the three surveys on Chancellor Ridge. Combined results are also shown for all plane and marker veins measured in Chancellor Ridge surveys. Mean shear plane has been shown on the marker vein projections for reference in graphical representation of intersection pitch. Projections are on lower hemisphere, equal area, stereographic plots and uncertainties are in degrees for a 95% confidence ellipse about the mean line or pole to the plane.

Fig. 3.16. Orientations of shear planes and marker veins from the two surveys at Baumann Glacier. Combined results are also shown for all plane and marker veins measured in Baumann Glacier surveys. Mean shear plane has been shown on the marker vein projections for reference in graphical representation of intersection pitch. Projections are on lower hemisphere, equal area, stereographic plots and uncertainties are in degrees for a 95% confidence ellipse about the mean line or pole to the plane.

sub-parallel to the pitch of the mineral fibre lineation or the assigned net-slip pitch in the shear plane. This results in a trigonometrically unstable cut-off geometry that hinders reliable calculation of shear displacement from the outcrop separation of the veins. Nodes where the cut-off pitch of these marker veins was within five degrees of the net-slip vector pitch were filtered from the survey to avoid these trigonometrically unstable shear displacements. Typically, ~14 % of the data was eliminated by this filtering (Table 3.2d); however, up to 60% of the data was removed in survey CH01, as many of the marker veins had a moderate pitching southwest cut-off (Table 3.2d). The pitch of the marker vein in the shear plane for each survey node can be found in Appendix B.

3.4.2. Calculation of shear displacement

The shear displacement (net-slip) calculated by the computer software of Little (1996) required planar measurements of the shear plane, the separated marker and the outcrop surfaces as well as the observed separation of the markers in the outcrop. The net-slip calculation process made by the computer software is illustrated graphically in Fig. 3.13 using a shear zone from the Baumann Glacier survey as an example. The shear displacement calculations have been carried out on the data for the preferred assigned net-slip pitch of 30° (Table 3.2; Fig. 3.17a) as well as net-slip pitches of 20° and 40° (Fig. 3.17a). These two additional net-slip calculations illustrate that the data is sensitive to net-slip pitch variations with steeper pitches in most surveys resulting in higher shear displacements. The mean shear displacement calculated from all the survey nodes is 9.9 ± 1.4 cm (n=380 of 435 nodes; Table 3.2c). The mean shear displacement in both of the Baumann Glacier surveys was higher than that at Chancellor Ridge with survey CH01 having the lowest displacement of 5.5 ± 1.9 cm and BM-01 having a higher displacement of 11.3 ± 2.8 cm (Table 3.2; Fig. 3.17a).

3.4.3. Calculation of finite ductile shear strain

During surveying the total and the ductile component of separation were both measured during the surveying (Fig. 3.14a) and the ratio of ductile to total slip (DTR) has been calculated. This ratio has been used to calculate the ductile component of the net-slip, which when divided by the ductile deformation width

a

(for net-slip pitch of 30°)	Survey:	CH01			CH02			CH03		
		mean	2 σ	n	mean	2 σ	n	mean	2 σ	n
Total shear displacement (cm)		5.48	1.87	19	15.20	8.24	82	8.93	2.83	131
Finite ductile shear strain		2.01	0.75	18	7.6	3.7	27	3.9	1.2	78
Shear spacing (m)		1.27	0.27	47	0.05	0.01	100	0.15	0.03	155
Marker vein thickness (mm)		9.5	2.9	24	5.5	1.2	38	6.3	1.0	129
Infilling vein thickness (mm)		2.4	0.5	24	1.6	0.7	100	2.3	0.8	155
Ductile deformation width (cm)		0.64	0.19	24	0.09	0.04	98	0.43	0.11	155
Displacement / spacing ratio		0.43	-	-	31.19	-	-	5.92	-	-
Ductile / total separation ratio		0.24	0.08	24	0.14	0.06	98	0.30	0.06	150

b

(for net-slip pitch of 30°)	Survey:	BM01			BM-f		
		mean	2 σ	n	mean	2 σ	n
Total shear displacement (cm)		11.28	2.80	91	13.47	4.42	21
Finite ductile shear strain		5.5	1.1	75	4.9	1.4	21
Shear spacing (m)		0.14	0.03	111	0.11	0.04	4
Marker vein thickness (mm)		10.5	1.3	101	8.7	1.4	22
Infilling vein thickness (mm)		1.7	0.5	61	2.1	1.3	7
Ductile deformation width (cm)		0.97	0.21	101	1.24	0.32	22
Displacement / spacing ratio		7.80	-	-	12.73	-	-
Ductile / total separation ratio		0.48	0.08	101	0.54	0.14	22

c

(for net-slip pitch of 30°)	All Surveys		
	mean	2 σ	n
Total shear displacement (cm)	9.9	1.4	344
Finite ductile shear strain	4.8	0.7	219
Shear spacing (m)	0.25	0.05	410
Marker vein thickness (mm)	8.0	0.7	314
Infilling vein thickness (mm)	2.0	0.4	347
Ductile deformation width (cm)	0.53	0.08	395
Ductile / total separation ratio	0.31	0.04	395
Shear normal convergence rate	19.7	0.4	435
Mean maximum strain-rate (sec ⁻¹)	8.6E-08	3.1E-08	224

d

Survey:	CH01			CH02			CH03			BM01			BM-f		
	Total	Filtered	%	Total	Filtered	%	Total	Filtered	%	Total	Filtered	%	Total	Filtered	%
P=40	47	30	63.8	100	15	15.0	155	29	18.7	111	24	21.6	22	2	9.1
P=30	47	28	59.6	100	18	18.0	155	24	15.5	111	20	18.0	22	1	4.5
P=20	47	26	55.3	100	34	34.0	155	30	19.4	111	19	17.1	22	0	0.0

Table 3.2. Results for structural surveys CH01, CH02, and CH03 at Chancellor Ridge (a) and BM01 and BM-f at Baumann Glacier (b). Survey results combined for all surveys, with the addition of the calculated mean shear normal convergence and calculated mean maximum strain-rate, are listed in Table (d). Nodes from the survey which had an intersection of the marker and shear plane $\pm 5^\circ$ from the net-slip pitch have been filtered from the survey data sets. Table (d) contains the statistics for the total number of survey nodes measured, the number of nodes removed and the fraction of the nodes removed from filtering. These are listed for each of the surveys and at different net-slip pitches from the southwest.

Fig. 3.17. Graphed results for survey data in Table 3.2 for different net-slip pitches (P= SW net-slip pitch: 20°-blue, 30°-green and 40°-red) and survey sites. a. Shear displacement (net-slip) for different surveys and SW net-slip pitches. b. Finite ductile shear strain for each survey and different net-slip pitches. c. Total shear displacement / shear normal spacing ratio and ductile / total separation ratio for each survey. Uncertainty bars $\pm 2\sigma$ for plots.

(DW) affecting the marker, allows the finite ductile shear strain (γ_d) for individual ductile sheared quartz veins to be calculated (Fig. 3.14b) using the equation:

$$\gamma_d = \frac{(\text{net slip} \times DTR)}{DW} \quad (3.1)$$

$$\text{where } DTR = \frac{\text{ductile_separation}}{\text{total_separation}} \quad (3.2)$$

The mean finite ductile shear strain calculated from all the survey nodes is 4.8 ± 0.7 (n=241). Chancellor Ridge surveys CH01 and CH02 showed the lowest and highest finite ductile shear strains with values of 2 ± 0.8 and 7.6 ± 3.7 , respectively (Fig. 3.17b). The other three surveys were all closer to the mean shear strain.

3.4.4. Shear spacing and ductile deformation of the veins

The difference in finite ductile shear strains between individual shears and in the surveys, may be related to ductile deformation width, the amount of ductile deformation that the marker veins have undergone, or the lithology of the Alpine Schist. The mean ductile deformation width for the surveys was 0.53 ± 0.08 m, but ranged from 0.09 ± 0.04 cm in survey CH02 to the largest width recorded in survey BM-f of 1.24 ± 0.32 cm (Fig. 3.17c; Table 3.2). The amount of ductile deformation was compared between the surveys using the ratio of ductile separation to total separation, averaging 0.31 across all the survey data but as low as 0.14 at survey CH02. Although survey CH02 had the lowest proportion of ductile deformation, it also had a narrow ductile deformation width, resulting in the highest finite ductile shear strain of all the surveys.

The large ductile deformation width and proportion of ductile deformation for survey BM-f is most likely due to a bias in the data collection. Because survey BM-f is a combination of shear zones measured at individual field sites, there exists a bias towards sheared veins which had undergone large proportions of ductile deformation and / or had thick deformed marker veins as these shear zones were more obvious in the field and preferentially studied. The proportion of ductile to brittle deformation

in this study does show an obvious increase with the structural depth of the survey throughout the BDSZ.

Shear normal spacing (see Fig. 3.13) was calculated from the survey data, yielding a mean shear spacing of 0.25 ± 0.5 m. The spacing at survey CH01, taken on pelitic schist, has a larger mean spacing of 1.27 ± 0.3 m compared to the spacing in the psammite schist dominated survey CH02 with a mean spacing of 0.05 ± 0.01 m. The proportion of ductile deformation or the ductile deformation width does not explain the lower shear displacement or finite ductile shear strain at survey CH01 so the ratio of shear displacement to shear normal spacing was compared to the lithology of the schist in each transect. A very low displacement to spacing ratio was calculated for survey CH01 that was predominantly in pelitic schist, compared with much higher ratios for the remaining surveys undertaken on psammitic schist (Fig. 3.17c; Table 3.2).

Assuming that bulk ramping-related strain has been distributed evenly across the BDSZ, I infer that the pelitic schist must be accommodating strain within the schist and in a non-discrete distributed way rather than by discrete slip on the shears. In some instances, shear planes in psammite are observed to merge into a foliation plane in pelite along strike. Shear zones in psammitic schist, such as CH02 and CH03, have a smaller shear normal spacing and shear planes invariably crosscut the Alpine foliation at an acute angle (e.g. Fig. 3.11e). Again, assuming that the strain is distributed evenly across the BDSZ, the higher strain and displacement / spacing measurements in the psammitic sections of the BDSZ suggest that the discrete brittle-ductile shears are accommodating a higher proportion of the bulk strain than the shears in the pelitic sections of schist, where deformation is apparently more distributed (Little et al., 2002a). The spacing of the shears does not appear to be controlled by structural depth but primarily by the composition of the Alpine Schist.

The thickness of marker and infilling veins thicknesses were similar in all three surveys (Tables 3.2). The thickness of the deformed marker veins ranged from 1 to 35 mm with a mean thickness of 8 ± 0.7 mm for data collected from all the surveys. The thickness of infilling veins varied between nodes (shears) with a mean of 2 ± 0.4 mm. These infilling veins occurred in 80% of shear zones surveyed and showed no preference towards precipitation in psammitic or pelitic schist.

Thick marker veins are observed to undergo a greater fraction of ductile deformation than thin marker veins. However, plots of marker vein width vs. ductile deformation proportion reveal that marker veins as thick as 30 mm can be brittlely displaced and those as thin as 1 mm can be totally ductilely sheared (Fig. 3.18a). Overall the data shows an increase in the proportion of ductile deformation with increasing marker vein width (Fig. 3.18a) and fewer veins with widths >10 mm underwent brittle deformation compared with the thinner veins which generally underwent brittle-ductile or brittle deformation. Plots of marker vein width against ductile deformation width (Fig. 3.18b) show a dispersed correlation between these quantities, although there is a weak correlation that shows an increase in deformation width with marker thickness. The plots of ductile deformation width against the ductile / total slip ratio also show this weak correlation between the deformation width and the proportion of ductile deformation (Fig. 3.18a). Vein thickness data for the infilling and marker veins for each node can be found in Appendix B.

3.4.5. Calculation of maximum strain-rate

Maximum ductile strain-rates have been estimated from measurements of finite ductile shear strain (γ_d) and an estimate of the time over which the deformation occurred (e.g. Fig. 3.14b). Based on an escalator-like kinematic model for the formation of brittle-ductile shears, the time period between each shear zone's activation can be calculated. Assuming each shear zone is sequentially activated and all deformation is accommodated on that shear prior to the formation of the next shear zone, then its activation life can be estimated by dividing the average shear normal spacing (SNS) by the shear normal plate convergence rate (SNC) (i.e. the time to translate the Pacific Plate the distance between the shears). The SNC has been calculated from the velocity of the plate convergence vector (PCV) (NUVEL-1A solution of DeMets et al., 1994) and the acute angle (θ) between the PCV and the shear plane (e.g. Fig. 3.13). The maximum strain-rate is calculated from these properties for each node in transects where a marker vein has been ductilely deformed. The maximum strain-rate (ϵ_m) for the ductile deformation is calculated from the equations:

$$\epsilon_m = \frac{\gamma_d}{\text{time}} \quad (3.3)$$

Fig. 3.18. Plots of ductile deformation of marker veins in the shear zones. a. Ratio of ductile separation / total separations vs. marker vein width. b. Ductile deformation width against original marker vein width. c. Ratio of ductile separation to total separation against ductile deformation width.

$$\text{where } time = \frac{SNS}{SNC} \quad (3.4)$$

$$\text{and where } SNC = \sin \theta \times PCV \quad (3.5)$$

The calculation of strain-rate from this data assumes that only one shear was active at a time and that the current plate convergence rate was similar to the rate at the time of deformation. The maximum strain-rates calculated from the transect data range from 5×10^{-10} to $2 \times 10^{-7} \text{ sec}^{-1}$ with a mean rate of $8.6 \times 10^{-8} \pm 3.1 \times 10^{-8} \text{ sec}^{-1}$. The fast and slow end members of the maximum strain-rate range reflect the difference in spacing in surveys CH01 and CH02. These strain-rates are fast compared to expected natural strain-rates of 1×10^{-12} to $1 \times 10^{-14} \text{ sec}^{-1}$ in continental crust (Mercier et al., 1977; Pfiffner and Ramsay, 1982; Twiss and Moores, 1992). Maximum strain-rates from this study may be faster than the expected natural rates because of the underlying assumption in the escalator model that only one shear is active at a time. Calculated strain-rates would reduce to $1.5 \times 10^{-12} \text{ sec}^{-1}$ if the entire 2 km wide zone of the BDSZ was actively accommodating the strain or reduce to $3.0 \times 10^{-11} \text{ sec}^{-1}$ if a 100 m wide zone of shears was accommodating the bulk ramping-related shear strain.

3.5. Proposed field-based deformation sequence

Based on the field observations and transect data, I propose a deformation path for the shearing of quartz-calcite veins and the brittle-ductile shear zones. This deformation sequence is illustrated in Fig. 3.19 which shows eight steps in the development of a single shear zone that displaces several marker veins of different thickness and orientation. Steps (a) and (b) show initial brittle fracturing of the Alpine Schist; at this time the two thinnest veins (blue and yellow) were transected by the fault (Fig. 3.19c inset magnification); the two thicker veins (green and white) are not but underwent ductile deformation. In stages (c) and (d) the ductile deformation of these thicker veins continued as the tips of the brittle crack was unable to propagate across. Eventually the crack tips propagated along the already deflected vein-schist boundary (Fig. 3.19f inset magnification; e.g. Fig. 3.11a). With increased shear strain in stage (e), the thinner of the two ductilely deforming veins (green) was finally penetrated by the crack tips and began to undergo a late increment of brittle slip (Fig. 3.19e inset magnification; e.g. Fig. 3.11b). The thicker

Fig. 3.19. Schematic deformation sequence (a-h) proposed for brittle-ductile deformation in shear zones. Four hypothetical veins of different thickness undergo shear deformation with a displacement vector pitching 30° SW in the shear plane. Veins undergo different brittle-ductile deformation (explained further in the text) while Alpine Schist undergoes brittle deformation. Final figure (h) shows precipitation of infilling vein and mineral fibre lineations. All block diagrams are eroded down to a flat surface after each deformation and a wire frame represents the eroded material. Note: no erosion is implied during actual brittle-ductile shearing. Inset figure are enlarged images of a section in the deforming blocks for the associated stages.

white vein continued to deform ductilely in stages (f)-(g) until the vein has been sufficiently attenuated to allow the brittle crack tips link up across the narrowest part of the sheared vein (h). In stage (h) the infilling vein was precipitated into the brittle fracture and deformation continued by ductile deformation of the infilling vein material and by brittle slip along the crack.

This deformation sequence seems applicable to most of the shear zones but the behaviour of individual veins and propagating crack tips can vary. For example, some shear zones have thick veins that undergo only brittle deformation, and in others the crack tips never penetrate them completely or no infilling vein is precipitated.

CHAPTER 4: Optical microscopy of the brittle-ductile shear zones

Results obtained using optical microscopy techniques can provide insights into rock fabric development and rheology that would be unobtainable from field-based structural studies alone. In the present study, petrographic (polarised transmitted light) microscopy and universal stage methods have been used to examine the deformation microstructures and determine the temperature and differential stress conditions when fabrics were imprinted in the late Cenozoic during deformation of the Pacific Plate across the Alpine Fault ramp. Quartz-calcite veins, and the Alpine Schist rock hosting them, that have been deformed by brittle-ductile shearing (along individual shear zones) within the brittle-ductile shear zone (BDSZ), have been sampled and used to undertake this petrographic research.

Samples from the sheared veins have been used to identify the microstructures which have been used to determine the types of active deformation mechanisms and the shear sense during deformation. Further analysis of these veins yielded estimated final increments of strain using grain shape fabrics, the approximate deformation temperature using quartz and calcite slip systems and the differential stress that may have dominated during phases of the deformation using recrystallised grain size and calcite twins. From these microscopic analyses an approximate microstructural evolution of the sheared and shear infilling veins has been determined.

4.1. Sample locations and orientations

Samples were collected from rocks in (or in some cases below) the BDSZ at Sam Peak (Fig. 4.1; Table 4.1), Chancellor Ridge (Fig. 4.2; Table 4.2) and Baumann Glacier (Fig. 4.3; Table 4.3) field areas. These samples were of quartz-calcite veins deformed by the brittle-ductile shears, the shear infilling veins and the Alpine Schist that hosts these veins. Sample numbers, grid references, and orientations for samples from the BDSZ are listed in Table 4.1–4.3. For descriptive purposes, samples are divided into four types for description: the Alpine Schist host rock; the strongly sheared and most attenuated parts of deformed veins (internal vein sections); the less deformed part of the vein external to the shear zones (external vein sections); and the syntectonic vein material that infills the shears (shear infilling vein sections).

Fig. 4.1. Location map for samples collected in the Sam Peak field area. Maps are as in Chapter 3 with 100 m contours from the LINZ 1:50,000 digital data set, grid in metres for the New Zealand Map Grid projection system. Major geological structures are shown for reference.

Field Number	VUW Collection #	Easting (X)	Northing (Y)	Elevation m	Sample Type	Orientation of reference surface			
						Strike	Dip	Side	Surface
MHSP04	39410	2273385	5738506	1,700	Schist	210	56	T	O
MHSP06	39411	2272925	5738335	1,680	Schist	182	62	U	O
MHSP07	39412	2274496	5737332	1,860	Schist	208	72	T	O
MHSP08	39413	2274495	5737213	1,865	Schist	212	64	T	O
MHSP09	39414	2274514	5737163	1,865	Infilling vein	216	46	T	O
MHSP10	39415	2274555	5737213	1,875	Schist	204	64	T	O
MHSP11	39416	2274762	5737045	1,900	Infilling vein	206	48	T	S4
RW35b	39431	2274172	5737505	1,820	Infilling vein	193	68	T	O
TJFA43	39432	2274409	5737321	1,824	Infilling vein	216	62	T	O
TJFA47	39433	2274502	5737234	1,865	Infilling vein	212	60	T	O
TJFA50	39434	2274300	5737390	1,815	Schist	206	65	U	S4
TJFA52	39435	2274288	5737385	1,797	Infilling vein	200	65	T	S4
TJFA56	39436	2274197	5737210	1,741	Sheared vein	207	73	T	AF

Table 4.1. Locations and orientations for samples collected in the Sam Peak field area. Field numbers are those displayed in Fig. 4.1 and VUW Collection number refers to the Victoria University of Wellington rock collection. Grid references are in metres for the New Zealand Map Grid projection system and elevations are above mean sea level. Sample type refers to either shear infilling vein or sheared quartz carbonate-vein. Orientation is listed for the marked surface on the sample with the side referring to either the top or bottom of the sample and the surface type for which the orientation markings are on; AF - Alpine Foliation plane, S4 - infilling vein plane or brittle-ductile shear plane and O - other surface. Strikes are all listed in right-hand-rule.

Fig. 4.2. Location map for samples collected in the Chancellor Ridge field area. Maps are as in Chapter 3 with 100 m contours from the LINZ 1:50,000 digital data set. Grid in metres for the New Zealand Map Grid projection system. Major geological structures are shown for reference.

Field Number	VUW Collection #	Easting (X)	Northing (Y)	Elevation m	Sample Type	Orientation of reference surface			
						Strike	Dip	Side	Surface
MHCH01	39380	2277105	5740078	1,671	Sheared vein	205	90	U	O
MHCH02	39381	2277249	5740071	1,685	Infilling vein	215	87	T	S4
MHCH03	39382	2277373	5740071	1,710	Schist	215	84	T	O
MHCH04	39383	2277675	5740243	1,771	Infilling vein	039	88	T	S4
MHCH05	39384	2277675	5740243	1,771	Schist	033	82	T	AF
MHCH06	39385	2277325	5740132	1,710	Infilling vein	218	84	T	S4
MHCH07	39386	2277286	5740163	1,689	Infilling vein	217	88	T	S4
MHCH08	39387	2277300	5740178	1,689	Infilling vein	215	87	T	S4
MHCH09	39388	2277300	5740178	1,689	Schist	214	84	T	O
MHCH10	39389	2277301	5740163	1,695	Infilling vein	217	86	T	S4
MHCH11	39390	2277272	5740207	1,665	Sheared vein	217	82	U	S4
MHCH12	39391	2277107	5740211	1,618	Infilling vein	221	85	T	S4
MHCH13	39392	2275675	5740507	878	Schist	034	60	T	AF
MHCH14	39394	2276050	5740450	1,183	Infilling vein	218	88	T	S4
MHCH15	39395	2276050	5740450	1,183	Infilling vein	208	81	T	S4
MHCH16	39396	2276050	5740450	1,183	Schist	040	82	T	S4
MHCH17	39397	2276050	5740450	1,183	Sheared vein	038	88	T	S4
MHCH18	39398	2277280	5740132	1,666	Sheared vein	213	85	T	S4
MHCH19	39399	2277280	5740132	1,666	Sheared vein	219	84	T	S4
MHCH20	39400	2277348	5740090	1,704	Sheared vein	222	88	T	S4
MHCH21	39401	2277348	5740090	1,704	Sheared vein	218	89	U	S4
MHCH22	39402	2277421	5740067	1,698	Sheared vein	219	89	T	S4
MHCH23	39403	2276926	5739676	1,452	Infilling vein	218	84	T	S4
MHCH24	39404	2276924	5739671	1,441	Sheared vein	035	82	T	AF
MHCH25	39405	2276935	5739670	1,450	Sheared vein	216	80	T	S4

Table 4.2. Locations and orientations for samples collected in the Chancellor Ridge field area. Field numbers are those displayed in Fig. 4.2. Sample type listing of schist refers to a sample of Alpine Schist. All other table definitions are as in Table 4.1. Strikes are all listed in right-hand-rule.

Fig. 4.3. Location map for samples collected in the Baumann Glacier field area. Maps are as in Chapter 3 with 100 m contours from the LINZ 1:50,000 digital data set. Grid in metres for the New Zealand Map Grid projection system. Major geological structures are shown for reference.

Field Number	VUW Collection #	Easting (X)	Northing (Y)	Elevation m	Sample Type	Orientation of reference surface			
						Strike	Dip	Side	Surface
MHBM01	39417	2280956	5744858	1,613	Infilling vein	048	74	T	AF
MHBM02	39418	2279922	5744478	1,780	Infilling vein	045	82	U	S4
MHBM03	39419	2279922	5744478	1,780	Sheared vein	050	70	T	O
MHBM04	39420	2279922	5744478	1,780	Sheared vein	041	86	U	O
MHBM05	39421	2279922	5744478	1,780	Sheared vein	184	84	T	O
MHBM06	39422	2279922	5744478	1,780	Infilling vein	046	80	U	S4
MHBM07	39423	2280153	5744359	1,940	Infilling vein	040	72	U	S4
MHBM08	39424	2279994	5744738	1,744	Infilling vein	044	88	U	S4
MHBM09	39425	2280081	5744689	1,737	Sheared vein	152	20	T	O
MHBM10	39426	2280081	5744689	1,737	Sheared vein	197	65	T	O
MHBM11	39427	2280100	5744678	1,750	Sheared vein	221	89	T	AF
MHBM12	39428	2280112	5744667	1,759	Sheared vein	042	88	U	O
MHBM13	39429	2280123	5744672	1,764	Sheared vein	056	80	U	S4
MHBM14	39430	2280123	5744672	1,764	Infilling vein	225	82	T	S4

Table 4.3. Locations and orientations for samples collected in the Baumann Glacier field area. Field numbers are those displayed in Fig. 4.3. Definitions for all terms in this table can be found in Tables 4.1 and 4.2. Strikes are all listed in right-hand-rule.

Analysis of the different types of sample sections will allow us to make conclusions about the deformation path during brittle-ductile shearing of the veins.

Additional samples were also collected from Alpine Fault mylonitic chert at Hare Mare Creek (Fig. 4.4a) and from non-mylonitic Alpine Schist metacherts outcropping along the Waiho River (Fig. 4.4b). Grid references and sample orientations for these samples are listed in Table 4.4. These additional, structurally deeper, samples have been used for microstructural and crystallographic comparisons with the sheared quartz vein samples from the BDSZ's at Sam Peak, Chancellor Ridge and Baumann Glacier.

Every sample was marked using a standard orientation marking on one of the planar surfaces (usually on the dominant foliation or shear plane). This marking is a line parallel to the strike of the plane *in situ* with a half arrow on the more northern end of the strike line. Samples marked on the top side of the rock have a single tick label in the down dip direction. Samples marked on the bottom side of the rock have dip labels with a loop in the up-dip direction and a tick symbol in the down-dip direction. These symbols are illustrated in Fig. 4.5.

4.2. Methods of optical microscopy used in this study

A petrographic (polarising transmitted light) microscope was used for mineral identification, the observation and measurement of microstructural fabrics, and the determination of mineral proportions. A similar microscope fitted with a 5-axis universal stage was used for measurement of crystallographic orientations of quartz and calcite c-axes, as well as the angle between this axis and microstructural features such as quartz subgrain boundaries and calcite twins.

Thin-sections suitable for standard optical microscopy and crystallographic orientation measurements of quartz and calcite have been made for the samples collected in this study. For the microstructural and quartz crystallographic thin sections were made 30 μm thick, but were reduced to 15 μm for the crystallographic measurements of calcite to reduce interference due to the high birefringence of that mineral. Thin-sections were cut perpendicular to the shear plane and parallel to one of three orientations: the shear plane's strike direction (-st cuts), the dip direction (-d cuts) or the mineral fibre lineation (-p cuts) direction (Fig. 4.6). For shear infilling

Fig. 4.4. Location map for samples collected in the Hare Mare Creek (a) and Waiho River (b) field areas. Contours are shown at 100 m intervals and are from the LINZ 1:50,000 digital data set. The grid is in metres for the New Zealand Map Grid projection system. Major geological structures shown for reference. SH6 refers to State Highway 6 on the west coast of the South Island in New Zealand.

Field Number	VUW Collection #	Easting (X)	Northing (Y)	Elevation m	Sample Type	Orientation of reference surface			
						Strike	Dip	Side	Surface
MHFJ01	39406	2281034	5748112	261	Chert	048	75	T	AF
MHFJ02	39407	2281021	5748082	274	Chert	037	75	T	AF
MHFJ03	39408	2281195	5747688	279	Chert	035	75	T	AF
MHHM01	39409	2273722	5747569	275	Mylonitic chert	061	32	U	MF

Table 4.4. Locations and orientations for samples collected in the Baumann Glacier field area. Field numbers are those displayed in Fig. 4.4. Definitions for all terms in this table can be found in Tables 4.1 and 4.2 with the addition of sample types of chert and mylonitic chert which refer to chert rich section of the non-mylonitic Alpine Schist and Alpine Fault mylonite rocks and the MF orientation surface which refers to the mylonitic foliation. Strikes are all listed in right-hand-rule.

Fig. 4.5. Cartoon showing the orientation marking system used on samples. One marking is on a plane in the Alpine Schist that is dipping 22° to the southeast. This marking is on the top of the sample and has a long line parallel to strike with a half arrow tick on north end and a short tick in the down dip direction. The second example is on the quartz-carbonate infilling vein. This marking is on the bottom of the steeply dipping vein and has a long line parallel to the veins strike and a half arrow tick on the north end. As the sample has the marking on the bottom the down-dip tick is annotated with a loop in the up-dip direction.

Fig. 4.6. Cartoon showing the orientation and notching system used on thin sections relative to the S_4 shear plane and L_4 lineations. The strike cut (-st) is parallel to the strike of the shear plane and perpendicular to the shear plane. This thin section cut contains the pole to the shear plane and the shear plane strike. The dip cut (-d) is parallel to the dip of the shear plane and perpendicular to the shear plane. This thin section cut contains the pole to the shear plane and the line pitching 90° in the shear plane. The lineation parallel 'p' cut (-p) is parallel to the lineation and perpendicular to the shear plane. This thin section cut contains the pole to the shear plane, and pitches parallel to the lineation.

vein samples, thin sections were generally cut in all three directions (-st, -d and -p). Sheared vein samples, however, were only cut parallel to the strike direction (-st) as the small volume of sample typically only allowed for one thin section to be made. Multiple thin-sections were often required to cover the extent of a single shear zone sample. Outside of the BDSZ (in the Alpine Schist), samples were cut perpendicular to the dominant foliation (S_2 or S_3) and parallel to both the strike and dip (-st and -d).

Quartz grain diameters were measured in two orthogonal directions using the intercept method (Christie and Ord, 1980; Stipp et al., 2002a). Grain boundaries were counted that intercepted a line of known length (usually 1.2 mm), from which a mean grain diameter was calculated for that line. The representative length of the long axis of the grains (a) was calculated from the average of counts along five lines parallel to the grain shape fabric, and the representative length of the short axis (b) was calculated from the average of counts along five lines orthogonal to the grain shape fabric. The 2-D grain diameter (D) was measured (as in Stipp et al., 2002a; Appendix C) from the equation:

$$D = \sqrt{a \cdot b} \quad (4.1)$$

Because three mutually perpendicular thin-sections were not cut from many samples, three-dimensional grain diameters (Smith and Guttman, 1953; Christie and Ord, 1980) were not calculated in this study. The intercept method for grain diameter measurement was only applied to quartz grains as other minerals did not occur in concentrations large enough for statistically significant numbers of grains to fall on a single intercept line.

Sizes of individual features such as large grains, micas and calcite twin widths were measured using a graduated reticle in the eyepiece of the petrographic microscope. This reticle was calibrated using a stage micrometer. The angular orientations of oblique grain shape fabrics, subgrain boundaries and calcite twins were measured by reading the vernier scale after rotation of the microscope stage.

4.3. Mineralogy and microstructures

4.3.1. *Alpine Schist*

The Alpine Schist at Sam Peak, Chancellor Ridge and Baumann Glacier typically consists of biotite grade metagreywacke that ranges in chemistry from relatively psammitic to relatively more pelitic bulk compositions (Fig. 4.7a, b, c and d). The dominant foliation in the Alpine Schist was generated during the D₃ deformation in the late Cretaceous (Vry et al., 2004) and reinforced during the late Cenozoic (Little et al., 2002a). Porphyroblasts of biotite, that include the earlier S₂ foliation, occur locally in Aspiring Terrane schist at Sam Peak (e.g. Fig. 4.7e) and record an earlier deformation that formed the S₃ foliation. A phyllitic cleavage is typically dominant structurally above the base of the BDSZ where minerals are not separated into obvious domains. Occasionally, quartz grains in these rocks are observed to have undergone brittle deformation where fractures are in-filled by micas (e.g. Fig. 4.7d). Structurally below the BDSZ, a well-developed schistosity occurs (Fig. 4.7c) defined by separate microlithon (quartzite-rich) and cleavage domain (mica and chlorite-rich) layering.

Minerals in the schist typically include quartz (Qtz) + biotite (Bt) ± white mica (Ms) ± titanite (Ttn) ± epidote (Ep) ± calcite (Cal) ± plagioclase (Pl) ± chlorite (Chl) ± graphite (Gr) ± illmenite (Ilm). Abbreviations used here are after Kretz (1983). In structurally lower regions of Sam Peak, the Alpine Schist contained garnet porphyroblasts, the first appearance of which defined the garnet-in (Grt) isograd plotted in Figs. 3.1 and 4.1. Alpine Schist from Sam Peak in the Aspiring Terrane samples contained up to ~30% graphite (Fig. 4.7f). The metachert samples from the Waiho River consist mostly of Qtz + Ms ± Bt (Fig. 4.7g). The mylonitic metachert sample from Hare Mare Creek consists of Qtz + Grt + Bt + Ms (Fig. 4.7h) with potassium feldspar (Kfs) + hornblende (Hbl) also present in the surrounding mylonitic schist. Quartz grain sizes in the schist typically vary from 20 to 100 µm for small recrystallised grains and may reach up to 250 µm in relict detrital or porphyroclastic sand grains (e.g. Fig. 4.7a).

The mapping of the textural zones (TZ's), after Turnbull et al. (2001), has been used to define an increase in metamorphic textural grade westwards in all of the field areas. These TZ's were initially based on field observations (see Chapter 3, this

Fig. 4.7. Photomicrographs of Alpine Schist fabrics and the Alpine Fault mylonite. For all photomicrographs (herein and subsequent figures) PPL is plane polarised light and CPL is cross-polarised light. a. Textural zone (TZ) 2B Alpine Schist with a relict quartz grain that has undergone subgrain rotation recrystallisation (CPL). b. TZ 3 Alpine Schist with muscovite and foliation parallel quartz (CPL). c. TZ 4 Alpine Schist (CPL). d. Brittle fracturing of a quartz crystal in the Alpine Schist (arrowed) (CPL). e. Biotite porphyroblast with graphite inclusion trails of the S_2 foliation (CPL). f. Graphite rich schist from the Aspiring Terrane on Sam Peak (PPL). g. Alpine Schist from a Waiho River chert sample (CPL). h. Alpine Fault mylonite sample taken with gypsum plate inserted (CPL).

study) and refined here on the basis of muscovite grain size and recrystallised quartz grains as observed in thin-section. The textural zones defined in this study are plotted in Figs. 4.1, 4.2 and 4.3 and their petrographic features are described below. Microfabrics from TZ 2B are distinguished typically by a fine grained schist (quartz grains 20-50 μm and white micas <75 μm long and <5mm thick) with detrital sand grains that have undergone subgrain rotation recrystallisation (e.g. Fig. 4.7a). In TZ 3 these detrital sand grains have been recrystallised into elongated quartz-rich layers that no longer preserve the relict grain shape and are frequently pinned by mica layers. In addition, TZ 3 shows an increase in length and width of muscovite crystals to 75-125 μm long and 5-15 μm wide (Fig. 4.7b). TZ 4 has a schistosity defined by segregated domains of micas and quartz; also the muscovite crystals are further enlarged to 125-200 μm long and 25-50 μm wide (Fig. 4.7c).

4.3.2. *Sheared quartz-calcite veins*

The sheared veins were variably emplaced into the Alpine Schist during the mid Cretaceous to the early Miocene D₃ deformation (Little et al., 2002a). Some of the sheared veins have undergone D₃ folding to develop a grain shape foliation in dynamic recrystallised grains and a macroscopically distinct axial planar foliation in the fold hinges (Fig. 3.11a). These veins have been sheared during the late Cenozoic and displaced by brittle-ductile deformation in shear zones within the BDSZ (Little, 2002b; Little et al., 2004; Wightman, 2005; also see Chapter 3 of this study). Petrographic study of these sheared veins has been divided into sections of the shear zone: the most strongly deformed internal section where ductile shearing has occurred and the external area where the veins are not deformed in the shear zone. This division has been made to differentiate between microstructures that may be related to the late Cenozoic shearing and those external to the deformation. The samples of sheared veins in this study have a mean finite ductile shear strain of 5.5 ± 1.3 (n=17) and are within the uncertainties of the mean ductile shear strain calculated for the BDSZ which is 4.8 ± 0.7 (see Chapter 3).

The veins include Qtz $\pm$ Cal $\pm$ Ms $\pm$ Chl (Fig. 4.8). Commonly chlorite, white mica and calcite concentrations are found along the vein boundaries with quartz and calcite the dominant vein forming minerals. Quartz makes up a minimum composition of 70% and micas (mostly white mica) and chlorite not more than 5% of

Fig. 4.8. Photomicrographs of microstructures in sheared quartz veins and infilling veins. a. View of internal section of sheared vein showing polygonal grain shape fabric (GSF) (CPL). b. Enlargement of polygonal GSF in (a) (CPL). c. Sheared quartz vein in Alpine schist showing attenuation of strongly deformed and deflected vein material and local development of a distinct Alpine Foliation in the vein external to the shear zone (PPL). d. Internal section of a sheared vein and adjacent infilling vein. Brittle fracture seen between the two shear zone sections indicated by arrow (CPL). e and f. Grain boundary migration clearly seen between two quartz grains (arrows) as enhanced with a gypsum plate (CPL). g. An island grain (arrowed) formed from grain boundary migration clearly visible when using a gypsum plate (CPL). h. Deformation lamellae (arrowed) in a quartz grain (CPL).

the veins composition. Calcite varies in abundance (not more than 30% of the bulk composition) and is commonly found in concentrated layers parallel to the vein boundaries with local concentrations exceeding 50%. A mean quartz grain size of $126 \pm 16 \mu\text{m}$ is characteristic of the internal sections and a relatively coarser $171 \pm 14 \mu\text{m}$ characteristic of the external veins sections.

Microstructures between different sections of the sheared veins are very similar, and although present, the quartz grains have few subgrain boundaries and only show minor grain boundary bulging. More common across the sheared veins are quartz grains with undulose extinction and deformation lamellae (Fig. 4.8a and b) and calcite grains with mostly thin planar (2-5 μm) twins. Small dynamically recrystallised quartz grains (<50 μm) are not found in abundance and the quartz grain size is typically homogeneous throughout the veins indicating that little recrystallisation has occurred. Microstructures fit Regime 1 of Hirth and Tullis (1992), as conditions do not appear to have been met to allow significant dislocation climb and subsequent recrystallisation to occur. Intracrystalline deformation however, has occurred in the veins.

A grain shape fabric (GSF) defined by elongated grains was found in approximately half of the sheared veins. The internal sections had these quartz and calcite GSF's elongated parallel to the vein wall (parallel to the shear plane) and were not found oblique to the shear plane in any of samples. The GSF's in the external sections were either parallel to the vein wall (at an angle to the shear zone in these sections) or parallel to the foliation in the Alpine Schist hosting the veins (Fig. 4.8c). Polygonal GSF's and uniformly sized quartz grains occurred in the internal sections of the remaining samples (e.g. Figs. 4.8a and 4.8b).

Microstructures such as the polygonal GSF's, the homogeneous grain size and similar internal and external microstructures reflect the strongly recovered nature of the veins and indicate that static recrystallisation may have occurred after deformation. This is confirmed by the absence of dynamic recrystallisation fabrics such as a progressive reduction to a small grain size (<20 μm) with increased shear strain (as in White et al., 1980) by grain boundary migration and subgrain rotation recrystallisation and microstructures such as oblique GSF's, deformation lamellae, and undulose extinction (Passchier and Trouw, 1998). After the high shear strains

that have apparently affected these veins (mean 5.5 ± 1.3), recrystallisation mechanisms such as grain boundary area reduction and static recrystallisation, may have removed many of the microstructures that were acquired during the shearing.

4.3.3. *Shear infilling veins*

The syntectonic shear infilling veins are 1–15 mm wide and composed of Qtz $\pm$ Cal $\pm$ Chl $\pm$ Ms $\pm$ Bt. The dominant mineral is quartz (abundances $>60\%$) with white mica (Ms) and chlorite (the most common phyllosilicate) occurring in smaller concentrations ($<10\%$). Calcite is not proportionally more than 40% but a vein is rarely found without this mineral present. In the veins, chlorite and muscovite are typically aligned with their cleavage surfaces parallel to the shear zone boundary and chlorite is sometimes also concentrated along the edges of some veins in thick 100–500 μm mica books near the contact with the Alpine Schist wall rock. Biotite occurs only as xenolithic inclusions in the veins which have become incorporated into the infilling vein from the schist. Quartz in the infilling veins has a mean grain diameter of $141 \pm 21 \mu\text{m}$ and commonly there are large grains up to 1000 μm in diameter. The shear infilling veins can be distinguished from the sheared veins by the commonly coarser and heterogeneous grain size (e.g. Fig. 4.8d).

Evidence for intracrystalline deformation and dynamic recrystallisation are common in the shear infilling veins. Grain boundary bulging and grain boundary migration fabrics in quartz are found in most samples (Figs. 4.8e and 4.8f); some include recrystallised island grains (Fig. 4.8g). Deformation lamellae and undulose extinction are common (e.g. Fig. 4.8h) and subgrain boundaries are especially common in the coarser ($>200 \mu\text{m}$) sub-population of grains (Fig. 4.9a), with some rare examples including core and mantle textures (Fig. 4.9b). Quartz crystals that have similar optical interference colours after insertion of a gypsum (440 nm retardation) accessory plate into the light path have a similar orientation. The use of this technique shows that for some samples there is no crystallographic preferred orientation (e.g. Fig. 4.9c). In others, a preferred orientation in large domains was caused by subgrain rotation recrystallisation, causing a mosaic of smaller grains to have a similar crystallographic orientation to an originally much larger host grain (Fig. 4.9f). There are no textures in the veins that suggest that the vein ever had a

Fig. 4.9. Photomicrographs of infilling vein microstructures. a. Quartz grain showing subgrain boundaries (arrowed) (CPL). b. Core and mantle (subgrain rotation) recrystallisation microstructure (CPL). c. Little crystallographic preferred orientation (CPO) of quartz as seen under gypsum plate (CPL). d. Domainal CPO seen under a gypsum plate (CPL). e. Weak oblique grain-shape fabric (GSF) (CPL and gypsum plate). f. GSF and CPO seen from orientation of quartz grains under gypsum plate (CPL). g. Oblique GSF enhanced by chlorite pinning (CPL). h. Muscovite crystal in shear infilling vein causing quartz grain pinning and at an oblique angle to the shear zone (CPL).

comb structure of originally euhedral quartz crystals that had grown inward from the vein walls into an open cavity.

Oblique grain shape fabrics were commonly observed in the infilling veins with varied intensities from weak (e.g. Fig. 4.9e) to strong (e.g. Fig. 4.9f), with long axes of the grains that making an angle of $<45^\circ$ to the shear plane. Elongated quartz and calcite grains commonly define the oblique fabric, however, in some veins pinning of quartz by micas oblique to the shear zone defines the GSF (e.g. Figs. 4.9g and 4.9h). The shear senses inferred from these fabrics are invariably dextral in the strike-parallel thin section cuts, west-side-up in the dip-parallel cuts, and dextral west-side-up in the lineation-parallel cuts. The oblique GSF angle in the lineation-parallel thin section cuts averages $27 \pm 4^\circ$ ($n=7$), and was always lower than that seen in the strike- or dip-parallel cuts. Grain boundary pinning has caused shear parallel GSF's in some veins where micas or calcite abut quartz crystals (Fig. 4.10a and 4.10b). This GSF is from pinning related grain growth anisotropies and not from high shear strains where the angle between the shear plane and the GSF approaches zero.

Brittle fractures are not uncommon along the margin of the infilling veins (Fig. 4.10c and 4.10d). Although these fractures have accumulated a proportion of brittle slip in the shear zone (see Chapter 3) there is no gouge or cataclasite along their margin. The only evidence for wall rock deformation during the brittle slip is from xenolithic inclusions of schist along the crack boundaries and their incorporation into the shear infilling veins. Incorporation of this material suggests that antitaxial vein growth was occurring in the shear zones, potentially as a crack-seal mechanism (e.g. Cox and Etheridge, 1983).

In the shear infilling veins, secondary two-phase (vapour-liquid) fluid inclusions (Fig. 4.10e) are sometimes found in single trails across quartz crystals (Fig. 4.10f). The single fluid inclusion trails may cross grain boundaries (Fig. 4.10b) or occur along subgrain boundaries. Veins from some Sam Peak samples contain large quartz grains that have multiple trails in them (Fig. 4.10c). The multiple fluid inclusion trails are inferred to be healed microcracks whereas the single fluid inclusion trails are may have been either a healed grain or subgrain boundary (Roedder, 1984; pers. comm. T. Takeshita, 2004). The inclusion trails that cross the

Fig. 4.10. Photomicrographs of fluid inclusions and other microstructures in infilling vein samples. a. Chlorite pinning quartz crystals in an infilling vein sample (CPL). b. Chlorite and muscovite pinning quartz crystals (CPL). c. Sheared vein and infilling vein separated by fracture (arrowed) (CPL). d. Sheared and infilling vein samples with brittle fracture between them and incorporated wall rock (xenolithic inclusion) (arrowed) (CPL). e. Two phase fluid inclusions (PPL). f. Single fluid inclusion trail (arrowed) (PPL). g. Single fluid inclusion trails crossing grain boundaries (arrowed) (CPL). h. Multiple parallel fluid inclusion trails (PPL).

grain boundaries must have occurred prior to the grain boundaries or developed in the semibrittle faulting regime of Hirth and Tullis (1994) where microcracks can crosscut several grains. Cracks that do not crosscut the grain boundaries are more likely to occur in the semibrittle flow regime where dislocation glide accommodates some of the crack stress at the grain boundary (Hirth and Tullis, 1994). The semibrittle faulting and semibrittle flow regimes are inferred to be at lower temperatures and / or higher differential stresses than the Regime 1 microstructures that they crosscut, which deform by plastic rather than brittle creep mechanisms. Primary fluid inclusions are also found in quartz grains throughout the shear infilling veins. Their occurrence suggests that vein precipitation was from the conversion of amorphous silica to quartz, rather than from the growth of euhedral crystals from the fracture walls (Herrington and Wilkinson, 1993).

Calcite crystals in the infilling veins are mostly twinned (e.g. Fig. 4.11a). Some of the twins are curved and show evidence for twin boundary migration (sutured edges along the twin boundary); however, most are thin (2-10 μm) and straight (Fig. 4.11b). Some larger calcite grains are volumetrically dominated by twinning (Fig. 4.12a) and where grain boundaries are shared by quartz, twinning is frequently more intense (Fig. 4.12b). These larger grains on occasion had several sets of twins at different angles (Fig. 4.12c) potentially caused by multiple deformations. Calcite is found either in concentrated bands (Fig. 4.12d) or as isolated grains within the quartz (Fig. 4.12e) and is commonly enriched along the boundaries of the infilling veins (Fig. 4.12f). Thin twin sets commonly intersect on another at an angle of 128° (Fig. 4.12g). The curved and oblate grain boundaries between quartz and calcite (Fig. 4.12h) in some samples are inferred to have been formed from solid-state diffusion creep (as in Gower and Simpson, 1992; Passchier and Trouw, 1998).

4.4. Grain shape fabric based estimates of finite incremental ductile shear strain in deformed and infilling veins

Calculations for a late increment of strain have been made from the oblique grain shape fabrics and from the aspect ratios of elliptical recrystallised quartz grains from the shear infilling veins. These strain calculations have provided information about the proportion of strain that the microfabrics represent compared with the total strain that deflection and offset of the sheared veins represent. Oblique angles of

Fig. 4.11. Photomicrographs of deformation twinning in calcite crystals. a. Type I and II twinned calcite crystals in an infilling vein (CPL). b. Type III calcite twins (Burkhard, 1993) with thick, curved twins that have undergone twin boundary migration (arrowed) (CPL). c. Type I calcite e-twins which are thin and straight (CPL). Calcite grain boundary migration is seen in all photomicrographs along calcite-calcite grain boundaries.

Fig. 4.12. Photomicrographs of calcite in infilling veins. a. Type III twinned calcite grain showing curved twins and twin boundary migration (CPL). b. Type IV twinned calcite showing thick curved twins and quartz intergrown (CPL). c. Multiple twin orientations in the same calcite crystal (CPL). d. Calcite layer in quartz vein parallel to the shear zone (CPL and gypsum plate). e. Intergrown calcite and quartz crystals of equal grain size without layering in a shear infilling vein (CPL). f. Calcite concentration on the edge of infilling vein in contact with wall rock Alpine Schist (CPL). g. Calcite e-twins evident from the angle of the twins from the crystallographic c-axis of the grain (CPL). h. Sutured grain boundaries of quartz and calcite (arrowed) indicating solid-state diffusion creep (CPL).

grain shape fabric long axes to the shear zone boundary (θ') were measured and converted to shear strains (γ) assuming a simple shear deformation and using the equation of Ramsay and Huber (1983):

$$\tan 2\theta' = -\frac{2}{\gamma} \quad (4.2)$$

Aspect ratios (R) were calculated from grain long axis (a) and the grain short axis (b) measurements (see section 4.5.1) using the equation:

$$R = \frac{a}{b} \quad (4.3)$$

Aspect ratios were then converted into extensional strains ($1+e_1$) assuming that there was no volume change out of the shear plane ($\Delta A = 0$) using the equation:

$$(1 + e_1) = \sqrt{R} \quad (\text{Assumes that } \Delta A = 0) \quad (4.4)$$

The extensional strain calculations were then converted into shear strains for infilling veins using the equation of Ramsay (1967):

$$(1 + e_1)^2 = \frac{\gamma^2 + 2 + \gamma\sqrt{\gamma^2 + 4}}{2} \quad (4.5)$$

$$\gamma = \frac{(1 + e_1)^2 - 1}{(1 + e_1)} \quad (\text{Rearranged to solve for } \gamma) \quad (4.6)$$

In the shear infilling veins, oblique grain shape fabric measurements were made in all three thin sections cuts; however, the p-cuts parallel to the lineation invariably had the lowest angle between the long axis and the shear zone boundary, and the strongest GSF fabrics. Aspect ratios were also higher in the mineral fibre lineation-parallel cuts than in the strike- or dip-parallel cuts. Shear strains have only been calculated for these lineation-parallel cuts. In the infilling veins, calculations from oblique GSF's yield moderate shear strains of 1.51 ± 0.46 , but the results of calculations based on aspect ratios from the same samples yielded shear strains of 0.8

± 0.1 . The two measurements should have been very similar for simple shear deformation and the difference between them suggests that a component of pure shear may have been involved or that grain growth may have occurred after the development of the oblique GSF. These shear strains are much lower than the mean finite ductile shear strain for the sampled shear zones that the shear infilling veins were in which is 5.5 ± 1.3 . This difference shows that the microstructures in the infilling veins were formed during a late incremental stage of the shear deformation.

In the sheared veins, mean aspect ratio (R) calculations yielded estimates of 1.5 ± 0.19 in the internal sections and 1.7 ± 0.2 in the external sections. GSF fabrics in the internal sections of the sheared veins were parallel to the shear plane. These fabrics therefore represented either very large shear strains (< 10) where the long axis would have approached the shear plane, a pure shear deformation where the veins were flattened but not sheared, or where a growth anisotropy controlled by mineral impurities controlled the grain shape. None of these possibilities could be confirmed, although grain growth anisotropies are possible adjacent to the calcite-rich layers and in mica-rich layers parallel to the shear plane because of pinning of quartz grains. There is very little difference between the aspect ratios calculated for the external and internal vein sections. This suggests that since their recrystallisation the entire shear zone has undergone a similar increment of strain that was not related to displacement on the brittle-ductile shear plane.

4.5. Active crystallographic slip systems in quartz and calcite minerals

4.5.1. Quartz slip systems

Subgrain boundaries and grain boundary bulging microstructures in quartz can be used to determine the active slip systems (Fig. 4.13) and temperature conditions during deformation. In this study the angle between a quartz subgrain boundary and the c-axis was measured with a universal stage to determine the direction of glide on quartz prism planes. Quartz subgrain boundaries are commonly near parallel to either the basal plane or the prism planes because of prism glide in the $[c]$ or $\langle a \rangle$ directions respectively (Kruhl, 1996). Intracrystalline slip can occur by either edge dislocations or screw dislocations; however, subgrains are dominantly formed from edge dislocations joining during dislocation climb and slip on the prism planes (Twiss and Moores, 1992). Therefore, prismatic subgrains typically form

Fig. 4.13. a. Simplified 3D view of quartz crystal and the slip planes used for deformation. b. Plan view of quartz crystal and the slip systems used for deformation. (a) and (b) are redrawn from Twiss and Moores (1992). c. Stereographic, upper hemisphere, equal angle projection of crystallographic planes and poles of quartz. d. Main potential slip systems for deformation of quartz (from Lister et al., 1978).

parallel to the $\langle a \rangle$ direction during prism $[c]$ slip and parallel to the $[c]$ direction during prism $\langle a \rangle$ slip with both perpendicular to the slip plane (Fig. 4.14). Subgrain boundaries can form during basal $\langle a \rangle$ slip (Kruhl, 1996) but are usually not formed by edge dislocations during this deformation. Therefore, in this study the method has been restricted to the determination of slip directions on the prism planes only.

For the Southern Alps samples the mean angle between subgrain boundaries and the c -axis was measured using a universal stage on a polarising microscope. Using the method outlined in Passchier and Trouw (1998), the quartz c -axis was rotated parallel to the A4 stage axis on the microscope in grains that have visible subgrain boundaries. The angle between the c -axis and subgrain boundary was measured on the microscope stage after a rotation about the A5 stage axis that brought the subgrain boundary parallel to the A4 stage axis. These angles were measured in five samples resulting in a total of 100 measured grains. These angles are plotted in Fig. 4.15a and have a mean of $4.2 \pm 0.7^\circ$. Several subgrain boundaries were parallel to the c -axes (angle = 0°), the maximum angular difference was 13° , and no significant variation was seen between samples. Four of these measured grains are displayed in Fig. 4.15b. The low mean angle measured between the c -axes and subgrain boundaries indicates that glide took place on the prism or basal planes in the $\langle a \rangle$ direction and rules out significant glide in the $[c]$ direction (after Kruhl, 1996; Morgan and Law, 2004).

A temperature range for prism $\langle a \rangle$ slip has been estimated from the minimum temperature required for dislocation climb (formation of edge dislocations) and the maximum before prism $[c]$ slip occurs. Basal subgrains commonly occur with prism subgrains at high temperatures of $\sim 650^\circ\text{C}$ and form chessboard patterns (Mainprice et al, 1986; Kruhl, 1996) whereas prismatic subgrains will form as soon as conditions for dislocation climb and subgrain formation are met at $\sim 400^\circ\text{C}$ (Stipp et al., 2002b). A temperature range estimate for the subgrain rotation deformation is therefore between 400 and 650°C .

Grain boundary bulging and grain boundary migration in quartz occurs at lower temperatures than subgrain boundary formation (Hirth and Tullis 1992; Stipp et al, 2002b). The presence of these microstructures in the BDSZ samples (Fig. 4.8) suggest that temperatures may be less than the 400°C minimum for prism $\langle a \rangle$ slip

Fig. 4.14. Orientation of common quartz subgrain boundaries to the main slip planes of the crystal. Crystal faces are those from Fig. 4.13a. a. Slip on the prism $\{m\}$ plane in a Burgers vector (BV) of $\langle a \rangle$ where a subgrain boundary is forming perpendicular to the slip plane and parallel to the edge dislocation (ED). b. Slip on the basal $\{c\}$ plane in a Burgers vector (BV) of $\langle a \rangle$ where a subgrain boundary is forming perpendicular to the slip plane and parallel to the edge dislocation (ED). c. Slip on the prism plane $\{m\}$ in the Burgers vector (BV) of $[c]$ where a subgrain boundary is forming perpendicular to the slip plane and parallel to the edge dislocation (ED). Screw dislocations (SD) are shown for reference on the prism planes.

Fig. 4.15. Quartz subgrain boundary angles from the c-axis. a-d. Photomicrographs of quartz crystals with visible subgrain boundaries. c-Axis pole trend orientations are found using a universal stage microscope and marked for comparison with the subgrain boundary orientations (some have been marked with arrows). All c-axis poles marked are horizontal in the plane of the photomicrograph and near parallel to the subgrain boundaries within the quartz crystals. e. Graph of 100 measured angles between the subgrain boundaries and the trend of the c-axis pole in quartz crystals. Angle is noted at the top of each column with the mean angle for the data set plotted as the dashed line across the columns.

and that basal and rhomb slip systems may have been active. A minimum temperature for deformation is therefore estimated to be as low as 280°C, a temperature that has been associated with the frictional-viscous transition in natural rocks and the beginning of grain boundary bulging recrystallisation (Stipp et al. 2002b).

4.5.2. Calcite twinning deformation and slip systems

Calcite crystals in the sheared and shear infilling veins have been deformed by intracrystalline plastic deformation that has been accommodated by twinning and dislocation creep. By determining the style of twin deformation and which calcite slip systems (Fig. 4.16) were active during deformation, an approximate temperature can be estimated for the deformation. Calcite c-axes were measured (same method as for quartz in Section 4.51) and compared with the twin plane orientations. As illustrated in Fig. 4.12g, the twinning planes occur in pairs at 128° about the c-axes, which make a 26° angle to the basal planes. Crystallographic twin planes in calcite with these angles are e-twins (Fig. 4.16). This is the most common type of deformation twinning in calcite (Wenk, 1985c). Deformation on the e-twin planes can occur at temperatures from 25 to 500°C and can take place as a result of critical resolved shear stress (CRSS) of less than 10 MPa (De Bresser and Spiers, 1997).

Evidence for slip systems other than e-twinning are found from grain boundary migration and twin boundary migration microstructures of some calcite crystals from the shear zones (sheared and infilling veins). For this type of deformation to occur, intracrystalline deformation by slip on the {r} and {f} planes is required (De Bresser and Speirs, 1990; Burkhard, 1993). Use of these planes could be from one, or a combination, of the following three conditions: 1) a higher CRSS and temperature where {r} and {f} slip become dominant (De Bresser and Speirs, 1997), 2) the grain is unable to twin because of a poor crystallographic orientation (Turner and Weiss, 1963; Schmid et al., 1987; Barhoon et al., 2004), or 3) the maximum shear strain (0.68) that a calcite grain can accommodate by twinning (without causing recrystallisation) has been reached (Wenk, 1985c).

Temperature estimates can be made for deformation of calcite based on the style and appearance of twin deformation. Calcite twins can fall into one of the four classifications of twin appearance defined by Burkhard (1993). Type I twins are

Fig. 4.16. a. Selected crystallographic forms of calcite that show the main slip planes (e, r, f, m and c) used for the deformation of calcite. 3D models redrawn from Hurlbut (1971). b. Angles of crystallographic planes in calcite from the basal (c) plane. Redrawn from de Bresser and Spiers (1990). Angles from basal plane to e-twin and r and f rhombs from Turner and Weiss (1963) c. Stereographic, upper hemisphere, equal angle projection of calcite planes and crystallographic poles.

thin, straight (e.g. Fig. 4.11c) and occur at low temperatures ($<200^{\circ}\text{C}$). Type II twins are thicker ($>1\ \mu\text{m}$), possibly slightly lens shaped (e.g. Fig. 4.11b) and occur at temperatures between 150 and 300°C . Type III and IV twins have undergone twin boundary migration, are curved and thick (e.g. Fig. 4.12a, b and c), and form from at temperatures of $>200^{\circ}\text{C}$. At these higher temperatures ($>200^{\circ}\text{C}$), $\{r\}$ and $\{f\}$ slip systems are more dominant and existing twin boundaries grow by twin boundary migration and twins become distorted and curved during intracrystalline deformation of grains (Burkhard, 1993; Ferrill et al., 2004). At lower temperatures, however, the twins are not able undergo this deformation and remain thin and straight (Ferrill, 1991).

Calcite twins in the sheared and infilling veins in this study are dominantly Type I twins and cut across the grains without distortion. Type II–IV twins are much less common and only occur in large grains which have not undergone complete grain recrystallisation. The small Type I twins therefore represent late stage deformation at low temperatures after recrystallisation whereas the Type II–IV twins record a snapshot of the earlier deformation higher temperatures.

4.6. Palaeopiezometry

4.6.1. Palaeopiezometry from calcite twinning

A technique for determining differential stress from calcite twin characteristics is based on deformation experiments on marble by Rowe and Rutter (1990). Temperatures of $200\text{--}800^{\circ}\text{C}$, strain-rates of 10^{-3} to $10^{-7}\ \text{sec}^{-1}$ and confining pressures of 100–200 MPa were used in these experiments up to a strain of 30% shortening. Although these are not the same deformation conditions as those argued by Wightman (2005) to have prevailed in the transient brittle-ductile shear zones (t-BDSZ's), the resulting formula for calculating differential stress can still be used to determine a reasonable approximation of stress during the development of the calcite twins in this study.

The differential stress can be determined from three different methods by Rowe and Rutter (1990): volume percent of twinning, twin density, and twinning incidence. The volume percent method uses the characteristic that calcite undergoes a higher volume of twinning with increased differential stress. This increased

volume could be in the form of many thin twins (low temperature) or just a few thick twins at higher temperatures (Burkhard, 1993). The twin density (number of twins per millimetre) method is based on the assumption that at higher differential stresses the number of twins in a grain will increase. Twinning incidence (percent of grains that are twinned for a particular grain size) method uses the differential stress threshold that must be reached to twin a grain of a particular size. Smaller grains require higher differential stresses to undergo twinning compared with larger grains that twin easily (Rowe and Rutter, 1990). These three methods have been used with caution in this study as none of the formula for the differential stress determinations take into account the deformation temperature or the amount of strain that the grain has undergone, both of which have been shown to affect the twin density and the volume percent of a grain that is twinned (e.g. Burkhard, 1993; Newman, 1994; Ferrill, 1998).

The volume percent of twinning was calculated in this study from the number of twins in the grain, the mean twin width and the diameter of the grain. The twin width was measured using a stage micrometer and was multiplied by the number of twins to give a total width of twinned calcite in the grain. All the twins measured maintained a constant thickness and cut all the way across the grain (Type III and IV twins are uncommon and were not found in any of the grains analysed here) which allowed the total width of twinned calcite divided by the grain diameter to approximate the fraction of the grain volume that has undergone twinning (V). The grain diameter was measured the length of the grains long axis (D_L) to ensure that calculated differential stresses were not over estimated. The differential stress was calculated from all the grains out of the 300 examined for each sample that had twins. The method yielded a mean differential stress (${}_D\sigma$) of 128 ± 10 MPa (Fig. 4.17a; Table 4.5) with results calculated from the following equation determined by Rowe and Rutter (1990):

$${}_D\sigma = 2.72 + 0.40(\log V - \log D_L) \text{ MPa} \quad (4.6)$$

Twin density was calculated from the same data as that used to measure the volume percent of twinning. The diameter of the twinned calcite grain was divided by the number of twins to obtain the density of twins per millimetre (d). The differential stress was calculated for all measured grains in which twins occurred.

Fig. 4.17. Differential stress ($D\sigma$) calculated from calcite twins. An example from sample TJFA47-p from an infilling shear vein. Calculated using the technique of Rowe and Rutter (1990) from the volume % twinning (a), the twin density (b), and the twinning incidence (c). Formula for differential stress calculations are inset into each graph where D_L is the diameter of the calcite crystals long axis, D_m is the median grain diameter for each grain size class, d is the twin density, I_t is the incidence of twinning for a given grain size class and V is the volume percent of a grain that is twinned. Graph (a) is contoured for grain diameter and graph (c) is contoured for percent of twinned grains in the sample.

Sample		Calculated differential stress		
Field stn. number	Type of vein	Twin Incidence MPa	Twin density MPa	Vol% MPa
MHCH17	Infilling	185	143	129
MHCH17	Internal	188	140	142
MHCH17	External	198	134	146
MHCH20	Internal	189	133	135
MHCH20	External	208	145	150
MHCH20	Internal	197	134	134
MHCH12b	Infilling	187	129	116
MHCH12b	Infilling	145	120	107
MHCH14	Infilling	178	129	103
TJFA47	Infilling	215	144	120
mean:		189	135	128
2 σ :		12	5	10

Table 4.5. Differential stress calculated from calcite twinning using the Rowe and Rutter (1990) technique for samples from Chancellor Ridge and Sam Peak. Calculations made from formula in Fig. 4.17 with mean values for all of the values in the sample plotted for each sample in this table. Differential stress calculated for each sample is divided into the three different calculation methods; twin incidence, twin density and volume % of twinning with mean values for each method across the samples listed at the bottom of the table. Type of vein listed to identify the location of the calcite being measured in the shear zone.

This method yielded a mean differential stress of 135 ± 5 MPa (Fig. 4.17b; Table 4.5) with results calculated from the following equation determined by Rowe and Rutter (1990):

$${}_D\sigma = -52.0 + 171.1 \log d \text{ MPa} \quad (4.7)$$

The incidence of twinning differential stress calculation was made from the median grain diameter (D_M) of the class range (e.g. grain diameter (D_L) size class of 50-100 μm had a D_M of 75 μm) and the percent of grains in that size class that had undergone deformation by twinning (I_t). The data set of measured grain diameters (D_L) was divided into 10 class sizes with a range of 50 or 100 μm (as in Rowe and Rutter, 1990) depending on the maximum grain diameter measured. All of the 300 measured grains in each of the 10 samples analysed were used in the calculation. Differential stress was calculated for each grain diameter class (e.g. Fig. 4.17c; Table 4.5). This method yielded a mean differential stress of 189 ± 12 MPa and results were calculated from the following equation determined by Rowe and Rutter (1990):

$${}_D\sigma = 523 + 2.13I_t - 204 \log D_M \text{ MPa} \quad (4.8)$$

The volume percent of twins and the twin density calculations are treated with some scepticism in this study. Both the twin thickness and the number of twins are affected by temperature (Ferrill, 1991; Ferrill, 1998) and the amount of strain that the grain has undergone (Burkhard, 1993). The thin and low density twinning style of calcite in this study, associated with low temperatures and small strains, (Burkhard, 1993; Ferrill et al., 2004) is reflected in the lower calculated differential stresses for these methods. As in Newman (1994), the incidence of twinning calculation of differential stress is considered a more reliable indicator of differential stress during twin formation. The incidence of twinning is not dependant on the amount of strain, and temperature is not considered to be as dominating a factor as stress and grain diameter for this method. However, because of the polymineralic samples used in this study (as in Newman, 1994), the differential stress calculated from twinning incidence probably represents a maximum. Impurities around the calcite grain boundaries (quartz and micas) may cause stress concentrations where twins may nucleate at lower differential stresses than in the monomineralic marble used in the experimental study of Rowe and Rutter (1990). The differential stress for

the twinning deformation in calcite is therefore considered to represent a maximum value of 189 ± 12 MPa.

4.6.2. *Palaeostress from recrystallised grain size*

Palaeostress can be calculated from the grain diameter of recrystallised minerals such as calcite and quartz. Using results from experimental deformation and grain growth studies, formulae have been empirically developed to estimate the differential stress required to recrystallise a grain to a particular steady-state grain size during deformation. Care must be taken with these types of palaeostress calculations if grain growth or grain boundary pinning has occurred. Microfabrics such as grain boundary migration, polygonal grain shape fabrics, fluid inclusion planes and twin boundary migration all suggest that grain growth has occurred in the deformed samples studied here. Therefore the palaeostress calculated will at best represent a minimum differential stress for the ductile deformation of the veins. Grain boundary pinning microstructures are also seen in some samples. In these cases the calculated differential stress may be greater than the actual one during ductile shearing of the quartz veins. Quartz and calcite minerals have been used to determine minimum differential stresses during ductile shearing of the quartz-calcite veins.

The quartz palaeopiezometer of Twiss (1977) and revised by Twiss (1980) has been used to determine the differential stress for the finite recrystallisation of quartz in the external, internal and infilling veins. The Twiss (1980) palaeopiezometer, although criticised because of its assumptions of equilibrium thermodynamics, is regarded as the most applicable to wet quartz in natural settings (Stipp et al., 2002a). Many authors prefer the Twiss (1980) piezometer as it is based on sound experimental constraints, uses easily measured recrystallised quartz grain sizes and it does not give unrealistically high differential stress results for naturally deformed quartz samples (Ord and Christie, 1984; Zulauf, 2001; Stipp et al., 2002a). The Twiss (1980) piezometer uses the grain diameter (D) calculated from the intercept method (as in Twiss, 1977 and Stipp et al., 2002a) to calculate the differential stress (${}_D\sigma$) in the equation:

$${}_D\sigma = 6.03D^{-0.68} \text{ MPa} \quad (4.9)$$

The calcite palaeopiezometer of Rutter (1995) was used in this study (after Brodie and Rutter, 2000) and allows a minimum differential stress for recrystallised calcite to be calculated. This technique has been applied to the same external, internal and infilling veins as for the quartz piezometer above. The Rutter (1995) piezometer has been used with grain long axis diameters (D_L) and approximated mean grain diameters (D), assuming an elliptical grain with an R value of 2 (see section 4.4; Ramsay and Huber, 1983). The ellipticity value (R) was assigned based on the maximum measured ellipticity in shear infilling veins of 2.1 ± 0.2 and was calculated an approximate minimum mean grain size. These two diameters allow the minimum (when using D_L) and maximum (when using D) differential stress for calcite grains to be estimated. The constants for migration recrystallisation piezometry from Rutter (1995) have been used instead of those for rotational recrystallisation, because of the evidence for migration recrystallisation in the calcite microstructures. The following formula has been used to calculate a minimum differential stress for deformation of calcite:

$${}_D\sigma = 2691.5D^{-0.89} \text{ MPa} \quad (4.10)$$

$$\text{where } D = \sqrt{D_L \times \frac{D_L}{R}} \text{ } \mu\text{m for maximum stress estimates} \quad (4.11)$$

The differential stress estimates from the quartz and calcite grain sizes in the external, internal and infilling veins are listed in Table 4.6 and displayed graphically in Fig. 4.18. The mean quartz differential stress estimates are between 16 and 65 MPa and there is no significant difference between the three vein sections. The small quartz grain sizes preserved in the pinned microstructures from MHCH20 and MHCH22 record higher differential stress values than the mean values as expected. The average calcite maximum differential stresses (calculated from D like the quartz mean) are higher than the mean quartz values; however considering the assigned high R value of 2 and the experimental uncertainties of the two piezometers, they broadly agree well. These palaeostress calculations from grain size for the sheared and shear infilling veins are lower than those expected for dynamic recrystallisation of quartz (e.g. 50-100 MPa from Hirth and Tullis, 2002). This is not unexpected as the quartz and calcite grains are known to have undergone grain growth after dynamic recrystallisation during shearing of the veins (Wightman, 2005), as

Fig. 4.18. Graphs of differential stress for recrystallised grain diameters from Twiss (1980) for quartz and Rutter (1995) for calcite. Quartz graph is labeled with mean recrystallised grain diameters (D) for each of the vein sections. Calcite graph is also label for each of the vein sections with mean recrystallised grain diameters (D) for the maximum differential stress. Formulae for the recrystallised grain size piezometers are plotted in the lower left hand corner of each graph.

	Section of shear measured	Mean grain diameter			Differential stress			Piezometer	
		mean ^a (μm)	2σ	min (μm)	max (μm)	mean ^b (MPa)	min ^c (MPa)	max ^d (MPa)	used for calculation
Qtz	Internal	126	16	52	200	25	-	45	Twiss (1980)
	External	145	14	90	208	22	-	31	Twiss (1980)
	Infilling	248	123	38	1504	16	-	56	Twiss (1980)
Cal	Internal	116	5	14	1420	-	39	53	Rutter (1995)
	External	93	6	5	448	-	47	65	Rutter (1995)
	Infilling	225	12	24	3731	-	22	30	Rutter (1995)

Table 4.6. Grain size palaeopiezometry of recrystallised quartz and calcite. Quartz differential stress calculated from Twiss (1980) and calcite differential stress calculated from Rutter (1995) assuming grain boundary migration recrystallisation. a - For quartz: mean recrystallised grain size calculated from intercept method (D). For calcite: mean length of crystal long axis diameters (D_L). b - calculated from the mean grain diameter of quartz crystals for each section. c - calculated from D_L for calcite crystals. d - For calcite: calculated assuming a maximum R value (ellipticity) of 2 where grain diameter (D) was calculated from $D = (D_L \times (D_L \times 0.5))^{0.5}$. For quartz: calculated from the minimum grain size measured.

observed in the vein microstructures. At these low differential stresses the grain growth is most likely to have occurred by grain boundary area reduction (GBAR) in quartz and calcite which can occur at near static conditions.

4.6.3. Maximum differential stress from Coulomb failure criteria

In addition to the palaeopiezometric techniques above, the differential stress during shearing in the transient brittle-ductile transition zone (t-BDTZ), ~21 km below the Southern Alps, can be estimated from the stress required to achieve brittle failure and ductile flow in quartz and calcite at that depth. The maximum differential stress possible would be that required to achieve shear failure of the rocks at a near hydrostatic fluid pressure, an underestimated fluid pressure which likely did not in general, prevail (Sibson et al., 1988; Twiss and Moores, 1992; Wightman, 2005) in the t-BDSZ. The differential stress active during ductile shear must have been lower than this maximum differential stress estimate, and can be approximated using the field-based strain-rates and determined from experimental flow laws for the intracrystalline plastic creep of quartz and calcite.

A maximum differential stress can be calculated for ductile deformation of the quartz by considering the differential stress that would place the rock in conditions where brittle Coulomb failure would occur, thus preventing ductile flow. The vertical stress component (σ_v) acting on the shear zone is calculated from an average rock density (ρ_r) of 2.67 g/cm³ and the rock overburden thickness (h) of 21 km (depth of the t-BDSZ below the Southern Alps estimated by Wightman, 2005), yielding an overburden pressure of 550 MPa. For a vertical strike-slip fault, Anderson's theory of faulting predicts that the mean intermediate stress (σ_2) is vertical. We here, assume that the intermediate stress (σ_2) direction of the near vertical fault planes is approximately equal to the vertical stress component (σ_2). Assuming that the intermediate stress (σ_2) is approximately equal to the mean lithostatic normal stress ($^L\sigma_n$), then $^L\sigma_n = 550$ MPa by the following equation:

$$^L\sigma_n = \sigma_2 \approx \sigma_v = \rho_r \cdot g \cdot h \quad (4.12)$$

Microstructures indicate that fluid was present during deformation (e.g. fluid inclusions) and needs to be taken into consideration as fluid pressure (P_f) reduces the

mean lithostatic normal stress (${}^L\sigma_n$) affecting the rocks by an amount equal to the fluid pressure, resulting an effective normal stress (${}^e\sigma_n$). The vertical hydrostatic fluid pressure created by a connected column of water down to the depth of the t-BDSZ (21 km) can be calculated using the mean density of water, ρ_w (1.0 g / cm³) and the height of the water column (h) of 21 km. The hydrostatic fluid pressure (P_H) at 21 km depth (open column of fluid) is 210 MPa, resulting in an effective normal stress of 340 MPa and a fluid pressure ratio (λ) of ~0.4, calculated using the equations below:

$$P_H = \rho_w \cdot g \cdot h \quad (4.13)$$

$${}^e\sigma_n = {}^L\sigma_n - P_f \quad (4.14)$$

$$\lambda = \frac{P_f}{{}^L\sigma_n} \text{ or } \lambda = \frac{{}^L\sigma_n - {}^e\sigma_n}{{}^L\sigma_n} \quad (4.15)$$

The maximum possible differential stress (${}_D\sigma$) during shearing at a given effective normal stress (${}^e\sigma_n$) can be determined from the shear stress required to achieve brittle Coulomb failure ($*\sigma_s$). Assuming a cohesive shear strength (c) of 40 MPa (Sibson, 2000; Lockner, 1995) and a coefficient of internal friction (μ) of 0.75 (Byerlee, 1978), a differential stress (${}_D\sigma$) of 472 MPa was required to achieve brittle failure as an effective normal stress (${}^e\sigma_n$) of 340 MPa (Fig. 4.19), using the equations:

$$\frac{{}_D\sigma}{2} = \cos \phi \cdot *\sigma_s \quad (4.16)$$

$$\text{where } *\sigma_s = c + \mu \cdot {}^e\sigma_n \quad (4.17)$$

$$\text{and } \mu = \tan \phi \quad (4.18)$$

It is unlikely the fluid pressure was hydrostatic ($\lambda = 4$) at a depth of 21 km, and may, in fact, have been approaching lithostatic ($\lambda = 1$) (Twiss and Moores, 1992). The differential stress calculated above for shear failure under hydrostatic conditions would therefore be a maximum. A fluid pressure at the time of shear infilling vein precipitation of 310 ± 90 ($\lambda = 0.6$), recorded in fluid inclusions trapped

Fig. 4.19. Mohr circle diagram for brittle Coulomb failure. Coulomb fracture criterion ($*\sigma_s$) calculated from the normal stress (σ_n), the cohesive shear strength (c), the coefficient of internal friction (μ), the tensile strength (T) and the angle of internal friction (ϕ). The Coulomb fracture criterion is calculated from the formula $*\sigma_s = c + \mu \cdot \sigma_n$ where $c = 2T$, $T = 20$ MPa (Lockner, 1995), $\mu = \tan(\phi) = 0.75$ (Byerlee, 1978). Lithostatic normal stress ($^L\sigma_n$) is calculated as 550 MPa for 21 km under the Southern Alps. Here it is assumed that the mean lithostatic normal stress ($^L\sigma_n$) is equal to the vertical stress (σ_v) as for a near-vertical fault plane, where the intermediate principle stress direction (σ_2) is approximately vertical ($\sigma_2 \approx \sigma_v$). Differential stresses required for brittle Coulomb failure have been calculated at $\lambda = 0.4$, $\lambda = 0.6$ and $\lambda = 0.9$ for hydrostatic, shear infilling vein precipitation, and near-lithostatic fluid pressures respectively. These are represented by the circles shown with differential stress calculated from formula $\sigma_d/2 = *\sigma_s \cdot \cos\phi$.

in the shear infilling veins after initial brittle fracturing (Wightman and Little, 2003; Wightman, 2005), has been used to calculate a more realistic maximum limit for differential stresses expected for ductile deformation in the t-BDTZ before Coulomb shear failure of 353 MPa (Fig. 4.19). In detail however, fluid pressures may have cycled between this post-failure value and near lithostatic fluid pressures ($\lambda = \sim 0.9$) before Coulomb failure of the rock (Sibson et al., 1988; Wightman, 2005). The differential stresses required for shear failure at these elevated fluid pressures ($\lambda = 0.9$) could have been as small as 129 MPa (e.g. Fig. 4.19) or ~ 100 MPa for hybrid extensional failure (Wightman and Little, 2003).

4.6.4. Estimated maximum differential stress during brittle-ductile shearing

Experimental flow laws for intracrystalline plastic creep can be used to calculate an approximate differential stress for ductile deformation in the t-BDSZ. The flow law parameters of Hirth et al. (2001) for quartz and Schmid et al. (1980) for calcite were used here. This approximation assumes that the quartz and calcite flow laws can be extrapolated to low temperatures in order to calculate realistic differential stresses for natural ductile deformation in the crust (< 500 MPa). The flow law equation given below has a standard power law creep form (with an additional factor for water fugacity in quartz) from which differential stress ($D\sigma$) can be calculated:

$$\dot{\varepsilon} = A \cdot D \sigma^n \cdot f_{H_2O}^w \cdot \exp\left(\frac{-Q}{RT}\right) \text{ sec}^{-1} \quad (4.19)$$

Where the ideal gas constant (R) of $8.31451 \text{ J.mol}^{-1}.\text{K}^{-1}$ and the temperature (T) of 723.15°K (450°C as in Wightman, 2005) are constant for both quartz and calcite in the calculation for this study. The strain-rate ($\dot{\varepsilon}$) was estimated from the field-based transect data. The flow law for quartz from Hirth et al. (2001) uses a material parameter (A) of $10^{-11.2}$, a stress exponent (n) of 4, a water fugacity (f) of 35 MPa, a water fugacity exponent (w) of 1, and an activation energy (Q) of 135 kJ.mol^{-1} . The water fugacity in this study was not able to be calculated, so the 37 MPa fugacity of Hirth et al. (2001) was used as a minimum as their deformation temperatures and lithostatic pressures were lower than those used in this study. The flow law parameters for calcite from Schmid et al. (1980) are $A = 10^{-3.1}$, $n = 7.6$ and $Q = 418 \text{ kJ.mol}^{-1}$.

As derived in Chapter 3, maximum strain-rates can be calculated using the escalator model for shear zone formation, the mean finite ductile shear strain, the shear spacing, and the convergence rate (see Fig. 3.14). This maximum strain-rate of $8.6 \times 10^{-8} \text{ sec}^{-1}$, when used in the quartz and calcite flow laws above, yields differential stresses for dislocation creep of 1208 MPa in quartz and 436 MPa in calcite. These stresses are greater than the maximum threshold calculated for ductile vein deformation without brittle failure (353 MPa for $\lambda=0.6$). Assuming that the experimental flow laws adequately predict natural ductile deformation, this result suggests that the estimated strain-rates are too fast for ductile deformation to occur.

Additional strain-rates have been used in this study to investigate variations in the escalator model to a more realistic scenario where more than one shear could be accommodating strain at a time. This involved deforming a wider block of rock, allowing individual shears to be accumulating deformation simultaneously, resulting in a longer period of time over which the deformation is achieved. This time period variation was made by using different deformation widths that ranged from 10 cm to 2 km (Table 4.7; Fig. 4.20). Of these variations, a 100 m wide deformation width is used as the best approximation. This deformation width is based on results of fault ramp numerical modelling by Erickson et al. (2001) that showed zones of deformation between successive backshears 100-200 m thick. Deformation widths <10 m are considered unlikely based on the flow law parameters, given the calculated differential stresses for these smaller deformation widths are high enough to undergo brittle failure (>353 MPa) and not ductile flow at near-hydrostatic fluid pressures (Table 4.7; Fig. 4.20). A maximum deformation width of 2 km, where the entire array of shear zones would be active simultaneously, is not realistic, based on modelling of recrystallisation times by Wightman (2005), as the time taken to accumulate deformation in 2 km wide block does not leave sufficient time for quartz annealing and grain growth to occur before exhumation of the Alpine Fault hanging wall.

The preferred 100 m deformation width yielded an estimated maximum strain-rate of $3.0 \times 10^{-11} \text{ sec}^{-1}$. This rate is an approximate differential stress for ductile deformation in the sheared veins from the flow laws of 165 MPa for quartz and 153 MPa for calcite. Brittle failure at these differential stresses would require

Fig. 4.20. Graphs of strain-rate against differential stress from power law creep equations for quartz (a) and calcite (b) showing calculated differential stress results for estimated strain-rates in Table 4.7. a. Flow behaviour of quartz for the flow law parameters of Hirth et al. (2001). b. Flow behaviour of calcite for estimated strain-rates calculated from the flow law parameters of Schmid et al. (1980). Points are labeled from 'Sample or width' column in Table 4.7 for different widths of deforming rock. Differential stress threshold for brittle coulomb failure (at $\lambda=0.6$) shown as dash-dotted line at 353 MPa in both graphs.

Sample or width	Width of def. rock (mm)	Convergence rate (mm/yr)	Time (years)	Shear strain	Strain-rate (sec ⁻¹)	Differential stress	
						Quartz (MPa)	Cal (MPa)
10 cm	100	19.7	5.08	4.8	3.0E-08	929	380
1 m	1000	19.7	50.8	4.8	3.0E-09	519	281
10 m	10000	19.7	507.8	4.8	3.0E-10	294	207
50 m	50000	19.7	2538	4.8	6.0E-11	197	168
100 m	100000	19.7	5076	4.8	3.0E-11	165	153
2 km	2000000	19.7	101,523	4.8	1.5E-12	78	103
MHCH25	100000	22.2	4505	6.7	4.7E-11	185	163
MHBM13	100000	14.3	6993	3.1	1.4E-11	137	139

Table 4.7. Data used to calculate the estimated maximum strain-rates and differential stresses for ductile deformation in the brittle-ductile shears for varied width of deforming rock and from 2 samples. Shear strain is the mean finite ductile shear strain for the BDSZ and the convergence rate is shear normal plate convergence rate and varies depending on field area (mean for all field areas = 19.7 mm/yr). Strain-rates calculated as in Section 3.4.5 and Fig. 3.14b. Differential stress calculated for quartz from the flow law parameters of Hirth et al. (2001) and for calcite from the flow law parameters of Schmid et al. (1980) for power law creep.

near lithostatic fluid pressures of $\lambda=0.85$, with ductile flow potentially occurring at lower fluid pressures after the initial failure event.

4.7. Changes in deformation conditions up the Alpine Fault ramp

From the palaeopiezometry of the brittle-ductile shears and microstructural observations, three periods of deformation for the quartz-calcite veins are proposed: 1) shearing, 2) stress drop with grain growth and dislocation creep and partial exhumation followed by 3) semibrittle faulting and calcite e-twin deformation. These occur in order of decreasing inferred temperature.

Brittle-ductile deformation of the quartz-calcite veins is estimated to have taken place at 450 ± 50 °C (Wightman, 2005). At this temperature and an estimated maximum strain-rate of 3.0×10^{-11} sec⁻¹ (100 m wide deformation width), power law creep flow laws for quartz and calcite estimate differential stresses of ~160 MPa during ductile deformation. During the brittle-ductile shearing a maximum differential stress of 353 MPa is estimated based on brittle Coulomb failure of the rocks at a fluid pressure of 310 MPa ($\lambda=0.6$). However, the fluid pressure is likely to have been closer to lithostatic prior to failure. If $\lambda=0.85$, brittle failure would occur at the estimated differential stress for ductile deformation of 160 MPa. Microstructures preserved in the veins are not related to this period of ductile shearing and veins may have had a smaller grain size generated from dynamic recrystallisation and an oblique grain shape fabrics generated from the shearing.

After dynamic recrystallisation, grain growth occurred at an estimated minimum, near-static, differential stress of 16-65 MPa. This was calculated using recrystallised grain size piezometers and is a significant decrease in differential stress from the initial period of ductile shearing in the veins. With the low differential stress, GBAR may have been the active recovery mechanism overprinting any existing rock fabrics generated during shearing. After, or synchronously, with this GBAR, veins underwent intracrystalline deformation that produced Regime 1 (of Hirth and Tullis, 1992) microstructures (e.g. grain boundary bulging, deformation lamellae and some subgrain boundaries) that are found preserved in the veins across the shear zone. Oblique grain shape fabrics indicate that a late stage shearing occurred in the shear infilling veins with a minimum shear strain of ~1.5. Based on microstructures in the sheared and infilling veins a temperature of range of 280-

650°C was estimated; however, this temperature is more likely closer to the cooler end of the range based on the Regime 1 microstructures. The homogeneous grain size, Regime 1 microstructures, moderate temperatures and near-static differential stress across all parts of the veins in the shear zone suggests that this deformation occurred after the main ductile shearing event and further up the Alpine Fault ramp.

Calcite grains that have been recrystallised and undergone grain growth typically have e-twin deformation lamellae which are estimated to occur at temperatures <200°C. Grain growth does not appear to have occurred after this twinning as they are in most cases straight, and intercept the grain boundaries. Fluid inclusion trails found in all vein sections, inferred to be healed microcracks, are also inferred to be at lower temperatures when plastic creep is not easily accommodated. From calcite twin incidence palaeopiezometry, the differential stress for this deformation is estimated to be <189 MPa. Even though this stress is a maximum, it is more than triple that of the previous static grain growth and plastic deformation period. The third deformation period is proposed to occur at a higher differential stress due to the rocks proximity to the contemporary seismically defined brittle-ductile transition zone (s-BDTZ; see Chapter 2 and Fig. 2.3) where elevated differential stress occurs (Twiss and Moores, 1992). Under these higher differential stress and lower temperature conditions strain is accommodated by semibrittle faulting in quartz and by e-twinning in calcite.

CHAPTER 5: Crystallographic preferred orientation of quartz c-axes

During crystal-plastic deformation a preferred orientation of quartz crystallographic axes can occur from intracrystalline deformation and dynamic recrystallisation (Lister and Williams, 1979; Wenk, 1985a; Passchier and Trouw, 1998; Bons and den Brok, 2000). Pole diagrams of quartz crystallographic c-axis orientations can be used to infer the aspects of deformation conditions and mechanisms that accompanied shearing, as crystals will align differently depending on the differential stress, temperature, strain and slip systems that are active (e.g. Tullis, 1977; Lister et al., 1978; Lister and Hobbs, 1980; Hobbs, 1985; Schmid and Casey, 1986; Law, 1990). In this study crystallographic orientations were measured using a universal stage microscope to obtain more information about the kinematics and rheology of the brittle-ductile shear zone (BDSZ).

A data set of 30,800 quartz c-axis orientations has been measured from samples collected within the BDSZ at Sam Peak, Chancellor Ridge and Baumann Glacier. Measurements have been made for sheared quartz-calcite veins, both inside and outside of the discrete shear zones, as well as for the syntectonic shear infilling veins to provide a complete crystallographic overview. c-Axes have been plotted on stereographic projections for each of the 102 selected areas within shear zone samples collected across the BDSZ. In some cases measurements from up to seven of these selected areas were analysed across a single shear zone (e.g. MHCH20, Appendix D). Crystallographic measurements were also made on metacherts in the non-mylonitic Alpine Schist at Waiho River and in the Alpine Fault mylonite at Hare Mare Creek in order to compare the crystallographic preferred orientation (CPO) fabrics in these structurally lower samples to those veins in the BDSZ.

The CPO fabrics have been used as a tool to determine the stretching direction, whether the flow was coaxial or non-coaxial, to approximate temperature during deformation, and to infer aspects of the strain path in the shear zones. The kinematic interpretations are unfortunately limited in this study because of the unexpectedly weak and diffuse nature of the CPO fabrics. The cause for this fabric weakness or weakening is a major concern for this study, and will be explained using a combination of CPO fabrics and microstructural observations.

5.1. Measurement of quartz c-axes and presentation of fabric plots

5.1.1. Measurement of a quartz c-axis using a universal stage microscope

Quartz c-axis orientation measurements were made using a 5-axis universal stage fitted to a Leitz polarising microscope (Fig. 5.1a). Marked and orientated thin-sections (30 μm thick) were mounted between glass hemispheres, using a mounting fluid with a refractive index of 1.56 to avoid refraction effects (as in Turner and Weiss, 1963). Rotation of the universal stage was made following the technique in Passchier and Trouw (1998) to find the c-axis orientations. These were converted to pole orientations suitable for display on stereographic, lower hemisphere, equal area projection (CPO fabric plots) using methods outlined in Wenk (1985b) and Phillips (1971). Typical errors on angular measurements for c-axes of quartz crystals are $\pm 5^\circ$ with the smallest size crystal able to be measured typically between 30 and 50 μm (Mainprice et al., 1993; Ullemeyer et al., 2000).

A minimum c-axis pole sample size of 300 was measured for each CPO fabric. 300 c-axes are determined as a statistically representative sample size, as incremental increases of 100 measurements from 300 to 900 resulted in no significant change in the generated CPO fabric. Slides were moved on the stage parallel to the shear plane pole (parallel to the c+ direction in Turner and Weiss, 1963) and every grain which fell under the crosshairs of the microscope was measured (Fig. 5.1b). Multiple runs were made parallel in this direction and spaced ~ 0.5 mm apart to ensure that grains were not measured twice and that a representative area of slide was covered without possible bias towards domains present within the samples. Typically, the orientation measurements were made in an area ~ 10 mm².

Thin-sections of vein segments that lie in the external and internal areas of the most attenuated vein sections and of shear infilling veins (Fig. 5.1c) were all cut perpendicular to the shear plane and parallel to the strike of the shear zone. This was the only orientation of thin-section made for the external and internal vein sections due to the limited sample size. However, some shear infilling veins had sufficient sample volume for additional cuts to be made perpendicular to the shear plane and parallel to the dip direction; and / or perpendicular to the shear plane and parallel to the fault surface mineral fibre lineation. Mutually perpendicular sections normal to

Fig. 5.1. Slide orientations on the universal stage microscope and locations of sections in the shear zones. a. Photograph of the 5-axis universal stage mounted on a polarising microscope that was used in this study. Top (T) and right (R) directions annotated on the side of the microscope for reference with (b). b. Schematic plan view of the universal stage microscope stage with a mounted thin section. North and east relate to directions on the microscope (a). c. Cartoon of a shear zone with brittle-ductile marker vein and a shear infilling vein. The vein sections used to differentiate between the different parts of the shear zone are labelled. External vein section - part of vein that has not been sheared by the brittle-ductile deformation. Internal vein section - the attenuated section of the vein that has been sheared by the brittle-ductile deformation. Shear infilling vein - the infilling vein material precipitated along the shear plane.

the shear plane made in some samples were rotated into a common orientation to ensure that a bias in c-axis measurements was not being created as a result of thin-section orientation. In addition, serial thin-sections were often required to cover a large enough lateral extent of the veins in the shear zones and be representative. All the analysed samples of deformed veins had a cut in the external section and one or more cuts in the more strongly deformed, internal vein section. Thin-sections for infilling veins were made where material was available and taken from several areas along the vein length to ensure that there was not a bias toward any particular fabric domains. Thin-sections were positioned in the microscope with the top of the shear plane and its pole pointed upward in the “top” position, and the more northern end of the strike (or the down-plunge or down-dip direction of the side) pointing towards the “right” position of the microscope stage (c+ and b+ directions, respectively of Turner and Weiss, 1963; Fig. 5.1b).

5.1.2. Quartz c-axis CPO fabric and CPO pattern plots

CPO fabrics are plotted with reference to a vertically positioned shear plane that strikes east-west on the lower hemisphere stereogram, and with the top of the sample in the north position (as in Lister and Hobbs, 1980; Figs. 5.2 and 5.3). These CPO fabric plots differ from the conventional orientation used by Llana-Fúnez (2002) and Law et al. (2004) for example, in that it is the shear plane rather the foliation that is the reference plane. As no obvious foliation occurs in the quartz veins examined in this study, the shear plane has been used as the planar reference for the CPO fabric plots. This means that the minimum and maximum principle strain axes would be anticipated to lie at an oblique angle to this reference plane in the case of a non-coaxial deformation involving ductile shear, unless that deformation involved a very large strain (i.e. $\gamma = 10$ for simple shear).

CPO fabric plots have been produced using the computer software StereoNet for Windows (Geological-Software, 1995). A scatter plot and a contour plot were generated for each set of CPO fabric data. These are displayed side-by-side, in accordance with the method recommended by Marshak and Mitra (1988). Contour plots were generated using the Kamb contouring method (Kamb, 1959) and plotted with shading in either a greyscale or a colour spectrum according to the point density (percent of total points). The Kamb contouring method was used as it takes into

Fig 5.2. a. 3-D schematic illustration of shear zone features. a-b-c reference frame for initial CPO data collection with the mineral fibre lineation [a] plotted parallel to the east-west direction on the stereogram. x-y-z reference frame for rotated CPO fabrics with stretching direction [x]. Stereographic reference frames for CPO fabric plots are shown in 3-D positions for both a-b-c and x-y-z positions. Shear plane (and shear sense), mineral fibre lineations and Alpine Schist foliation are illustrated as well as a sheared vein. Rock hammer used for approximate scale and a mean shear normal spacing of ~0.25 m shown on schematic outcrop surface. b. Initial stereographic reference frame used for collecting CPO data. c. Rotated stereographic reference frame with CPO fabric symmetry axes aligned relative to [x]. [x] is the inferred elongation direction.

Fig. 5.3. CPO patterns (skeletal outlines) of non-coaxial (a and b) and coaxial (c, d, e and f) strain. Dashed line represents the foliation, half arrows indicated the shear sense, and full arrows represent the stretching directions. a. Progressive changes in the CPO pattern with increasing simple shear strain adapted from Schmid & Casey (1986). CPO pattern on the left has an initial random fabric. With a small increase in simple shear a Type I girdle develops an internal and external asymmetry with the dominant girdle section perpendicular to the shear zone. With increased strain a single girdle is developed perpendicular to the shear zone and the angle between the foliation and the shear plane ($90-\psi$) approaches 0° (as in Lister and Hobbs, 1980). Strain calculated from $(90-\psi)$ for simple shear as in Platt & Behrmann (1984) using formula in Ramsay (1983). b. Type I girdle with labels indicating ω - the girdle opening angle, ψ - the angle from the dominant girdle to the foliation, x, y & z - pole orientation, and the shear sense (half arrows) observed from the external and internal asymmetry. c. Type I crossed girdle CPO pattern generated from plane strain. d. Type II crossed girdle CPO pattern generated from general extension e. Small-circle girdle CPO pattern generated from simple flattening. f. Cleft girdle CPO pattern generated from simple extension. CPO patterns c, d, e and f have the foliation parallel to the shear plane. k values calculated from ratio of extension axes (from Twiss and Moores, 1992).

account the statistical significance of the number of c-axes measured (Kamb, 1959). Counting circles of 1σ were used to generate most contour plots (e.g. Sample 03 in Fig. 5.4a), instead of the standard 3σ (Kamb, 1959) as the weak CPO fabrics measured in this study required increased fabric detail (reduction of σ as in Miller and Christie, 1981). Contour plots for stronger fabrics (e.g. Sample 10 in Fig. 5.4b) were made using a 3σ counting circle to reduce the detail and produce a clearer contour plot.

CPO patterns (skeletal outlines of Lister and Williams, 1979) have been overlain on each CPO fabric plot to delineate the concentration of c-axes in the stereogram. The term ‘CPO pattern’ is used here for the interpretation of a skeletal outline and the inferred kinematics associated with that pattern, whereas the term ‘CPO fabric’ is reserved for reference to a c-axis pole diagram or contour plot (as in Schmid and Casey, 1986). The types of CPO patterns recognised in this study are outlined in Fig. 5.3. Fig. 5.3a shows an idealized progressive pattern development by simple shear; Fig. 5.3b show angular relationships used here for asymmetrical CPO patterns; and Fig. 5.3c-f show other types of symmetrical CPO patterns referred to in this study and their generally interpreted stretching and compression directions.

CPO patterns were plotted ‘by eye’ from CPO fabrics in this study. However, eigenvalue ratios have also proven useful for describing some patterns (e.g. girdled, domainal, or random CPO patterns) using the Woodcock (1977) method and calculated eigenvalues from the computer software Stereonet for Windows (Allmendinger, 2003). The eigenvalue ratio of $S_2:S_3$ has been used as a guide for girdle strength (ratios <1.4 define a weak girdle), whereas the ratio of $S_1:S_2$ measures the strength of a fabric cluster (a significant cluster has a ratio >1.4). The $S_1:S_3$ ratio can be used as a guide for randomness (ratio <1.44 is random; also see Section 5.6.1). However, these ratios are limited in their application, as some CPO patterns are not well described by orthorhombic eigenvalues. As noted by Woodcock (1977), caution should be exercised when interpreting fabrics that are multimodal or have small-circle patterns. Eigenvalue ratios are used here in conjunction with the visual interpretation of a contour and scatter plot, where CPO patterns are assigned to fabrics based on contour densities.

Fig. 5.4. a. Rotation method used to find the CPO-derived stretching direction. Rotation of the CPO fabric about the c-pole is made from the mineral lineation direction [a] to the stretching direction [x] as defined by the Type II quartz CPO pattern measured in Sample 3. SP= shear plane. b. Sample 10 is used to test the rotation method with a known stretching direction [x+a] on a strong CPO pattern. Rotation occurs from down-dip to the position where the single girdle CPO pattern crosses the y-axis. Measured direction of mineral stretching lineation [x+a] rotates into east-west direction when girdle crosses the y-axis. Kamb contouring method used with a 1σ counting circle for Sample 3 and a 3σ counting circle for Sample 18. Both samples have a sample population of 300 c-axis measurements and are contoured by percent and shaded according to illustrated scale. Specific down plunge or top of sample directions represented by pole labels in square brackets (e.g. [x] - down plunge; [z]- top of sample). Brackets are not used in CPO fabric plots, instead, labelled ends of the poles represent these specific directions.

Fig. 5.5. Stereographic projection of 19 measured quartz CPO-derived stretching poles from internal and infilling vein sections and 25 mineral fibre lineation directions from field-based measurements. Stretching poles derived from rotated quartz CPO fabrics are divided into those with a west-side-up shear sense (filled triangles) and stretching poles with no shear sense (stars). The west-side-up shear sense is inferred from internal asymmetries from fabrics with Type I CPO patterns. Uncertainties represent a 95% confidence ellipse surrounding the mean lineation or pole-to-plane orientation.

5.2. Quartz CPO-derived stretching directions

The quartz CPO fabrics were initially viewed in the a-b-c reference frame (Fig. 5.2) with the a-pole parallel to the displacement vector (assumed to be represented by the mineral lineation measured in the field). If the CPO patterns when viewed in this reference frame were not centred about the b-pole (e.g. Fig. 5.4a) one might infer that the stretching or shear direction was not parallel to the observed lineation and finite displacement vector (a-pole). In these cases the CPO fabrics were rotated about the c-pole to bring CPO pattern into alignment as best as possible with the b-pole (as in Klaper, 1988; MacCready, 1996; e.g. Fig. 5.4). Based on this rotation, a CPO symmetric reference frame (x-y-z) was defined (Fig. 5.2). A stretching direction, referred to here as the quartz CPO-derived stretching direction, has been found from the direction of the x-pole in the shear plane. All CPO fabrics in this study are plotted in Appendix E and presented in the rotated x-y-z reference frame. Shear plane orientations, with pitches of x-pole from the southwest (as derived from rotations of the CPO data) for each plot, are listed in Appendix H.

A rotation about the b-pole was not required for the CPO fabrics measured from deformed internal vein sections and shear infilling veins, as once rotated about the c-pole these patterns were in mirror symmetry across the y-z plane. This symmetry indicates that the shear plane measured in the field (the x-y plane) was indeed the shear plane of the ductile deformation that generated the CPO fabrics. The CPO fabrics measured from the external sections of the veins did not show mirror symmetry about the y-z or the x-y planes after rotation. This implies that the deformation which produced these CPO patterns was unrelated to the shearing.

To avoid confusion, a CPO fabric pole label inside square brackets represents a specific direction or pole end (in all cases the down-plunge end when viewed in a geographic projection such as Fig. 5.5). For example the symbol [x] refers to the down-plunge end of the x-pole. For simplicity, the square brackets are only used in the text and not in CPO fabric plots. In the fabric plots the labelled ends of the poles represent the down plunge directions for [a] or [x] and the top of the sample for [z].

The method of rotating fabrics to find the stretching direction is based on replicating the CPO patterns produced from numerical modelling and experimental deformation of quartz where the stretching directions for the deformation are known

(e.g. Tullis, 1977; Lister, 1978; Lister and Williams, 1979; Schmid and Casey, 1986). A CPO pattern, Type II for example (Fig. 5.3d), is generally in mirror symmetry about the shear plane (also the foliation for coaxial CPO patterns in Fig. 5.3, and a-b or x-y planes in Fig. 5.2) and the plane perpendicular to the shear plane (the b-c or the y-z plane in Fig. 5.2). This symmetry only occurs when the shear plane is plotted in the east-west vertical orientation in the CPO fabric plots and the finite stretching lineation is aligned east-west and horizontal (e.g. a- and x-poles in Fig. 5.2). An example of this rotation is shown in Fig. 5.4a, where a CPO pattern has been plotted with the a-pole (parallel to the mineral fibre lineation) in the east-west direction but the pattern is not in mirror symmetry about the shear plane. Therefore the stretching direction is not aligned parallel to the a-pole and a rotation of the fabric is required. A rotation about the c-pole was made until the CPO pattern aligned symmetrically about the shear plane (Fig. 5.4a). The x-pole, which is inferred to be parallel to the stretching direction during CPO fabric development, now lies in the east-west [x] direction of the stereogram. The a-pole (parallel to the mineral lineation) still lies in the shear plane but is no longer plotted parallel to the east-west direction and has been rotated about the c-pole away from that position (Fig. 5.4a).

The rotation of the CPO fabrics was made using Stereonet for Windows (Allmendinger, 2003) and rotated according to visual and statistical methods. For the visual method rotations were made until the CPO pattern was determined visually 'by eye' to be symmetrical about the y-pole or shear plane. The statistical method utilised the eigenvector statistics of the CPO fabric to find the centre of the CPO pattern that should have intercepted the y-pole in the x-y plane. The plane containing both the S_1 and S_2 eigenvectors was used to define the girdle patterns or the centres of Type I, Type II or Cleft girdle CPO patterns (Fig. 5.3). Once this centre or girdle was established, a rotation of the fabric in the shear plane (about the c-pole) was made until it was centred symmetrically about the b-pole. By knowing how many degrees, and in which direction the rotation was made, the new x-pole and [x] orientation was established.

This rotation method for finding the apparent fabric stretching direction was confirmed by two tests. The first test involved measuring CPO fabrics from two slides cut perpendicular to each other from the same sample and rotating them to find the stretching direction. Although each required a different rotation about the c-pole

due to the difference in the original orientation, the rotations resulted in both slides having the same final x-pole orientation and coincident x-y-z reference frames. This exercise confirmed that the rotation method for determining the [x] direction was robust.

The second test was employed to ensure that rotations were determining a stretching direction from a CPO fabric. The CPO fabric from a metachert in the Alpine Fault mylonite zone was used to perform this test as a mineral stretching direction (elongated quartz porphyroclasts, aligned micas, and boudinaged hornblende and feldspar crystals) is measured and interpreted here to represent ductile stretching in the rocks which have undergone an estimated shear strain of >120 (Norris and Cooper, 2003). The CPO fabric in this rock, with an asymmetric, single girdle CPO pattern, was measured in a slide that was cut in the dip direction and subsequently rotated giving a stretching direction pitch 34° from the northeast in the shear plane (Fig. 5.4b). This quartz CPO-derived stretching direction [x] is only 4° steeper than the actual mineral stretching lineation [a] measured in the field and their near-coincidence confirms that the fabric rotation method provides reasonable results. The shear sense measured from the internal asymmetry of this CPO pattern girdle (method of Law, 1990) was found to be dextral-reverse and is consistent with many other microfabric and field-based estimates of shear sense in this rock (see Sibson et al., 1979; Wightman, 2000; Little et al. 2002a; Appendix F this study). These two tests confirm that with a known shear plane and a CPO pattern the ductile stretching direction for quartz can be reliably determined after a rotation about the c-pole.

From this study, CPO patterns from the most deformed, internal, vein sections and shear infilling veins used to infer a stretching direction (excludes small circle, domainal and random CPO patterns which did not have determinable or reliable stretching directions) were rotated to find the quartz CPO-derived stretching direction. These are plotted in Fig. 5.5 along with the orientations of the mineral fibre lineations observed on the shear planes in the field for comparison. The quartz CPO-derived stretching directions pitch steeply towards the down dip direction in the shear plane with a mean orientation of $239, 79^\circ \pm 11$ (uncertainty represents a 95% confidence ellipse surrounding the mean orientation). These are clearly not

coincident with outcrop measured mineral fibre lineations that decorated the shear planes in the field and pitch moderately at 35° from the southwest (Fig. 5.5). A notable exception to the general trend of quartz CPO-derived stretching directions is in Sample 7 (an infilling vein section). This sample has a stretching direction that pitches 18° from the southwest, which is coincident with the mineral fibre lineation measured on the outcrop for that sample (Fig. 5.5). The steeply pitching quartz CPO-derived stretching directions from most deformed internal and shear infilling vein sections of the remaining samples, suggest that the ductile elongation of the quartz recorded in the CPO fabrics was not coincident with displacement vector (interpreted as parallel to the mineral fibre lineations) on the adjacent brittle faults cutting the quartzofeldspathic wall rocks.

5.3. CPO fabrics and CPO patterns found across the brittle-ductile shear zones

5.3.1. Measured quartz c-axis CPO fabrics

Crystallographic preferred orientations for quartz c-axes have been measured in sixteen hand-samples of sheared quartz-carbonate veins: one from Sam Peak, seven from Chancellor Ridge and eight from Baumann Glacier (Appendix D). A representative sample of four of these are illustrated as cartoons in Fig. 5.6 which represent the main types of vein deformation and CPO patterns across the BDSZ. The finite ductile shear strain of the deformed veins in Samples 1-3 was calculated using a lineation parallel slip vector pitching southwest at 30° . In Sample 4, which lacked a lineation, a slip vector was calculated from a piercing point construction and yielded a southwest pitch of 2° (see Fig. 3.12 for this calculation). CPO patterns are shown in Fig. 5.6 for each location in the shear zone where quartz c-axes were measured and illustrate progressive changes taking place across individual shear zones. CPO fabrics for each of the patterns are plotted in Fig. 5.7. Interpreted shear senses, interpreted CPO patterns, and the trace of the external Alpine Schist foliation are plotted on each of these fabrics as appropriate. All CPO fabrics have been rotated into the x-y-z reference frame (see Table 5.1 for [x] direction in the shear plane). An exception to this was Sample 7 where no rotation was required as the [a] and [x] directions were coincident.

The CPO patterns found in the strongly deformed internal vein sections were variable. These include small circles (e.g. Fig. 5.6b), cleft girdles (Fig. 5.6f), Type II

Fig. 5.6. Sheared quartz-carbonate veins with finite ductile shear strains (γ_d) ranging from 3.1 - 7.7 with interpreted CPO patterns. Complete CPO fabric plots for CPO patterns A to X can be found in Fig. 5.7 with orientation and fabric strength data in Table 5.1. Samples 1 & 4 dip west, and 2 & 3 dip east. 1. Sample 1 showing two shear zones, one with a small circle and the other a cleft girdle CPO pattern. 2. Sample 2 showing shear zone with cleft girdles in the ductile sheared sections of the vein. 3. Sample 3 showing shear zone with internal, external and infilling vein sections. CPO pattern J from Sample 3 (shown) and I from Sample 5 (not shown, but has the same shear strain and scale of offset as Sample 3). Sample 3 infilling CPO pattern W and representative infilling CPO patterns from Samples 6-10. 4. Sample 4 showing two sheared veins; one with asymmetric girdles and the other with cleft and small circle girdles.

Fig. 5.7. Quartz c-axis fabrics and patterns for veins deformed by shears in Fig. 5.6. Quartz c-axis poles plotted on equal area, lower hemisphere, stereographic projections. Contours were calculated using a counting circle of 1σ and plotted as lines of equal concentration percentage. Contours are shaded for concentration and scaled according to the graduated scale bars. Contour and scatter plots are paired for complete and objective fabric interpretations. Pitch of [x] in the shear plane can be found in Table 5.1. CPO fabric analysis I is from the internal vein section in Sample 5 which is very similar in strain and scale to Sample 3 (Fig. 5.6c). Great circles, drawn on external vein section CPO fabrics, represent the Alpine Schist foliation. CPO patterns illustrated on scatter plots as in Fig. 5.3.

Fig. 5.7 continued... Quartz c-axis CPO fabrics and patterns for veins deformed by shears in Fig. 5.6. Details as in caption on previous page. CPO patterns marked on scatter plots as in Fig. 5.3 with the addition of a domainal CPO pattern in CPO fabric X. All fabrics have been rotated in the x-y-z reference frame with the exception of CPO fabric V (Sample 7) which is in the a-b-c reference frame.

CPO fabric Fig. number	Vein sect.	Sample number			Grid Reference (New Zealand Grid)		Shear plane orientation (x-y plane)	Sheared vein orientation	Alpine Schist / mylonitic (S _m) fol. orientation	Calculated finite ductile shear strain	Pitch of CPO derived [x] in shear plane	Eigenvalue ratios			Visual fabric strength	CPO pattern code	Mean grain dia. (μm)																		
		This study	VUW Collect.	Field number	Easting	Northing						S1/S3	S1/S2	S2/S3																					
Fig. 5.7 A Fig. 5.7 B Fig. 5.7 C Fig. 5.7 D	E I I E	1	39405	MHCH25	2,276,935	5,739,670	216@80 W	017@80 E	042@78 SE	6.7 6.4	90 - - 90	1.41 1.85 1.50 2.04	1.22 1.65 1.11 1.51	1.15 1.12 1.35 1.35	1 4 0 3	R SC R CG	130 120 124 144																		
Fig. 5.7 E Fig. 5.7 F Fig. 5.7 G Fig. 5.7 H	E I I E										2	39429	MHBM13	2,280,123	5,744,672	056@80 E	014@80 E	215@84 NW	3.1 80 73	68 86 80 73	2.08 2.03 1.66 2.12	1.32 1.34 1.35 1.44	1.57 1.51 1.23 1.47	3 4 3 3	SG3-f CG CG SG3-f	145 109 106 208									
Fig. 5.7 I	I																			5	39404	MHCH24c	2,276,924	5,739,671	218@82 W	020@76 E	035@82 SE	6.8	-	1.44	1.23	1.17	0	R	108
Fig. 5.7 J Fig. 5.7 K	I E																												3	39397	MHCH17	2,276,050	5,740,450	038@88 E	016@87 NE
Fig. 5.7 L Fig. 5.7 M Fig. 5.7 N Fig. 5.7 O Fig. 5.7 P Fig. 5.7 Q Fig. 5.7 R Fig. 5.7 S Fig. 5.7 T	E I I E E I I I E	4	39400	MHCH20	2,277,348	5,740,090	222@86 W	104@64 S	027@75 SE	6.8										70 70 70 60	1.96 1.62 1.73 2.14	1.15 1.29 1.10 1.23	1.71 1.26 1.58 1.74	4 3 4 4	SG2-f SG2 SG2 SG2-f	118 149 76 90									
											002@82 E			4.4	- - - 80 -	1.52 1.52 1.35 2.31 1.55	1.26 1.10 1.17 1.11 1.32	1.21 1.38 1.16 2.08 1.18	0 3 4 4 1	R SC SC CG R	116 135 122 52 142														
Fig. 5.7 U Fig. 5.7 V Fig. 5.7 W Fig. 5.7 X	In In In In														6 7 8 9	39402 39391 39397 39385	MHCH22 MHCH12 MHCH17 MHCH06	2,277,421 2,277,107 2,276,050 2,277,325	5,740,067 5,740,211 5,740,450 5,740,132	219@85 W 221@85 W 038@88 E 218@84 W	- - - -	- - - -	- - - -	105 18 - -	2.35 1.97 1.50 1.82	1.31 1.44 1.13 1.67	1.79 1.37 1.33 1.09	4 3 0 4.0	CG T2 R D	38 143 150 140					
Fig. 5.4 B	-														10	39409	MHHM01	2,273,722	5,747,569	foliation	-	061@32 SE (S _m)	> 120*	146	21.09	2.48	8.50	5	SG3	76					

Table 5.1. CPO fabric and pattern data for each of the sheared veins in Fig. 5.6 and CPO fabric plots in Figs. 5.4 and 5.7. Sample numbers are given for those used in this chapter (this study), Victoria University Collection numbers and for the field collection numbers. Orientation of the shear planes in the sample and CPO fabrics, the Alpine Schist or mylonitic (S_m) foliation are given, as well as the finite ductile shear strain calculated for each sample. Finite ductile shear strain calculated from displacement vectors (using net-slip pitch of 30° for all samples other than Sample 4 where a pitch of 2° is used). Ductile strain for Sample 10 is from Norris and Cooper (2003). Vein sections are noted for each of the samples where 'E' is the external vein section, 'I' is the internal veins section and 'In' is the infilling vein section. Vein sections are illustrated in Fig. 5.1c. The pitch of [x] (down plunge end of x-pole in CPO fabric plots) and is from the southwest in the shear plane. Eigenvalue ratios used for CPO fabric strength (S_1/S_3), domainal strength (S_1/S_2) and girdle strength (S_2/S_3) are given as well as the fabric strength ranking. CPO pattern codes are from Fig. 5.3 with the addition of D for a domainal pattern. Mean grain diameters have been calculated from the intercept method for each vein section. The symbol '-' denotes where data was not applicable to a sample.

cross girdles (Fig. 5.6j), Type I cross girdles (Fig. 5.6m) and random patterns (Fig. 5.6i). All the CPO patterns found in the internal vein sections are in mirror symmetry about the shear plane and are different from the patterns in the less deformed external vein sections (Fig. 5.6). Some veins show the generation of a CPO pattern from random crystallographic orientations in the external section (e.g. Sample 1, in Fig. 5.6), whereas other veins show the generation of a new fabric overprinting an already existing external fabric (e.g. Sample 2, Fig. 5.6). Some veins with the same external pattern and have undergone similar deformation and have different internal patterns. For example, Sample 3 (Fig. 5.6), which has two internal CPO patterns plotted (one for each of the two deformed veins that the cartoon represents); a Type II for one vein and a random CPO pattern for the other. Sample 4 illustrates two sheared veins in the same shear zone. These have the same slip but different shear strains because of deformation zone width differences. Their resultant CPO patterns are different (Fig. 5.6); the thin vein (Vein 1) has Type I whereas the thick vein (Vein 2) has small circle and cleft girdle CPO patterns. Overall, random and types of coaxial CPO patterns are most common in the internal vein sections. The progressive development of a single girdle CPO pattern with the stretching direction [x] sub-parallel to the known displacement vector (a-pole) (Fig. 5.3a after Schmid and Casey, 1986 and Lister and Hobbs, 1980) was not observed in any samples.

The CPO patterns found in the less deformed, external parts of the veins were variable like the internal vein sections. The patterns however, were not symmetrical about the shear plane and instead often had mirror symmetry about the external Alpine Schist foliation plane. E.g. CPO patterns E, K and L in Fig. 5.7 show this where the foliation has been plotted on CPO fabrics from external sections. As expected, these external CPO patterns are similar on both sides of the shear zone, but are different from the CPO patterns found in the strongly deformed internal parts of these veins.

Quartz samples from 32 shear infilling veins (Appendix E) also yielded diverse and generally weak CPO fabrics and patterns. Unlike the sheared veins, domainal CPO patterns were found from some infilling samples (e.g. CPO fabric X from Fig. 5.6 and 5.7). All domainal concentrations were located in regions away from the z-poles and were typically in samples where the microstructures included

many large quartz grains (200-1000 μm) containing a subgrain substructure, and in some cases, a core-and-mantle microstructure. For example, CPO fabric X (Fig. 5.7) is from an infilling vein (shown in micrograph Fig. 4.9f) that contains large grains (~ 1000 μm) with subgrain boundaries, and small recrystallised grains (~ 100 μm). The range of CPO patterns from shear infilling veins is illustrated on Sample 3 (Fig. 5.6c). Type I CPO patterns were not found in any of these veins and random patterns were more common than in the internal or external vein sections.

For comparison three quartz c-axis CPO fabrics were measured in samples below the BDSZ to investigate the CPO patterns and stretching directions in structurally lower sections of the Pacific Place crust. These non-mylonitic Alpine Schist samples from the Waiho River area were taken from metachert layers to ensure an abundant monomineralic composition of quartz grains. They had Type I CPO patterns in a mirror symmetry about the Alpine foliation (S_3) and yielded quartz CPO-derived stretching directions pitching southwest at 25-60° (Appendix E).

5.3.2. Strain path and kinematics for deformation recorded in CPO's

Quartz c-axis CPO fabric measurements made across the sheared veins have revealed a significant variation of CPO patterns between, and in some cases, within individual shear zones, showing that the deformation of quartz was not homogenous. CPO patterns in the more strongly deformed, internal sections of the sheared veins all show a reorganisation of the CPO pattern relative to the external parts of those veins. These internal CPO patterns are in mirror symmetry about the shear plane and are therefore related to the ductile shearing of the deformed vein in the shear zones (Fig. 5.7). 60% of the measured internal CPO patterns, somewhat unexpectedly, yielded CPO patterns that suggest irrotational strain deformation, such as plane strain, pure shear flattening or constriction rather than a rotational strain such as simple shear (e.g. Fig. 5.3). These irrotational CPO patterns suggest that the steep quartz CPO-derived [x] direction represents a finite extension direction associated with irrotational deformation rather than one associated with simple shearing in the vorticity plane.

The highly variable nature of the CPO patterns found across adjacent shear zones and in different veins within the same shear zone may reflect local variations in deformation conditions. This has been documented in studies such as White et al.

(1980) and Hippertt and Tohver (1999) where CPO patterns and measured shear senses change between adjacent shear zones and even between layers in multilayered rock. Variations in CPO patterns between shear zones may also be caused by a partitioning of strain from the quartz into different sections of the shear zone such as the shear infilling veins, the brittle fracture, or even calcite enriched layers within the veins.

The external CPO patterns are frequently in mirror symmetry about the Alpine Schist foliation plane (Fig. 5.7) suggesting that their generation is related to deformation that generated this foliation and not from late Cenozoic brittle-ductile shearing. The Alpine foliation, in many cases, is axial planar to the cleavage observed in fold hinges of the veins external to the shear zone (e.g. Vein 2 from Sample 4 in Fig. 5.6) indicating involvement of the veins in the older schistosity formation, so these fabrics are not unexpected. It is inferred that these CPO patterns are indeed proto-fabrics to the internal shear fabrics and were generated during earlier deformation of the Alpine Schist before brittle-ductile shearing.

The external vein CPO fabrics have similar patterns with mirror symmetry about the foliation and variable quartz CPO-derived stretching directions (southwest pitches of 37-110°) to those measured from the Waiho River metachert samples further supporting the interpretation that the external fabrics are related to vein deformation during development or strengthening of the Alpine Schist foliation. Wightman (2005), Little et al. (2002a) and Little (2004) have argued that the brittle-ductile shears did not accommodate all of the strain related to tilting onto the Alpine Fault ramp at depth, and infer that some late Cenozoic strain must have been accommodated by microscale ductile deformation in the schist between successive shears. Therefore, the external fabrics may not be entirely inherited in the sense that they may include an effect of the late Cenozoic shearing overprint. The foliation parallel CPO patterns are therefore interpreted as strengthening or reinforcement of existing fabrics by the microscale shear along the foliation planes during uplift.

CPO fabrics measured from the shear infilling veins have a broad variety of CPO patterns, like the internal sections, but include more random and domainal CPO patterns (Appendix E). The domainal CPO patterns found in the infilling vein sections are most likely due to a primary crystallographic anisotropy that was

inherited from the original growth of the veins by precipitation. This anisotropy was not generated by euhedral quartz grains growing inward from the fracture wall as the CPO fabrics do not show domains of intense c-axis concentration about the z-axis as expected for this type of vein precipitation (Fournier, 1985; Appendix G, this study). Instead, the inclined domains of intense c-axis concentration (e.g. Fabric X, Fig. 5.7) could have been generated from subgrain rotation recrystallisation of an original mosaic of very coarse grains, with their recrystallised grains retaining similar orientations to the original host grain, thus yielding a domainal fabric.

Random CPO patterns found in some infilling veins could have been preserved from primary crystallographic orientations that were similarly random and which have not undergone significant further deformation and fabric development. This is likely as the large and broad range of grain sizes in these veins (mean of 248 μm with a maximum of 1500 μm) does not resemble the equigranular polycrystalline texture typically of a dynamically recrystallised quartzite aggregate (Passchier and Trouw, 1998). Randomisation by a deformation processes cannot be ruled out completely though, as several infilling veins had a weak alignment of crystallographic c-axes (e.g. Fig. 5.7u and v) consistent with at least some dislocation creep (Wenk, 1985; Knipe, 1989; Bons and den Brok, 2000). The CPO patterns were symmetrical about the shear plane in these samples and therefore are likely to be related to dislocation creep during shearing.

5.4. Shear sense from CPO fabrics

CPO patterns generated from plane strain, such as a Type I or single girdle patterns, are often used to determine the shear sense if they had an asymmetric CPO fabric (e.g. Lister, 1977; Lister and Williams, 1979; Schmid and Casey, 1986; Dell'Angelo and Tullis, 1989; Law et al., 1990). In particular the, 'external asymmetry', or obliquity between the shear plane and the foliation reflects the shear sense. This method works best when the foliation is distinct, when the shear plane is easily determined from CPO patterns, and when the two fabric elements are not too similar or sub-parallel in their attitude (e.g. Schmid and Casey, 1986). Unfortunately, external asymmetries could not be resolved in this study because the strongly recrystallised sheared veins lack a macroscopically distinct foliation. However, an internal asymmetry of the Type I girdles in the CPO fabrics,

where present, does provide a potential measure of shear sense. This internal symmetry is defined by recrystallised grains that have c-axis orientations which form a concentration on one limb of the girdle during rotational shear (as in Fig. 5.3b).

Shear senses for four CPO fabrics in the strongly deformed, internal sections of the sheared veins measured in this study have been determined from internal asymmetries (after Law, 1990). In addition, five were measured from external sections of these veins, and one from a shear infilling vein. Two of the CPO fabrics from internal sections of the vein have a sense of shear that is top-away-from-[x] and are plotted in Figs. 5.6 and 5.7 (fabrics M and N). As [x] in this sample has a steep southwest pitch that lies in a west dipping shear plane (Table 5.1), the indicated shear sense is interpreted to be dextral and west-side-up. The same shear sense was also measured in the three other samples of strongly deformed internal vein sections (Appendix D) and for the shear infilling vein sample (CPO fabric V, Fig. 5.7). By contrast, the less deformed (inherited) CPO fabrics in external parts of deformed veins can have a reverse shear sense (e.g. Fig. 5.7 l and o) and is presumable related to the earlier deformation and unrelated to the brittle-ductile shears. The shear senses for the internal and shear infilling CPO patterns are plotted in Fig. 5.5, and are all dextral with a west-side-up shear sense.

Shear senses for deformed internal sections were only observed in the x-y-z reference frame (after fabric rotation) and not in the vorticity plane (a-b-c reference frame) where shear related fabrics would be expected during simple shear deformation. Considering the large shear strain that all the sampled veins had undergone (mean $\gamma = 5.5 \pm 1.3$), the oblique grain shape fabrics (see Chapter 4) and the well known displacement vector it was expected to find strong fabric asymmetries in the vorticity plane. It was however surprising to find rotational CPO fabrics with a shear sense in the plane parallel to the CPO-derived stretching direction ($\sim 50^\circ$ away from the vorticity plane).

Measured shear senses from quartz CPO patterns are not considered as reliable when based solely on internal asymmetries (Passchier, 1983; Law, 1990; Hippertt and Tohver, 1999). This is because reorientation and concentration of c-axes may not be related to shearing, but may also reflect an inherited CPO fabric from an earlier phase of deformation (Lister and Hobbs, 1980; Shelley, 1982). An

asymmetry can be enhanced by a late stage coaxial overprint where one limb that is already slightly asymmetric can develop a stronger asymmetry from a deformation that is not rotational (Lister and Williams, 1979) or from later grain growth (Shelley, 1989). From this study external CPO fabrics, presumably related to the older Alpine Schist deformation, contain asymmetric concentrations of c-axes which may have influenced the asymmetries in the more deformed, internal vein sections.

The shear sense using variable rotation of biotite porphyroblasts related to the Alpine Schist foliation (Holcombe and Little, 2001), grain shape fabrics (Little, 2004), and mineral lineations (Little et al., 2002a) is west-side-up and dextral, with a steep moderate to down-dip direction of maximum finite stretch in the non-mylonitic schist. This ductile elongation direction matches those in this study found from quartz CPO-derived stretching directions in the CPO fabrics from vein sections external to the shearing. Asymmetries in these external CPO fabrics (near where Type I limbs would develop in the internal fabrics, e.g. Fig. 5.7 CPO fabrics E and H) could have been inherited from earlier Alpine Schist deformation and strengthened further during shear in the internal sections. All shear senses measured from internal asymmetries are therefore used with discretion as they may be inherited in part from an earlier deformation.

For a reliable shear sense measurement, other shear sense indicators such as external asymmetries and field observations should be used in conjunction with the internal asymmetry method and inferred from asymmetric features in the vorticity plane (Passchier, 1983; Law, 1990; Passchier and Trouw, 1998). For example, Sample 7 (a shear infilling vein), has a dextral-reverse shear sense measured from an internal asymmetry in the vorticity plane (Fig. 5.7v in the a-b-c reference frame), matches the oblique quartz grain-shape fabric (GSF) microstructure (see Fig. 4.9e) and is parallel to the fault surface mineral lineation (the displacement vector; Fig. 5.5). This sample's shear sense inferred from the internal asymmetry is therefore considered reliable. Unfortunately, such a shear sense comparison could not be made for the internal vein sections as no oblique GSF's were observed and stretching directions were not parallel to the displacement vector.

5.5. Slip systems and approximate deformation temperature from CPO fabrics

Aspects of the CPO fabrics can be used to interpret the operative slip systems that accommodate the crystal-plastic deformation in the quartz grains from the location of c-axis concentrations in the fabric plots (e.g. Law, 1990). Concentrations about the z-poles, y-pole and x-poles are commonly used as evidence of basal $\langle a \rangle$, prism $\langle a \rangle$ and prism $[c]$ slip respectively. Orientations of c-axes that are inclined away from these poles may reflect slip on the rhomb planes in the $\langle a \rangle$ direction or on the rhomb and prism planes in the $\langle c+a \rangle$ direction (Schimid and Casey, 1986; Law, 1990). The interpretation of active slip systems from CPO fabrics in natural quartz CPO fabrics by Law (1990) illustrates the reliability of this method. Experimental deformation modelling by Tullis (1977) also supports these with results showing that small circle patterns are a result of slip on the basal and rhomb planes and for a connecting girdle to occur slip must be starting to occur on the prism planes.

Concentrations of c-axes between the z- and y-poles are seen in the CPO fabric plots presented here (e.g. CPO fabrics Q, S, and X in Fig. 5.7) and show that rhomb planes are important in accommodating deformation. For example, CPO fabric Q (Fig. 5.7q) shows c-axis concentrations approximately halfway between the z-pole ends and y-pole, suggesting that the crystals have aligned for ‘easy glide’ on the rhomb planes. Some fabrics show stronger concentrations about the y-pole suggesting that both prism and rhomb slip occurred (e.g. CPO fabric S in Fig. 5.7). Very few samples have strong concentrations about z-pole ends suggesting that basal $\langle a \rangle$ slip was not dominantly accommodating the deformation. The complete absence of c-axes about the x-poles in many samples suggests that prism $[c]$ slip was not occurring in any samples.

During shearing, dynamic recrystallisation will generate grains oriented for slip on the crystallographic plane that is easiest to activate, a process which is known as geometric softening (White et al., 1980; Fliervoet and White, 1995). During simple shear deformation the crystallographic slip plane most favourable for slip will typically align parallel to the shear plane in an orientation for ‘easy glide’ (Wenk and Christie, 1991). To activate slip on these planes, the critical resolved shear stress (CRSS), which is dependant on differential stress, strain-rate and temperature, must

be exceeded by the shear stress resolved on that particular slip plane (Wenk and Christie, 1991). More than one slip system can be used simultaneously to accommodate deformation, so more than one ideal orientation of crystal for ‘easy glide’ may exist.

Lister et al. (1978) showed that different quartz slip systems (Fig. 4.13) became dominant as the CRSS was exceeded on the slip planes. Generally in greenschist facies deformation, slip occurs in the $\langle a \rangle$ directions on basal planes (Schmid and Casey, 1986). Basal slip is not as temperature or shear stress sensitive as some other slip systems in quartz (Hobbs, 1985; Lister et al., 1978). With increased temperature and differential stress, slip on the rhomb and prism planes in the $\langle a \rangle$ and $\langle c+a \rangle$ directions are favoured or activated (Lister and Williams, 1979; Linker et al., 1984). Granulite facies conditions ($>650^{\circ}\text{C}$) are needed for slip to occur in the $[c]$ direction on the prism planes (Mainprice et al., 1986; Okudaira et al., 1995).

Using microstructural observations to determine which slip systems are active at known temperatures in naturally deformation rocks (e.g. Stipp et al., 2002b), a CPO fabric showing a dominant slip system can be used as a thermometer. This method is somewhat limited as the precise temperature and CRSS required to activate a slip system in quartz are difficult to determine because of water content in the crystal lattice, and the fact that multiple slip systems are generally active simultaneously. A minimum estimate of $\sim 280^{\circ}\text{C}$ for the Southern Alps sample here can be inferred from the temperature required for the frictional-viscous transition (Stipp et al., 2002b) to activate basal $\langle a \rangle$ slip. A more likely temperature of $\sim 400^{\circ}\text{C}$ is proposed here, as the sheared quartz veins contain subgrains and thus must have been deformed at temperatures allowing subgrain boundary rotation (Regime 2 of Hirth and Tullis, 1992), which is a result of slip on the prism planes (Kruhl, 1996; Stipp et al., 2002b). Activation of rhomb and prism plane slip systems in the Southern Alps samples also indicate that a more moderate temperature above the minimum must be required (e.g. Lister et al., 1978; Price, 1985; Schmid and Casey, 1986). The temperature could not have been greater than $\sim 650^{\circ}\text{C}$ as there is no evidence for slip on the prism planes in the $[c]$ direction. This estimated temperature compares well with that measured by Wightman (2005) of $450 \pm 50^{\circ}\text{C}$ from stable

oxygen isotope thermometry and chlorite thermometry of quartz-calcite veins that infill the brittle-ductile shear and from ^{40}Ar - ^{39}Ar thermochronology of muscovite in schist surrounding the BDSZ.

5.6. Strength of quartz c-axis CPO fabrics

The most remarkable aspect of the CPO fabrics observed from the BDSZ in this study, is their weak intensity despite the high finite shear strain known to exist in these veins. The strength of the quartz CPO fabrics are not as strong as expected considering the amount of ductile shear strain the veins have undergone, based on comparison with other previous quartz deformation studies (e.g. Schmid and Casey, 1986; Law, 1987; Joy and Saha, 1998; Bestmann et al., 2004). In this section I will compare measured fabrics from the BDSZ samples with those measured in other studies of sheared quartz veins, including numerical, experimental and field-based research of naturally deformed veins. These fabric strength comparisons, combined with the microstructural relationships, will lead to interpretations as to why the quartz CPO fabrics in the New Zealand samples are so weak.

5.6.1. Measuring the strength of CPO fabrics

The strengths of the CPO fabrics have been measured using the eigenvalue ratio method of Woodcock and Naylor (1983), the fabric intensity method of Lisle (1985), and from a visual estimation method of the contoured CPO fabric plots. These methods provide a basis for determining whether the interpreted CPO pattern is significant and the strength of the CPO fabric.

Eigenvalue ratios have been used to determine the strength of CPO fabrics and have been particularly useful in defining a random fabric, the strength of a girdle CPO pattern and the existence of a c-axis cluster. Normalised eigenvalues (Woodcock, 1977) used in each of the methods below have been calculated using Stereonet for Windows (Allmendinger, 2003) and are listed for each CPO fabric in Table 5.1 and Appendix H. The uniformity, or randomness of the CPO fabrics, has been measured using the ratio of the S_1 to S_3 eigenvalues (Woodcock and Naylor, 1983). A random fabric for 300 measured points (at a 99% confidence) has a $S_1:S_3$ ratio below 1.44 (ratios of 1.32 and 1.23 are for 500 and 900 measured points respectively). This fabric randomness test has been criticised by Lisle (1985) and

Benn (1994) for small data sets (<200) but is used in this study as all the CPO fabrics are generated from 300 c-axes or more. The mean $S_1:S_3$ ratios for the shear zones were 1.75 ± 0.1 (n=26), 1.79 ± 0.14 (n=26), and 1.65 ± 0.1 (n=33) for the internal, external and shear infilling vein sections respectively. The strongest fabric ratio was 2.6, in an external vein section, with the weakest fabric ratio of 1.02, in a shear infilling vein. The shear infilling veins clearly having weaker fabrics with a lower mean ratio and 11 fabrics with a ratio <1.5 compared with only 3 for more deformed internal vein sections.

The Lisle (1985) method of measuring fabric intensity by was also used here as a measure of fabric strength. This method uses the eigenvalues, S_i (where: $i = 1, 2, 3$), to calculate the fabric intensity (I) of CPO fabrics using the equation:

$$I = \frac{15}{2} \sum_{i=1}^3 \left(S_i - \frac{1}{3} \right)^2 \quad (5.1)$$

Values of I vary from 0 for random orientations to a maximum of 3.5 for very strong planar fabrics. Using Equation 5.1, I values for internal and external sections in this study had a mean of 0.14 ± 0.03 and the shear infilling veins had a mean I value of 0.11 ± 0.02 . Sample 18, the Alpine Fault mylonite, had an I value of 1.65 which was the highest value for a CPO fabric in this study. Fabric strength calculations from the Woodcock and Naylor and Lisle method were plotted against each other revealing a positive linear correlation between the two. This indicates that both methods provide comparable results.

Some visually “strong” CPO patterns yielded a random result using the uniformity test of Woodcock and Naylor (1983) and the intensity method of Lisle (1985). Type I, Type II, small circle and cleft girdle CPO patterns can have an eigenvalue ratio that suggests that the fabric is random when it is in fact a significant pattern due to the non-orthorhombic symmetries of these fabrics. Therefore, visual measurements of point density along the contour plot ridges that define a CPO pattern have been made to determine the fabric strength. CPO fabrics were allocated a fabric strength ranking from 0 (as a random fabric, e.g. Fig. 5.7w) to 5 (as a very strong CPO fabric, e.g. Sample 10, Fig. 5.4b) based on the relative concentration percents of the ridges in contour plots. A fabric strength ranking of 5 needed to have

a ridge concentration of more than 5% (fraction of poles in a 1σ counting circle from the total measured in the sample), with ridge concentrations of 4%, 3%, 2.5% and 1.5% for fabric strengths of 4, 3, 2, and 1 respectively. A fabric strength ranking of 0 had no preferred orientation of c-axes (apparently random CPO pattern) and an eigenvalue ratio ($S_1:S_3$) of <1.5 . Visually non-random CPO patterns required the contour ridges defining the pattern to have a point concentration $>2\%$. Although this fabric strength ranking method may not be mathematically exact, it is sufficient for the comparisons that are made in this study. Fabric strength rankings when plotted against intensity (I) and uniformity ($S_1:S_3$ ratio) show a positive linear correlation indicating that this scheme is a robust way of qualitatively ranking fabric strengths.

The mean fabric strength ranking of 26 strongly deformed, internal CPO fabrics was 2.8 ± 0.5 . This is very similar to the 2.5 ± 0.5 for the external CPO fabrics. The 33 shear infilling veins had a mean fabric strength ranking of just 1.4 ± 0.5 . The distribution of fabric strengths between different sections in the shear zones are illustrated in Fig. 5.8a. Statistically the shear infilling veins have a much weaker fabric than the sheared veins with more than 50% of the infilling samples producing a random or very weak CPO fabric. The garnet-zone Alpine Schist metachert and mylonite samples have much stronger CPO fabrics than the sheared veins in the BDSZ, and have a mean fabric strength ranking of 3.8 ± 0.9 . These fabric strengths have also been compared to the measured finite ductile shear strain (from Chapter 3) and to quartz grain shape ellipticities (from Chapter 4) in the vein microstructures (Fig. 5.8b). There appears to be no correlation between CPO fabric strength and finite ductile shear strain or the strain represented by grain shape ellipticity in these recrystallised veins. Fig. 5.8b shows a broad scatter of finite shear strains for each CPO fabric strength ranking and importantly some random CPO fabrics are found in samples with high finite ductile shear strains and grain shape ellipticities. This shows that not only are the CPO fabrics weak, but they do not strengthen with increased ductile deformation or shear strain.

5.6.2. Comparison of quartz CPO fabric strengths to existing measured fabrics

The CPO fabric strengths measured in this study have been compared to those deformed in other quartzite aggregates that have similarly been subjected to a large finite ductile shear strain. These examples come from numerical modelling,

a **b**

Fig. 5.8. Graphs of fabric strengths measured from CPO fabrics in the brittle-ductile shears. a. Graph showing the fraction of CPO fabrics from different vein sections with a given fabric strength ranking. b. Graph showing fabric strength ranking against recrystallised grain shape ellipticity (R) and field-based calculations of finite ductile shear strain (γ). The Waiho River and Hare Mare Creek CPO fabrics are not included in this data set. Raw data for both of these plots can be found in Appendix H.

experimental and natural field studies of ductile shear zones in those rocks. The sheared quartz veins in this study had a mean finite ductile shear strain of 5.5 ± 1.3 ($n=17$). By comparison with the other studies, the natural Southern Alps samples all have remarkably weak CPO fabrics in relation to their known shear strain.

Lister et al. (1978) showed that a shear strain of just 1.6 was enough to significantly change a pre-existing quartz CPO fabric. Their numerical modelling predicts that any inherited CPO pattern that may have existed before the shearing would have been destroyed and replaced in the strongly deformed internal parts of the veins. Later numerical modelling by Lister and Hobbs (1980), showed that strongly asymmetric single girdle CPO patterns could be found in sheared veins after shear strains of ~ 4 . Deformation of halite and ice were used by Etchecopar and Vasseur (1987) to approximate quartz deformation. They found that single girdle CPO patterns were visible after shear strains of ~ 2.5 . CPO fabrics in this study, however, despite their high finite shear strains, do not show such strong asymmetric Type 1 or single girdle CPO patterns.

The increase in CPO fabric strength as a function of shear strain was numerically modelled for sheared quartz veins by Lister and Williams (1979) and experimentally investigated by Etchecopar and Vasseur (1987). Both studies showed that an increase in strain resulted in a corresponding increase in fabric strength. The experimental study showed that CPO fabrics strengthened with an increase in shear strain from 1 to 5 yielding pole density contours (a fraction of c-axis poles from the total measured) between 5 and 11% for the CPO pattern ridges. By comparison, the density contours of the BDSZ samples are only as high as 2-3% on the CPO pattern ridges and they do not increase as a function of finite ductile shear strain (e.g. Fig. 5.8b).

Deformation of quartzites in laboratory experiments also have a consistently stronger CPO fabric than those found the BDSZ samples. Laboratory deformation of quartz by Tullis (1977) showed strong CPO fabrics were created after coaxial compression of 50% (equivalent to an approximate shear strain of 1.5). Laboratory studies by Heilbronner and Tullis (2002) showed that quartz which had undergone either coaxial or non-coaxial strain still maintained strong CPO patterns with density point maximums of $\sim 5\%$ and well defined ridges despite having undergone

subsequent static recrystallisation. These studies indicate that fabrics formed by coaxial strain as easily as non-coaxial strain and that static recrystallisation alone is not a likely cause for the weak strengths of the CPO fabrics in quartz from the natural shear zones in this study.

CPO fabric strengths of sheared quartz veins from other natural shear zones are much stronger than those measured in this study. For example, a sheared vein from Cap de Creus, Spain (Schmid and Casey, 1986), which is of a similar size, displacement, mineral composition and shear strain as the sheared veins in this study, shows a CPO fabric with concentrations up to 6 times the normal distribution (~10% point density equivalent for contoured fabrics in this study) and has an asymmetric single girdle CPO pattern observed after a ductile shear strain of 3.2–6.2. A sample from the Tauren window, Eastern Alps that has been subject to a shear strain of ~2.5 had density concentrations of 5–10% (Brunel, 1980). Tagami and Takeshita (1998) in a buckled quartz vein from the Sambagawa metamorphic belt, central Shikoku, Japan measured a mean intensity (I) of 1.05 for a vein that had been subject to a minimum shear strain of 1.1 (minimum estimate derived from grain aspect ratios). By comparison, a finite ductile shear strain of 4.4 that yielded a mean intensity (I) of 0.25 in this study (Sample 4, CPO fabric S, Fig. 5.7), is much weaker. Also shear infilling veins with a shear strain of 0.8 (minimum estimate derived from grain aspect ratios as in Tagami and Takeshita, 1998) had an intensity (I) of 0.11, which again is much weaker than those from Japan. Miller and Christie (1981) showed that as the strain increased in the Elba Quartzite, the CPO fabric also strengthened in the naturally deformed quartz clasts, a correlation not seen in this study (Fig. 5.8b).

5.6.3. Quartz CPO fabric strength in polymineralic and monomineralic veins

The relationship of quartz CPO fabric strength to mineral impurities in the veins has been investigated by comparing fabric strengths of monomineralic ($\leq 5\%$ calcite $\pm$ chlorite) shear infilling veins to that of polymineralic ones (quartz and calcite). The quartz c-axis CPO fabric strengths (fabric strength rankings and eigenvalue $S_1:S_3$ ratios), quartz CPO patterns and the fraction of calcite or chlorite in the vein and show considerable differences between veins that contain $>5\%$ calcite and those that are almost 100% quartz (Table 5.2). Of the quartz CPO fabrics in Fig. 5.9, monomineralic quartz veins have a mean $S_1:S_3$ ratio of 2.0 whereas

MONOMINERALIC

POLYMINERALIC

Figure 5.2. Stereographic projections of quartz c-axis CPO for 20 samples with (polymineralic) and without (monomineralic) calcite. The left column shows lower-hemisphere, equal-area, lower hemisphere, stereographic projections. Contours are plotted at intervals of 1σ and are plotted as lines of equal concentration percentage. Dark gray shading represents high concentrations of c-axes. Percent of calcite and chlorite are indicated by the graduated scale bar. Fabric information is listed in Table 5.2.

Sample number	Field	Eigenvalue ratios			CPO pattern code	Fabric strength ranking	Mean grain diameter (μm)	% of calcite and chlorite	
		$S_1:S_3$	$S_1:S_2$	$S_2:S_3$				Calcite	Chlorite
12	MHCH22	2.35	1.31	1.79	CG	4	38	0	25
13	MHCH17	1.61	1.01	1.59	R	0	150	40	2
14	MHCH12	1.97	1.44	1.37	T2	3	143	5	2
15	MHCH14	1.35	1.09	1.23	R	0	155	20	1
16	MHSP11	2.00	1.19	1.68	T2	3	138	0	10
17	MHSP09	1.23	1.02	1.21	R	0	138	30	10
18	RW35b	1.59	1.34	1.19	SC	3	133	0	5
19	TJFA43	1.46	1.09	1.33	R	0	143	45	5
20	TJFA52	2.21	1.64	1.35	T2	2	145	1	2
21	TJFA47	1.26	1.16	1.09	R	0	127	45	5

Table 5.2. Fabric strengths for samples with and without calcite. Sample numbers, eigenvalue ratios, pattern codes, fabric strength rankings and grain sizes are given as in Table 5.1. Percent of calcite and chlorite in the samples visually estimated from area of thin-section slide containing calcite.

polymineralic quartz-calcite veins have a ratio of only 1.2. Monomineralic quartz veins typically have an identifiable pattern and polymineralic quartz-calcite veins have a random or very weak one (Fig. 5.9). Chlorite is also present in many veins but does not seem to affect the fabric strength (in contrast to research by Joy and Saha, 1998). For example, Sample A (Fig. 5.9, Table 5.2) is ~25% chlorite but has a relatively strong CPO fabric. The proportion of calcite in the veins therefore needs to be considered as a possible explanation for weaker quartz CPO fabrics in veins that have undergone deformation.

5.6.4. Possible reasons for weak CPO fabrics

Compared with examples from the published literature, CPO fabrics obtained from the veins deformed in the shear zones in this study are surprisingly weak considering their high shear strains. The fabric strengths in this study are also not related to the amount of ductile shear strain that the veins have undergone, whether it is the final ductile shear strain or the final increment only. Unfortunately, the weak CPO fabrics measured in this study restricts the structural and kinematic interpretations that can be made, but it does pose the question as to why the fabrics in these ductilely sheared veins are so weak compared to other sheared fabrics in both laboratory studies and other natural shear zones.

The random or domainal CPO patterns in the shear infilling veins may be preserved because most of the finite shear strain may have predated their emplacement into the shear zone (see Fig. 3.19). An initially random orientation of crystals in these veins may still be preserved. This random orientation could have formed from precipitation of amorphous silica in the shear zones in response to a drop in fluid pressure (Herrington and Wilkinson, 1993). The domainal CPO patterns also suggest that the fabrics preserve a primary imprint that was inherited from vein precipitation where crystal orientations reflect the large host grain orientations. On the other hand, a shear infilling vein sample that contains an oblique GSF (Sample D, Fig. 5.9) and has a random CPO pattern shows that dynamic recrystallisation has been occurring in this sample but a CPO fabric hasn't formed. The maximum calculated shear strain required to form the GSF is 2.4, theoretically enough to form a strong CPO pattern (e.g. Brunel, 1980). This evidence suggests that some other processes in the infilling veins must be maintaining a weak CPO

fabric or weakening the fabric during the dynamic recrystallisation that formed this oblique GSF.

Most of the infilling and sheared veins are polymineralic (quartz and calcite). Such rocks distribute strain differently than monomineralic ones that are commonly imitated by numerical modelling, deformed in laboratory experiments, and measured from many natural shear zones (Herwegh and Burger, 2004). Impurities such as calcite and micas can accommodate strain more easily than quartz during deformation (Joy and Saha, 1998; Brodie and Rutter, 2000); thus their presence in abundance can cause a reduction in development of a quartz fabric. As calcite deforms more easily than quartz (Brodie and Rutter, 2000), it maybe accommodating a high proportion of the ductile strain. In this study calcite is frequently observed in concentrated bands parallel to the shear zone boundary (e.g. Fig. 4.12d) so some strain may have been concentrated into these inherently weaker layers (e.g. Lister and Williams, 1979; Pauli et al., 1996). To support this, quartz CPO fabrics tend to be weaker in BDSZ samples containing >5% calcite (e.g. Fig. 5.9). It has also been shown that impurities (such as calcite) can allow for easier slip on the grain boundaries than by intracrystalline plasticity; in these circumstances an existing quartz fabric may randomise by grain boundary sliding (Starkey and Cutforth, 1978). Although impurities may have been affecting the fabric strength in the BDSZ, not all veins are polymineralic, therefore further processes must have been weakening the quartz rich veins.

Static recrystallisation is a process that can potentially weaken or randomise an existing CPO fabric. Although this process can weaken a CPO fabric to create a more diffused CPO pattern, near complete randomisation is not likely (Heilbronner and Tullis, 2002). Static recrystallisation will weaken all sections of a shear zone not just the most attenuated strongly sheared section of a deformed vein and may explain why the external and internal vein sections have similarly weak fabric strengths. This process however doesn't explain why there are relatively strong fabrics in the vein sections external to the deformation and random CPO patterns in the most strongly deformed sections of some samples (e.g. Fig. 5.6i).

Grain boundary sliding, accommodated by solid-state diffusion creep, is a process that might randomise a CPO fabric if a late component of the shearing of the

veins was accommodated by this deformation mechanism, as has been argued by Wightman (2005). This seems particularly likely in those samples for which there is a relatively strong CPO fabric in the external section and a random CPO pattern in the internal section of the shear zone. For remaining samples, grain boundary sliding may have only been a minor deformation process where veins have the same fabric strength in the external part of the shear zone as well as those in the most deformed parts.

Competitive fabric forming processes resulting from complex three-dimensional strain are another possible reason for weak CPO fabrics in the shear zones. In complex deformations where monoclinic or triclinic deformation is occurring, finite extension directions may rotate during deformation and could be competing for crystallographic orientations that would allow for easy slip and strain softening (Fossen and Tikoff, 1998). The difference between the near-vertical quartz stretching directions (from CPO fabric rotations) and the moderate-pitching displacement vector (interpreted from field analyses) are consistent with a general transpressional deformation with horizontal shear and flattening with vertical stretching. The temporal evolution of the stretching direction from horizontal to vertical, and the competition between the horizontal shear and the vertical extension, might cause a complex evolution and overprinting of CPO fabrics and an overall weakening of the resultant fabric.

Quartz CPO fabrics may also weaken, or appear to have been weakened, if polyphase deformation was occurring with different kinematic conditions active at different times (e.g. Shelley, 1989; Law, 1987). Sample 7 is an example of a CPO fabric that can be related to at least the final increment of strain recorded in the rock. This sample has a CPO-derived stretching direction and a shear sense that matches the displacement vector from the field and shear direction in the GSF microstructures. These microstructures that the CPO fabric matches have been interpreted to have developed after brittle-ductile shearing and are late stage (see Chapter 4). Other samples may not have generated this overprinting CPO fabric in its entirety and may have the combination of both initial near vertical irrotational strain and an overprinting, later stage, sub-horizontal shear fabric. This polyphase deformation could result in a weak overall resultant CPO fabric.

The weak c-axis CPO fabrics and CPO patterns measured in this study are most likely a combination of the fabric randomising and weakening processes that occurred during brittle-ductile shearing and during late-stage recrystallisation. In the most deformed internal vein sections grain boundary sliding is most likely a dominant deformation mechanism for fabric randomising along with overprinting by complex three-dimensional strain. The weak and random CPO patterns in the shear infilling veins are typically due to their primary random crystallographic orientation from precipitation and their late emplacement into the shear zone. Calcite concentrations that can accommodate some of the strain may have allowed for the retention of an existing weak fabric in these shear infilling veins, but also may have allowed for easier grain boundary sliding in the strongly deformed internal vein sections. Fabric weakening has been enhanced further in all parts of the shear zone by static recrystallisation and by a potential polyphase fabric overprinting during a late-stage deformation.

CHAPTER 6: Crystallographic preferred orientation of calcite c-axes

Calcite textures and microstructures in deformed carbonate rocks can provide information regarding the kinematics and deformation mechanisms in shear zones (Wenk, 1985c). Calcite c-axes have been measured in sheared quartz-calcite veins from the brittle-ductile shear zones in the Southern Alps using a universal stage microscope and are compared with quartz c-axis orientations measured from the same veins. Like quartz, a calcite crystallographic preferred orientation (CPO) can be generated during ductile shearing and used as an indicator of deformation style, recrystallisation mechanisms and the slip systems used to accommodate the strain (e.g. Busch and van der Pluijm, 1995; Bestmann et al., 2000; Ulrich et al., 2002). As calcite deforms more easily than quartz (Brodie and Rutter, 2000) and by dislocation creep at temperatures as low as 150–250°C (Kennedy and White, 2001), it can provide further insight into the shear zone deformation not available from quartz CPO fabrics, especially regarding the lower temperature, later stage parts of the deformation path (see Section 4.7).

Calcite has been found in proportions of up to 40% in some vein samples and is found concentrated in 1–2 mm wide layers oriented parallel to the shear zone and also as individual grains throughout the quartz aggregate (see Chapter 4). Both the calcite grains concentrated in layers, and the isolated grains outside them that are surrounded by quartz, have grain-shape fabrics. The grain long axis is orientated parallel to the shear zone boundary in the most highly deformed sheared vein sections (probably the result of a grain-growth anisotropy) but is often at an oblique angle to the boundary in the younger shear infilling veins (see Chapter 4). All these calcite grains have undergone recrystallisation, which is evident from the polygonal grain textures, and the grain boundary and twin boundary migration microstructures in many of the deformed veins. This recrystallisation contributed towards a strong CPO fabric by preferential selection of crystals that lie in orientations that are favourable for easy intracrystalline slip in the shear zones.

As presented in Chapter 5 for quartz, I will determine a finite extension direction and the slip systems based on the shape and symmetry of the calcite CPO fabrics that were generated by intracrystalline plasticity and dynamic recrystallisation

in the sheared veins. Understanding this deformation of calcite will lead to a better understanding of the complexities involved in polymineralic vein deformation compared to the monomineralic samples used in laboratory experiments (e.g. Herwegh and Bereger, 2004); a complexity that this study has already shown strongly affects CPO development in quartz.

6.1. Measuring the orientation of calcite c-axes

Calcite c-axis orientations were measured using a 5-axis universal stage fitted to a Leitz polarising microscope (Fig. 5.1a). Oriented thin-sections were cut to 15 μm thick to tone down the interference colours generated by the high birefringence. These slides were mounted on the universal stage as was done for quartz (see Chapter 5). Because of the high birefringence of calcite, a gypsum plate could not be used to determine the crystallographic fast direction required for measuring the c-axis orientation. The fast direction for calcite was instead determined from a rotation of the A2 universal stage axis once the calcite grain was placed into an extinct position by rotation about the A1 axis. If the grain moved out of an extinction position during an A2 rotation it required a 90° rotation about the A1 axis for the fast direction to be parallel to the A4 axis. If the grain remained in extinction during this A2 axis rotation then the crystallographic fast direction was aligned parallel to the A4 axis and no further rotation was required. Once the crystallographic fast direction was determined, the calcite c-axis orientation was measured, as for quartz, following the method of Passchier and Trouw (1998).

Calcite c-axes were measured for 300 grains from the same thin-sections of sheared veins as those from which quartz CPO data was gathered (Chapter 5). Thus the CPO fabric diagrams of the two minerals could be compared to one another. As was done for the quartz data, calcite CPO fabrics are plotted as both scatter and contour plots. Because of the strong calcite fabrics (fabric strength rankings of 5 for all samples), a counting circle of 3σ was used for contouring for the calcite point density data. Two types of CPO patterns (skeletal outlines) were assigned to the calcite fabrics based on these contour plots. The first type of pattern is a double girdle (similar to a cleft girdle of quartz) which defines a concentration of c-axes along a planar distribution in the plot. The second type is a cluster outline, which defines the approximate boundaries of a c-axis cluster. There were no asymmetric

calcite CPO fabrics observed in this study. This was no surprise, as domainal calcite CPO patterns typically found in the sheared veins here generally cannot be used as a shear sense indicator (see Lafrance et al., 1994).

6.2. Rotation of calcite CPO fabrics

Although the calcite CPO fabrics in the sheared veins were strong, the CPO patterns did not match the patterns observed in previous studies of calcite deformed by shear zones when the fabric plots were orientated in the a-b-c reference frame. This reference frame has the a-pole parallel to the mineral fibre lineation (displacement vector), the b-pole perpendicular to the mineral lineation in the shear plane, and the c-pole parallel to shear plane normal (see Chapter 5). As a known CPO pattern was observed in this orientation a rotation of the CPO fabrics (as for quartz fabrics in Chapter 5) has been used to determine the calcite CPO-derived stretching direction and the dominant slip systems during calcite deformation. This method rotates the pole data around the normal to the shear plane (z-axis here). A correctly orientated fabric will have the extension direction parallel to the east-west pole (x-pole) of the fabric plots and in this position the fabrics will be in mirror symmetry about the shear plane and intercept the z-y plane. Once a CPO pattern is identified for a fabric, it is rotated so that the inferred symmetry axis and extension direction is aligned parallel to the east-west axis of the CPO fabric plot (x-pole).

The calcite CPO-derived stretching direction [x] for each CPO fabric was measured precisely by rotating the plane containing the S_1 and S_2 eigenvectors about the z-pole until it was sub-parallel to the z-y plane (e.g. eigenvectors shown in Fig. 6.1a). This rotation was made using the stereonet software by Allmendinger (2003). This method works best when the eigenvalues are similar (i.e. when there is a distribution of c-axes along a plane rather than a cluster about the z-pole) and the eigenvalue ratio of $S_1:S_2$ is <2.5 . Larger ratios than this were not used to determine the mean CPO-derived stretching direction as the fabric was too clustered about the z-pole to clearly define the extension direction; however, a rotation was still performed on all fabrics to orient them based on their eigenvectors. An example of this rotation is presented in Fig. 6.1a that shows three differently orientated calcite CPO fabric plots for c-axes measured from a sheared vein on Chancellor Ridge. All

Fig. 6.1. Rotation of calcite CPO fabrics to find the CPO-derived stretching direction and the slip systems being used. a. Three different orientations of the same CPO fabric; i, ii and iii (Sample 4, fabric C, Fig. 6.4). The angle between the shear zone pole and the point maximum (ω) is shown in the first rotated fabric and the eigenvalues for the S_1 and S_2 eigenvectors are marked on the third rotated fabric. Contours of point density are generated using a 3σ counting circle. b. Stereogram of the three different x-poles for each of the rotated fabrics in (a). c. Orientation of the c- and a-axes, the poles to the rhomb planes $\{r\}$ and the basal plane of calcite for two c-axis orientations (after Pieri et al., 2001). All stereographic projections are equal area and lower hemisphere.

three fabrics are rotated about the z-axis and have different orientations of the x-pole (Fig. 6.1b).

The fabric in Fig. 6.1a(i) has been rotated so that the x-pole (x_1) has a horizontal pitch in the shear plane (Fig. 6.1a(i) and 6.1b). This fabric shows a strong point maximum at a 15° angle (ω) from shear plane normal (x_1 -pole). This angle is not large enough for this CPO fabric to have been generated from e-twin glide or $\{r\}$ $\langle s.d. \rangle$ slip, where ω is expected to be closer to 30° (see Schmid et al., 1987 and Pieri et al., 2001). This horizontal orientation of the x-pole does not, therefore, produce a significant calcite CPO fabric plot and the x_1 -pole is not parallel to the extension direction. The fabric plot in Fig. 6.1a(ii) has the x-pole (x_2) pitching 35° from the southwest (Fig. 6.1b). This reference orientation is equivalent to the a-b-c reference frame where the a-pole (x_2 -pole here) is parallel to the mineral fibre lineation (see Chapter 5). There is no CPO pattern observed in this orientation that can be related to any known deformation patterns in calcite, therefore it is assumed the x_2 -pole and the mineral fibre lineation are not parallel to the finite principle extension direction.

In Fig. 6.1a(iii) the fabric plot has an x-pole that has been rotated to a near-vertical (x_3) pitch of 90° in the shear plane (Fig. 6.1b). This fabric plot reference frame shows a significant CPO pattern similar to that found in many other deformed carbonate rocks (e.g. Schmid et al., 1987; Ratschbacher et al., 1991; Lafrance et al., 1994; Pieri et al., 2001; Barnhoorn et al., 2004). This rotated CPO fabric and pattern in Fig. 6.1a(iii) is diagnostic of either irrotational plane strain deformation or from a rotational deformation such as simple shear. In both irrotational and rotational deformation the principle extension direction is oriented parallel to the east-west axis (x-pole) when the CPO fabrics are in position, as shown, with concentrations about the z-pole and towards the y-pole. Fig. 6.1c (after Pieri et al., 2001) shows that the observed orientations of c-axis concentrations could be related either to slip on the basal planes in the $\langle a \rangle$ direction (grains oriented with c-axes parallel to the z-pole; e.g. Schmid et al., 1987; Barnhoorn et al., 2004); or to slip on the $\{r\}$ planes in the lesser known $\langle a \rangle$ direction (grains oriented with a steeper $\sim 45^\circ$ pitch in the z-y plane; Pieri et al., 2001). Slip in grains orientated between these two ideal positions in Fig. 6.1c could be accommodated by combinations of multiple slip systems (Barnhoorn et al., 2004).

Rotations of calcite CPO fabrics measured throughout the brittle-ductile shear zone (BDSZ) have been made to find the mean principle extension direction (calcite CPO-derived stretching direction) generated during the deformation of calcite. Eigenvalue ratios and the southwest pitch of the x-pole determined for all the fabrics measured in this study are listed in Table 6.1. The calcite CPO-derived stretching directions are plotted in Fig. 6.2 for the CPO fabrics obtained from the four deformed internal sections of the sheared veins and one from a shear infilling vein (all with $S_1:S_2$ ratios <2.5). These patterns yield a mean stretching direction orientation of $201, 85 \pm 7^\circ$ (uncertainty based on a 95% confidence cone about the mean pole). Calcite CPO fabrics from the less deformed, external parts of sheared veins were omitted from the mean orientation quoted above, as were any other fabric plots with $S_1:S_2$ ratios <2.5 . Table 6.1 shows that all calcite CPO fabrics have similar near-vertical x-pole orientations (even those excluded from the mean). This near-vertical CPO-derived stretching direction is not parallel to the finite slip direction [a] (the mineral fibre lineation) but closely parallel to the CPO-derived stretching direction determined from quartz CPO fabrics of $239, 79 \pm 11^\circ$ (Fig. 6.2); in the case of Sample 3, the quartz and calcite results are coincident (see Tables 5.1 and 6.1).

6.3. Calcite c-axis CPO fabrics in the brittle-ductile shear zones

The calcite CPO fabrics are all very similar across the differently deformed sections of the shear zones (Figs. 6.3 and 6.4), the only variation being minor changes in the distribution of c-axes between the z- and y-poles of the fabric diagrams (distribution measured by $S_1:S_2$ eigenvalue ratio; Table 6.1). All of the CPO fabrics have a mirror symmetry plane coincident with the shear plane, indicating that fabrics developed during deformation of the quartz-calcite veins parallel to the S_4 shear planes (as for quartz in Chapter 5). Calcite CPO fabrics from the external vein sections in Fig. 6.4 (fabrics A and D), however, are not in mirror symmetry about the Alpine Schist foliation plane, in contrast to the quartz CPO fabrics presented in Fig. 5.7. CPO patterns from fabrics obtained in the concentrated layers of calcite in the sheared veins (e.g. CPO fabric E in Fig. 6.4) were not significantly different from the patterns of CPO fabrics obtained from calcite grains dispersed amongst a dominantly quartz-rich matrix (e.g. CPO fabric H in Fig. 6.4). All of the calcite CPO fabrics measured in this study are considered to have a very strong fabric strength based on eigenvalue $S_1:S_3$ ratios that were all greater than 4

This study	Sample number			Grid Reference (New Zealand Grid)		Shear plane orientation (x-y plane)	Sheared vein orientation	γ_d	[x]	Eigenvalue ratios		
	Vein sect.	VUW Collect.	Field number	Easting	Northing					S1/S3	S1/S2	S2/S3
3	A	E	39395	MHCH17	2,276,050	038@88SE	016@70SE	7.7	94	6.45	1.67	3.87
	B	I							82	10.17	2.26	4.51
	C	In							86	10.96	2.26	4.85
4	D	E	39400	MHCH20	2,277,348	222@86NW	104@64S	6.8	78	9.18	2.24	4.10
	E	I					002@82E	4.4	90	6.63	2.50	2.65
	F	I							82	8.88	2.13	4.17
11	G	I	39419	MHBM03	2,279,922	048@78SE	020@76SE	6.3	89	8.18	2.36	3.47
	H	In							89	6.62	4.76	1.39
7	I	In	39389	MHCH12	2,277,301	5,740,163	221@85NW	-	160	4.52	2.67	1.70
12	J	In	39414	MHSP09	2,274,514	5,737,163	202@52NW	-	95	11.25	4.87	2.31
13	K	In	39394	MHCH14	2,276,050	5,740,450	218@68NW	-	19	4.40	2.74	1.61
14	L	In	39433	TJFA47	2,274,502	5,737,234	213@60SW	-	139	6.02	2.77	2.17

Table 6.1. CPO fabric data for calcite c-axes in Fig. 6.2 and 6.3. Sample numbers refer to those in Chapters 5 & 6 (this study), with the vein section also listed (E - external vein section, I - internal highly deformed vein section, In - shear infilling vein). Finite ductile shear strain (γ_d) for sheared veins in Fig. 6.2 and the pitch of the calcite CPO-derived stretching direction [x] in the shear plane. Eigenvalue ratios listed for fabric strength comparison. Samples 3 and 4 match corresponding sheared veins in Fig. 5.6 for CPO of quartz.

Fig. 6.2. Stereographic projection of 5 measured calcite CPO-derived stretching poles from highly sheared internal vein sections and the sheared infilling veins. Also plotted are mean orientations of the mineral fibre lineation directions from field-based measurements, the quartz CPO-derived stretching direction and the mean shear plane orientation. Uncertainties represent a 95% confidence ellipse surrounding the mean lineation or pole-to-plane orientation.

Fig. 6.3. Sheared quartz-carbonate veins with finite ductile shear strains (γ_d) ranging from 4.4 - 7.7 with interpreted CPO patterns from calcite c-axis CPO fabric plots. Complete CPO fabric plots for CPO patterns A to H can be found in Fig. 6.4 with orientation and fabric strength data in Table 6.1. Sample 4 dips west; 3 and 11 dip east. Sample 3 shows a shear zone with CPO fabrics measured from the sheared veins most deformed internal and less deformed external sections and from the shear infilling vein section. Sample 4 shows three sheared veins; a CPO fabric was measured from the most highly deformed section of Veins 1 & 2 and from the section external to the deformation in Vein 1. Sample 11 has had two CPO fabrics measured from it, one from the most highly deformed section and one from the shear infilling vein.

Fig. 6.4. Calcite c-axis fabrics and patterns for sheared and shear infilling veins. Fabric plots A-H are for CPO patterns from sheared veins in Fig. 6.2 and plots I-L are infilling vein samples from various locations. Calcite c-axis poles plotted on equal area, lower hemisphere, stereographic projections. Contours were calculated using a counting circle of 3σ and plotted as lines of equal concentration percentage. Contours are shaded for concentration and scaled according to the graduated scale bars. Contour and scatter plots are paired for complete and objective fabric interpretations. Sample names, geographic locations, fabric strengths and the SW pitch of [x] in the shear plane can be found in Table 6.1. Great circles, drawn on external vein section CPO fabrics, represent the Alpine Schist foliation. CPO patterns illustrated on scatter plots are cleft girdles or outlines of the domainal concentrations. All CPO fabric plots are in the rotated x-y-z reference frame (Figs. 5.2 and 5.3). Black circle with white labels represent internal sections (I) and external sections (E) of sheared veins and shear infilling veins (In).

(Table 6.1) and were all given fabric strength rankings (see Chapter 5 for definition) of 5. In contrast to the quartz CPO fabrics in the same veins, the calcite CPO fabrics show no evidence for late-stage fabric weakening and / or randomisation that may be caused by grain boundary sliding or diffusion creep deformation mechanisms (as in Busch and van der Pluijm, 1995).

As briefly mentioned in Section 6.2, the CPO patterns found in the sheared veins could have been formed by an irrotational or a rotational strain. Irrotational deformation with flattening perpendicular to the shear plane could have generated these CPO fabrics, for example during plane strain deformation with the principle extension direction [x] parallel to the x-pole of the CPO fabric (e.g. Wenk and Takeshita, 1987; Ratschbacher et al., 1991). Alternatively, the same CPO pattern could have been generated by rotational deformation (shearing parallel to the shear plane) after shear strains of 3-5, provided that the shear direction was oriented near-vertically and parallel to the x-pole of the CPO fabric (e.g. Schmid et al., 1987; Pieri et al., 2001; Barnhoorn et al., 2004). A full crystallographic orientation of the fabrics that includes the {r} pole and a-axis would be required in order to make an exact determination about the rotational nature of the shear zone deformation. However, considering that the quartz CPO fabrics have preferentially accommodated the irrotational component of a general shear deformation (a combination of shear zone flattening with the principle extension direction near-vertical and shearing parallel to the displacement vector), I have inferred that these CPO fabrics have also developed from an irrotational deformation.

Grain boundary migration is typically the main recrystallisation process that generates calcite CPO fabrics like those observed here in the sheared veins (e.g. Schmid et al., 1987; Lafrance et al., 1994; Pieri et al., 2001; Barnhoorn et al., 2004; Herwegh et al., 2005). A preferred crystallographic orientation is reinforced by the preferential growth of grains that are in an orientation for easy slip relative those grains that are misoriented with respect to the shear zone (Pieri et al., 2001). At high shear strains (approximately 3-5) a steady-state fabric can be achieved in calcite due to dynamic recrystallisation (Lafrance et al., 1994; Herwegh et al., 2005). Crystals with a c-axis aligned perpendicular to the shear zone remain in a position for easy slip along crystal planes and will preferentially grow forming a strong CPO with a concentration of c-axes around the z-pole in the fabric plots (Lafrance, 1994).

Dynamic crystallisation by grain boundary migration is easily achieved in monomineralic carbonate rocks or in calcite-rich vein layers; however, in polymineralic veins (such as those presented in this study) where two different minerals share a grain boundary, such grain boundary migration is impossible. In these situations, the calcite cannot migrate, and it undergoes a twinning process in order to accommodate additional deformation. Twin boundary migration between the host and the twinned crystal domains can then occur, recrystallising a grain into an orientation for easy slip (e.g. Rutter et al., 1994; Bestmann and Prior, 2003). Individual calcite grains that occur surrounded by quartz-rich areas of the sheared veins (e.g. CPO fabric K) have CPO fabrics equally as strong as which are concentrated together into layers (e.g. CPO fabric C). This implies that twin boundary migration has been an effective process in the individual calcite grains, whereas calcite concentrated in layers is likely to have undergone chiefly a grain boundary migration recrystallisation process. Both processes have apparently resulted in the equally strong preserved CPO's in these strongly deformed veins.

CPO fabrics generated from dislocation creep during dynamic recrystallisation (recrystallisation CPO fabrics) occur during deformation at higher temperatures than CPO fabrics generated solely by e-twinning as found in some shear zones (e.g. Schmid et al, 1987; Wenk and Takeshita, 1987). These recrystallisation calcite CPO fabrics must have been generated at temperatures where slip on the (c), {r} and {f} planes dominated over glide on the e-twin planes (Burkhard, 1993; De Bresser and Spiers, 1997). With estimated temperatures of $450 \pm 50^\circ\text{C}$ for shear zone deformation in the Southern Alps (Wightman, 2005) and shear strains of 4.7 ± 0.7 (see Chapter 3) these CPO fabrics in calcite are not unexpected. The sheared vein microstructures show evidence for grain boundary migration, twin boundary migration and grain boundary area reduction (a process which also favours grains well orientated for growth) supporting the interpretation that these fabrics were generated and strengthened from recrystallisation processes.

From the deformation map constructed in Fig. 6.5 from flow laws in Table 6.2, it can be seen that calcite never reaches a grain size sensitive (GSS) flow field (of $n = 1.7$) where grain boundary sliding can occur to weaken or randomise the fabric. Instead, at 450°C recrystallised calcite grains form at sizes in equilibrium

Fig. 6.5. Deformation map for calcite at temperature of 450°C and contoured for strain-rate. Flow behaviour of calcite is shown using flow laws for plastic creep (PC), grain size sensitive flow (GSS) and exponential creep (EC) from Table 6.2. PC flow law of the form $\dot{\epsilon} = A \cdot \sigma^n \cdot \exp(-Q/RT)$, GSS flow law of the form $\dot{\epsilon} = A \cdot \sigma^n \cdot d^m \cdot \exp(-Q/RT)$ and EC flow law of the form $\dot{\epsilon} = A \cdot \exp(-Q/RT) \cdot \exp(C \cdot \sigma)$ are used for this map. These flow laws have been used to plot fields boundaries (bold lines) for exponential creep (Rutter, 1974), plastic creep (Schmid, 1982) and grain size sensitive (GSS) flow in high and low stress conditions (Walker et al., 1990). The high stress GSS field where $n=3.3$ is where a CPO fabric can strengthen by recrystallisation and the low stress field where $n=1.7$ is where grain boundary sliding and diffusion creep (fabric weakening processes) can occur. Stress dependant recrystallised grain size palaeopiezometer of Rutter (1995) for migration recrystallisation of calcite also shown. Two differential stress calculation from Chapter 4 are shown and represent the estimated maximum and minimums during ductile deformation of the sheared calcite in the deformed veins. The estimated zone of deformation during the dynamic recrystallisation is indicated by the shaded grey box on the piezometer line that includes these two differential stresses.

Material and deformation mechanism	logA	n	m	Q	1/C	Reference
Iceland Spar - <25 MPa - GSS flow	4.9	1.7	-1.9	190	-	Walker et al. (1990)
Iceland Spar - 25-250 MPa - GSS flow	2	3.3	-1.3	190	-	Walker et al. (1990)
Power law creep in calcite	-5.5	6	-	314	-	Schmid (1982)
Carrara Marble - Exponential creep	5.8	-	-	260	11	Rutter (1974)
Cal recrystallised grain size piezometer	3.43	-	0.89	-	-	Rutter (1995)

Table 6.2. Flow laws parameters used to plot the boundaries for the deformation map in Fig. 6.5 for plastic creep (power law creep), exponential law creep and grain size sensitive (GSS) flow. Parameters listed for A ($\text{sec}^{-1} \cdot \text{MPa}^{-n} \cdot \mu\text{m}^{-m}$), Q ($\text{kJ} \cdot \text{mol}^{-1}$), f (MPa), w, n, m and c (dimensionless)

with the differential stress (palaeopiezometer line of Rutter, 1995 in Fig. 6.5) and do not leave the GSS flow field (of $n = 3.3$) where CPO fabrics can be developed and strengthened (Walker et al., 1990). Fig. 6.5 shows that for the differential stress range of 153–25 MPa calculated in Chapter 4 (when the veins were undergoing deformation at transiently high strain-rates through to low differential stress static recrystallisation) the deformation conditions remain in the field where the CPO fabrics will not be weakened (shaded box along piezometer line in Fig. 6.5). This prediction of the deformation conditions from flow laws shows that calcite CPO fabrics can be strengthened throughout the ductile deformation period estimated in Chapter 4 for the shear zones in the Southern Alps.

In contrast to the quartz CPO fabrics, the calcite fabrics throughout all sections of the shear zones are very similar indicating the strain forming the CPO was, in fact, more distributed throughout the shear zone than the localised strain in the most deformed and shear infilling vein sections suggested by the quartz CPO fabrics. This is not unexpected as the microfabrics show that recrystallisation has occurred away from the highly deformed sections in the sheared veins (Chapter 4). This observation and the very strong calcite CPO fabrics suggest that calcite was able to form a fabric from lower strains and has not been affected by the various fabric weakening processes outlined in Chapter 5.

CHAPTER 7: Discussion and conclusions

In this section I will summarise and discuss the deformation path of the brittle-ductile shears from their nucleation at $\sim 21 \pm 5$ km below the Southern Alps to the final imprints of ductile deformation affecting them during their upward transport on the Alpine Fault. The shear zones occur in the hanging wall of the Alpine Fault, where they accommodated ramping of the Pacific Plate crust onto the Australian Plate. Uplift of the Pacific Plate is in part accommodated by backshearing at the base of the Alpine Fault ramp, a site where transiently high strain-rates are predicted (e.g. Batt and Braun, 1999; Erickson et al., 2001; Chapter 2). These shears occur as part of a regularly spaced array, and have here been examined by means of field-based structural studies and by optical microscopy to gain a better understanding of their deformation path at mid-crustal depths in the Southern Alps of New Zealand.

The microstructures in sheared quartz-calcite veins deformed across the shear zones are recrystallised and have weak crystallographic fabrics which is unusual given that they have undergone a mean finite ductile shear strain of 4.8 ± 0.7 (Chapter 3). Preserved microstructures have shown that the veins have undergone three deformation phases during their progression up the Alpine Fault ramp: 1) static recrystallisation, 2) Regime 1 dislocation creep and 3) late stage semibrittle flow (Chapter 4). The crystallographic fabrics of quartz and calcite in the veins distinguish two earlier phases of deformation not observed in the microstructures: 1) dynamic recrystallisation, and 2) a period of CPO fabric weakening from grain boundary sliding (Chapter 5). The CPO fabrics in the sheared veins have also shown that the finite ductile extension direction [x] during shear zone deformation was not always parallel to the independently well known displacement vector for the shears and that the three-dimensional kinematics of flow during the evolution of the shear zones was more complex than previously thought.

In this discussion I will examine the three-dimensional strain that is associated with models of transpressional deformation. I will also suggest a five phase deformation path for the shears that represents a synthesis of all the data collected in this study. This path incorporates constraints that are derived from consideration of the relevant experimental flow law parameters for quartz and calcite. This proposed deformation path will attempt to explain the evolution of the

shear zones from their generation at the base of the Alpine Fault ramp through to their exhumation and erosion at the surface.

7.1. Triclinic deformation symmetry

In obliquely convergent orogens bulk deformation in a parallel-sided zone need not occur by simple shear, or even by a two-dimensional combination of simple shear and plane strain extension (e.g. Fig. 7.1a); but may, for example, occur by three-dimensional flow that includes some combination of irrotational vertical and horizontal extensions together with shear (Dewey et al., 1998; e.g. Figs. 7.1d and 7.1e). A commonly used model of transpression has a monoclinic symmetry and includes an irrotational vertical extension perpendicular to the shear direction together with a horizontal simple shear (e.g. Sanderson and Marchini, 1984; Tikoff and Greene, 1997). Natural transpressive strain maybe more complex than this, for example the flow may instead have a triclinic symmetry (e.g. Robin and Cruden, 1994; Jiang and Williams, 1998; Jiang et al., 2001). As I will argue, the shears in the Southern Alps have deformed internally by a triclinic pattern of general transpression. This triclinic symmetry is where the finite extension direction is neither parallel nor perpendicular to the shear vector, specifically, where the shear related vorticity vector is not parallel to any one principle direction of the symmetric strain tensor (Robin and Cruden, 1994). This flow pattern reveals complex three-dimensional strains that might be recognised by a combination of shear offset and finite extension that is oblique to the shear direction (e.g. Passchier, 1998; MacCready, 1996; Jiang et al., 2001).

I recognise triclinic symmetry in the pattern of flow affecting the deformed veins in the Southern Alps from the discordance between their near-vertical ductile extension direction (derived from CPO fabrics) and the moderately pitching finite displacement vector that is consistently recorded by the mineral lineations that decorate the shear planes and displaced planar markers. Within the mean shear plane, the mean displacement vector [a], pitches at 35° from the southwest and the mean CPO-derived shear direction [x], pitches southwest at 80° in deformed quartz and at 85° for deformed calcite (see Chapter 5, Chapter 6, Fig. 7.2). The extension direction is neither parallel nor perpendicular to the independently measured shear

Fig. 7.1. Models of deformation and the inferred crystallographic preferred orientation (CPO) patterns that would be seen in the vorticity plane (a-c plane). Use of the terms widening, lengthening and thinning are based on the strain facies of Tikoff and Fossen (1999) and CPO patterns are based on predictions by Passchier (1998) and this study. a. Model of simple shear and plane strain deformation with a Type I CPO pattern and an internal asymmetry. b. Thinning deformation without any shear which is inferred to yield a small circle CPO pattern. c. Thinning and shearing of a shear zone with principle extension in the shear direction (lengthening) that yields an inferred cleft girdle CPO pattern with an internal asymmetry to reflect the rotational component of the shearing. This could also be a Type I or Type II CPO pattern depending on the ratios of shear extension, vertical compression and thinning strain. d. Thinning and shearing with principle extension in the vertical direction (widening). A Type I CPO pattern centre with an internal asymmetry representing the rotational component of the deformation and a circle around the outside edge representing the finite vertical extension is predicted for this deformation. e. A complex combination of flattening, widening and lengthening shear deformation in a shear zone which may produce a random CPO fabric from the competition between extension directions for a preferred crystallographic preferred orientation.

Fig. 7.2. Schematic three-dimensional block diagram of a Southern Alps shear zone (a) and stereogram of extension directions and symmetry poles (b). The quartz CPO-derived stretching direction [x] of $239, 79 \pm 11^\circ$, the calcite CPO-derived stretching direction [x] of $201, 85 \pm 7^\circ$, and the mineral fibre lineation [a] (shear direction) of $226, 35 \pm 6.9^\circ$. The attitude of the shear plane is $221@89^\circ \text{ W} \pm 1.1^\circ$ and the vorticity plane is perpendicular to the shear plane and contains the shear direction line. The difference between the displacement vector [a] and the CPO-derived stretching directions [x] is not 90° but closer to $\sim 45^\circ$.

vector, indicating that the shear zone has not deformed by simple shear, plane strain or a general transpressive flow of monoclinic symmetry (e.g. Fig. 7.1).

The CPO fabrics that have been used to define the CPO-derived stretching directions [x] typically that have CPO patterns consistent with an irrotational strain that is either constrictional or plane strain. As I have argued in Chapter 5, these CPO fabrics are recording the finite extension direction resulting from the deformation. Apparently in the Southern Alps the irrotational component of the flow has the predominant affect on the CPO fabric alignment and asymmetry. These irrotational CPO patterns broadly compare with the tentative predictions by Passchier (1998) for CPO fabrics after deformation with a monoclinic symmetry (Fig. 7.1c and Fig. 7.1d). However, unlike Passchier's prediction, where both the irrotational stretching and the shear are represented in the finite CPO (e.g. Fig. 7.1d), the CPO fabrics in this study are dominated by an irrotational CPO that is centred about a near-vertical [x] extension direction. The CPO fabrics were only recording the near-vertical ductile extension and no CPO patterns (shear or flattening) were related to deformation in the vorticity plane (Fig. 7.2). This was unexpected, as the large finite ductile shear strains (5.4 ± 1.4 for sampled veins) would have been more than sufficient to produce a strong CPO fabric about the vorticity vector in the case of simple shear deformation (see Chapter 5).

The generation of a CPO fabric that is not related to deformation in the primary vorticity plane might be explained by the following strain modelling of Tikoff and Teyssier (1994). In a general flow the strain related to the shearing accumulates less efficiently than that related to the irrotational component. This appears to be reflected in the CPO fabrics of the Southern Alps shears. Numerical strain modelling shows that the maximum extension direction rotates progressively towards the shear zone boundary from an angle of $\leq 45^\circ$, and is not coincident with the instantaneous maximum extension direction. However, the intermediate principle strain axis (b-pole for monoclinic flow pattern) does not rotate during shearing so the finite and instantaneous extension directions are coincident. This material line therefore does not rotate during the flow. This coincidence might result in an efficient strengthening of the irrotational CPO fabrics related to the near-

vertical finite ductile extension direction, whereas CPO fabrics related to the rotational shearing are poorly reflected in the final CPO fabric.

The absence of a CPO fabric as viewed in the vorticity plane might be explained by the numerical strain modelling of Fossen et al. (1994). They show that in a monoclinic transpression the vertical extension direction will quickly become dominant over an initial horizontal maximum finite extension that temporarily is aligned in the vorticity plane at an acute angle to the shear direction. With increased finite shear strain (or initially if the convergence angle to the shear zone is $>20^\circ$), the maximum principle extension direction that is initially parallel to the shear direction [a] rotates into the vertical extension direction for monoclinic symmetry (Tikoff and Tessier, 1994). This means that the vertical extension undergoes more rapid lengthening than any other line in the deforming body. I infer therefore that the lack of a CPO fabric in the vorticity plane of the Southern Alps samples must be due to the fabric alignment being dominated by the effect of the near-vertical extension direction that is chiefly accommodating the irrotational thinning of the shear zones. The orientations of quartz and calcite c-axes are thus chiefly aligned for easy slip in this direction within the transpressive shear zone. The CPO fabrics might evolve in a complex way as a consequence of the shearing, shear parallel extension and near-vertical extension, but at high finite shear strains dominantly reflect the irrotational component causing the vertical maximum principle extension.

As discussed above, the stable finite extension direction in a monoclinic flow symmetry will be perpendicular to the shear direction (as illustrated in Fig. 7.1); however, in a triclinic flow symmetry the stable finite extension direction at high strain is not necessarily perpendicular to the shear direction by might be disposed at some other angle (Robin and Cruden, 1994; Llana-Funez, 2002). In the Southern Alps samples this angle, measured in the plane of shearing, is $\sim 45^\circ$ (Fig. 7.2). This is the pitch of the ductile extension direction, 80° , less that of mineral lineation direction, 35° . Due to the consistency of this angle in all of the shear zone samples measured ($n=17$) in this study, I infer that the CPO-derived extension direction [x] represents the steady-state direction of maximum finite extension in a general (triclinic) shear zone flow.

Asymmetric CPO fabrics were measured in ~2% of the samples from this study, i.e. those with Type I CPO patterns with an internal fabric asymmetry (e.g. Sample 4 from Fig. 5.6). The apparent vorticity plane related to this asymmetry is not parallel to the vorticity plane of finite shearing, but instead is perpendicular to the shear plane and contains the CPO-derived extension direction [x]. In other words, the only evidence in the CPO fabrics for shearing is near-vertical with a shear direction parallel to the finite extension direction. Jones et al. (2004) has shown that a rotational component to the flow can exist in both the primary shear direction and in a secondary direction that reflects the irrotational stretching. This is likely to be similar to that described by Tikoff and Fossen (1999) for porphyroblasts rotating in the vertical extension direction due to a reduction in the shear parallel extension. This secondary shear can be visualised as a consequence of heterogeneous vertical stretching near the boundary of the deforming zone, a situation which sets up a boundary shearing that is sub-parallel to [x] and that can be bi-vergent to the bulk shear sense (Fig. 7.3b).

Triclinic deformation symmetry that is inferred to have affected the shear zones in the Southern Alps is illustrated in Fig. 7.3. The block models in Fig. 7.3 represent a highly deformed sheared vein that it is undergoing a primary shear in the direction of the mineral lineations [a], but in which the maximum finite extension is accumulating in a near-vertical direction [x] as a result of the dominance of the irrotational aspect of the flow on the overall strain. These models show a ‘vertical escape’ of material from between two non-deformed blocks. This is schematic only as the wall rocks have probably also been extended to some extent parallel to the [x] direction, in a more realistic case of stretching faults (Means, 1989). With increased strain, the model in Fig. 7.3a with extension both shear parallel and in the near-vertical direction may evolve to a model such as 7.3b where the primary extension is in the near-vertical direction.

The observed variation in quartz CPO patterns in the highly deformed internal sections of sheared veins might be explained by variations on a triclinic flow with vertical extension. Varied proportions of thinning and extension in the [a] and the [x] direction could produce the observed range of CPO dispositions (e.g. Fig. 7.3). Small circle CPO patterns could form from the dominance of irrotational strain in a shear zone with orthorhombic extension symmetry (Fig. 7.3a). A range of CPO

Fig. 7.3. A model of triclinc deformation in a Southern Alps shear zone and some of the CPO patterns that might be anticipated. a. Schematic illustration of shearing with shear displacement and extension parallel to the mineral lineation [a] and the near-vertical extension [x]. This might generate a flattening CPO pattern (small circles) because of the dominant irrotational and flattening strain or a random CPO pattern from complex overprinting relationships during the deformation. b. Schematic illustration of shearing with the shear displacement parallel to the mineral lineation [a] and the finite extension in the near-vertical [x] direction. An array of CPO patterns (Type II, cleft girdle, or Type I) could be expected during this deformation depending on the ratio of extension between the shear normal compression, the shear parallel extension (or contraction) and the near-vertical principle extension direction. d. The CPO patterns plotted here have an internal asymmetry that represents possible boundary shearing in the [x] direction as a result of vertical extension and thinning between the two fault blocks (small shear sense arrows shown on the escaping section of rock).

patterns could be produced from a principle extension in the near-vertical direction (Fig. 7.3b) depending on the amount of constriction in the shear direction. Cleft girdles are anticipated for a more constrictional flow, whereas Type I and Type II CPO patterns would be expected for a more plane strain extension and may have a fabric asymmetry if a vertical shear was occurring as well as extension. The complexity of the flow, its triclinic symmetry, and evolving three-dimensional strain path might be anticipated to produce weak or random CPO fabrics as extension directions compete for easy crystallographic slip (Fig. 7.3a).

7.2. Deformation Sequence

A five phase deformation path is suggested here for the Southern Alps brittle-ductile shear zones. This deformation path reflects decreasing temperatures together with inferred variations in differential stress and strain-rate. These result from activation of the shear zones in the transient brittle-ductile transition zone (t-BDTZ), shearing along them, and finally a cessation of plastic creep as they were exhumed through the long-term (stead-state) brittle-ductile transition zone (s-BDTZ) on their way to the surface.

7.2.1. Phase A: Brittle-ductile shearing

The first phase of deformation accompanied initiation of the shears as brittle faults (in quartzofeldspathic schist) and ductile shear zones (embedded quartz veins) at a nucleation depth of 21 ± 5 km beneath the Southern Alps. This is the inferred depth of the transient brittle-ductile transition zone (t-BDTZ) related to the ramping of the Pacific Plate onto the Alpine Fault ramp (Little et al., 2002b; Wightman, 2005). Temperature estimates from oxygen isotope thermometry and chlorite thermometry by Wightman (2005) for the primary deformation at $450 \pm 50^\circ\text{C}$, compares well with the $\sim 400^\circ\text{C}$ estimate in this study based on CPO fabric concentrations and apparent slip systems in quartz (see Chapters 4 and 5). Field-based measurements of finite ductile shear strain have allowed for a maximum estimated strain-rate of $3.0 \times 10^{-11} \text{ sec}^{-1}$ to be calculated. This assumes that a shear was active for the time period required for a ~ 100 m wide block of rock to pass through the backshear zone (see Chapter 4).

Recrystallisation has removed the original deformation grain-boundary microstructures that were produced during the early phases of the quartz-calcite vein shearing rendering recrystallised grain size and calcite twin piezometers inappropriate. However, using the estimated maximum strain-rate, the deformation temperature, and experimental flow laws a differential stress of ~160 MPa for ductile shearing of quartz and calcite veins has been estimated. These veins and the Alpine Schist are however limited to a maximum differential stress of 353 MPa where brittle Coulomb failure of the rock will occur at a depth of 21 km with a near-hydrostatic fluid pressure ($\lambda = 0.6$). However, fluid pressure is more likely near-lithostatic ($\lambda = 0.9$) at these depths and is inferred to have caused the transient deep embrittlement of the schist and veins in the shear zones at the estimated nucleation differential stress of ~160 MPa.

From the crystallographic preferred orientation (CPO) of quartz and calcite grains, dislocation creep is inferred to have taken place in quartz during ductile shearing. At the inferred temperature of ~450°, this deformation in quartz would occur in Regime 2 or 3 of Hirth and Tullis (1992). Recovery mechanisms such as grain boundary migration and subgrain rotation recrystallisation during this dynamic recrystallisation would have caused grain size reduction in the quartz-calcite veins. Complex triclinic three-dimensional strain in the shear zones during this deformation phase may have geometrically weakened the CPO fabrics relative to a simple shear situation during the dislocation creep deformation.

The deformation of quartz and calcite to accommodate the shearing might be modelled using a flow law. Examples of these include power-law creep, exponential creep, grain size sensitive (GSS) flow and a grain size piezometer can also be used for grain size modelling. The flow laws used in this study are listed in Table 7.1 and are chiefly derived on the basis of experimental deformation studies. These flow laws take on the following equation forms:

$$\text{Power-law creep: } \varepsilon = A \cdot_D \sigma^n \cdot f_{H_2O}^w \cdot \exp\left(\frac{-Q}{RT}\right) \quad (7.1)$$

$$\text{Grain size sensitive flow: } \varepsilon = A \cdot_D \sigma^n \cdot d^m \cdot \exp\left(\frac{-Q}{RT}\right) \quad (7.2)$$

$$\text{Exponential creep law: } \dot{\varepsilon} = A \cdot \exp\left(\frac{-Q}{RT}\right) \cdot \exp(C \cdot {}_D\sigma) \quad (7.3)$$

$$\text{Grain size piezometer: } {}_D\sigma = A \cdot D^{-m} \quad (7.4)$$

Where: $\dot{\varepsilon}$ is the strain-rate (sec^{-1}), A is the material parameter, ${}_D\sigma$ is differential stress (MPa), n is the stress component, f is the water fugacity (MPa), w is the water fugacity exponent, Q is the activation energy ($\text{J} \cdot \text{mol}^{-1}$), R is the ideal gas constant ($\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), T is the temperature (K), d is the grain size (mm), m is the grain size exponent, C is the stress factor and D is the recrystallised grain size (mm).

From the estimated maximum strain-rate and $\sim 450^\circ\text{C}$ temperature inferred for the Southern Alps shearing a differential stress of 165 MPa has been calculated using the Hirth et al. (2001) flow law for plastic creep. The Hirth et al. (2001) flow law parameters (Fig. 7.4a; Table 7.1) best describe the natural quartz deformation of this study, unlike the Rutter and Brodie (2004a) parameters which extrapolate from experimental conditions to give unrealistically high differential stresses for ductile quartz deformation (Fig. 7.4a; Table 7.1). As seen in Fig. 7.4a, the predicted quartz recrystallised grain sizes of 8 μm from the Twiss (1980) piezometer are not small enough for grain size sensitive flow and the differential stress required to do so would exceed the maximum (353 MPa) for ductile flow (i.e. before brittle Coulomb failure; Fig. 7.4a). Calcite, on the other hand, under these conditions is predicted to undergo plastic and exponential creep ≤ 160 MPa. At these stresses calcite is predicted from the Rutter (1995) piezometer to recrystallise to a small enough grain size (23 μm) to undergo GSS flow (Fig. 7.4b). This reflects that calcite is weaker than quartz (as in Brodie and Rutter, 2000) and can accommodate strain more easily during the conditions estimated here for brittle-ductile shearing.

A prospective quartz deformation map has been constructed for the Southern Alps shears from the flow law parameters of Hirth et al. (2001) and Brodie and Rutter (2000) to show the boundary between power-law creep (e.g. dislocation creep) and GSS flow (e.g. diffusion creep or grain boundary sliding) for varied recrystallised grains sizes of quartz and differential stresses using equations of the form:

$$A_g \cdot {}_D\sigma^{n_g} \cdot d^m \cdot \exp\left(\frac{-Q_g}{RT}\right) = A_p \cdot {}_D\sigma^{n_p} \cdot f_{H_2O}^w \cdot \exp\left(\frac{-Q_p}{RT}\right) \quad (7.5)$$

Fig. 7.4. Flow behaviour of qua

Rearranged to solve for grain size:

$$\log d = \frac{(\log A_g - \log A_p) + (n_g - n_p) \log \sigma + \left(\frac{Q_g - Q_d}{2.3RT} \right) - w \log f}{m} \quad (7.6)$$

It can be seen in Fig. 7.5 that deformation at 450°C is predicted to occur solely by dislocation creep for recrystallised grain sizes following the piezometer law of Rutter (1995). Recrystallised grain sizes, strain-rates and differential stresses corresponding to varying widths of backshearing crust (including the preferred approximation of a 100 m width of deforming shears used for modelling purposes here) are also shown (see Chapter 4 and Table 4.7). These calculated recrystallised grain sizes are all less than the final mean grain size in the sheared veins (Fig. 7.5) which confirms that the microstructures remaining in the veins equilibrated during a lower stress period subsequent to their primary shearing.

A grain size reduction path has been determined for Phase A during early shearing of the quartz veins where grains recrystallise from ~1000–100 µm to 8 µm as the strain-rate initially builds up to its maximum value (Fig. 7.6). If the maximum strain-rate was faster than $3.0 \times 10^{-11} \text{ sec}^{-1}$ or if the fluid pressure was greater than $\lambda = 0.85$, then the veins may have undergone brittle failure and the grain size reduction would have been less and only reaching a possible maximum of 16 µm for a differential stress of 100 MPa (estimated differential stress required for hybrid extensional failure by Wightman and Little, 2003).

7.2.2. Phase B: Differential stress drop and grain boundary sliding

Phase B of the shear zones deformation took place during a period of inferred low strain-rates and shear deactivation as the rocks were transported away from the zone of transiently high strain-rates that resulted in their formation during Phase A. The temperatures at the beginning of this phase were $450 \pm 50^\circ\text{C}$, as in Phase A, but might have dropped slowly as the rocks were advected upwards towards the surface. Phase B was marked by a reduction in inferred differential stress to as low as 22 MPa and strain-rate as low as $1 \times 10^{-14} \text{ sec}^{-1}$. A pressure and rate determined from the mean finite recrystallised grain size measured in the veins of 126 µm (Fig. 7.6) using the Twiss (1980) piezometer and the Hirth et al. (2001) flow law parameters for

Fig. 7.5. Deformation map for quartz at temperature of 450°C and contoured for strain-rate. Produced from the flow law parameters by Hirth et al. (2001) for intracrystalline plasticity and Brodie and Rutter (2000) for grain size sensitive flow (GSS) of quartz. Equation for the boundary line can be found in the text and flow law parameters can be found in Table 7.1. Calculated recrystallised grain sizes (RGS) using palaeopiezometer (dash-dotted line) of Twiss (1980) for different widths of deforming rock (dashed and arrowed lines) of 10 cm, 1 m, 10 m, 100 m and 2 km (from Table 4.7) with mean finite ductile shear strain of 4.8 and shear normal convergence of 19.7 mm/yr. Preferred 100 m width of deforming rock shown in bold. Finite mean grain diameter measured in the highly deformed sheared vein sections from shear zone samples collected in this study (solid arrowed line).

Fig. 7.6. Deformation map for quartz (as in Fig. 7.5 above) at a temperature of 450°C and contoured for strain-rate and includes recrystallised grain size piezometer and the boundary line between GSS flow and dislocation creep flow conditions (dashed line). Bold centre line and arrows represent a potential movement of the boundary between the fields from increased water fugacity or easier grain boundary slip for the GSS flow deformation. GSS flow contours with increased water fugacity will move in the direction shown by small arrows. A, B, and C labelled arrows represent the deformation path phases as discussed in the text.

plastic creep. The decrease in differential stress and strain-rate is shown in Fig. 7.6 (Phase B deformation path arrow). The differential stress and strain-rate are approximates only and may have been higher or lower as they ignore the effect of post-deformational grain-growth on the palaeopiezometric relationship.

During Phase B, after the drop in differential stress caused by the rocks moving away from the Alpine Fault ramp-step, grain boundary sliding (GBS) is inferred to have been activated as a new deformation mechanism. This process resulted in the partial randomisation of CPO fabrics in the sheared veins. GBS is a deformation process where grains slide past each other without intracrystalline deformation and this process usually occurs in the presence of fluids which allow potential voids developed during the GBS to be prevented by solid-state diffusion creep (Passchier and Trouw, 1998). This is a grain size sensitive process where the grains need to be small enough and the differential stress low enough, for sliding to occur instead of dislocation creep (White et al, 1980; Lloyd et al, 1992; Brodie and Rutter, 2000).

Largely because of the obliterating affect of later grain growth, direct evidence for GBS, such as small ($<20\ \mu\text{m}$) grain sizes in the shears, has not been found in this study. However, very weak to random CPO fabrics in the highly sheared internal parts of quartz veins (see Chapter 5) and microstructural observations of lobate and sutured boundaries between quartz and calcite grains are indirect evidence for GBS. A quartz vein that has a CPO fabric in the section of the vein external to the shear zone and a random CPO pattern in the most highly sheared part of that vein is plausibly attributed to GBS causing a randomisation of the CPO in the most strongly deformed part of the vein (e.g. Behrmann and Mainprice, 1987; Lloyd et al., 1992; Passchier and Trouw, 1998; Wightman, 2005). The lobate and sutured grain boundaries between quartz and calcite grains are evidence for the process of solid-state diffusion creep (Gower and Simpson, 1992; Passchier and Trouw, 1998), required for the accommodation of GBS. From this evidence it is reasonable to assume that GBS occurred at some point during brittle-ductile shearing.

As seen in Fig. 7.5, GBS does not occur while dynamically recrystallised grain sizes are in equilibrium with the differential stress. Rather, a stress drop is

needed to activate GBS, so long as quartz has a small enough recrystallised grain size, for deformation in the GSS flow field (Fig. 7.5). The differential stress drop required to activate GSS flow and GBS in Phase B for a recrystallised grain size of $\sim 8 \mu\text{m}$ inherited from Phase A, is only 3 MPa, much less than 22 MPa (Fig. 7.6). Four possibilities might have allowed GBS to occur despite the $8 \mu\text{m}$ grain size: a) the grain size was smaller than estimated because of a faster strain-rate in Phase A, 2) the stress drop was actually greater than the that inferred from the final measured grain size, 3) the effects of fluids enhancing GBS not accounted for in the GSS flow law, and 4) the effects of calcite and micas aiding the GBS or quartz in polymineralic veins.

If the estimated minimum grain size from dynamic recrystallisation during Phase A was actually smaller than $8 \mu\text{m}$ because the strain-rates had been higher than $3 \times 10^{-11} \text{ sec}^{-1}$ (i.e. the deformation width was $<100 \text{ m}$) then the dislocation creep induced grain size might have been as low as $\sim 1 \mu\text{m}$, allowing GBS at differential stresses of 10 MPa. The drop in differential stress might also have been greater than shown in Fig. 7.6. The finite grain size and the quartz piezometer only give the finite differential stress after grain growth and this may have been lower before grain equilibrated with the lower differential stress.

The two other alternatives invoke a change in the GBS flow law to explain this deformation mechanism taking place in natural conditions in the Southern Alps. White et al. (1980) have shown that after considerable grain size reduction, when there is abundant fluid available, the boundary between GSS flow and dislocation creep will shift in favour of GBS (as shown in Fig. 7.6). For example, grains might undergo solid-state diffusion creep accommodated GBS at higher differential stresses than would be possible in dryer conditions. Such hydrological weakening is a common failure in extrapolated experimental flow laws which are used to predict natural quartz deformation (Farver and Yund, 2000; Tullis, 2002). The infilling veins and their fluid inclusions indicate that fluid was present during the shear zone deformation as well as diffusion creep microstructures (see Chapter 4). The plastic creep flow law parameters used in Fig. 7.5 take this fluid into account using a water fugacity function (equation 7.1), however the GSS flow laws currently available in the literature do not, and the effect of fluid in Equation 7.5 would cause the

deformation boundary to expand into the dislocation creep field (as approximated in Fig. 7.6).

Starkey and Cutforth (1978) have shown that the roll of impurities (such as micas and calcite) in a sample can enable GBS to occur at higher differential stresses or larger grain sizes. Relatively weaker mica and calcite crystals precipitated between quartz grains can enable quartz to slide more easily along its grain boundaries during deformation than by internal crystallographic slip. As shown in Chapter 5, the presence of calcite is associated with quartz CPO fabric weakening and therefore might have enhanced GBS in the sheared veins. Grain sizes of quartz as large 30 μm have been known to undergo GBS at strain-rates of $1 \times 10^{-16} \text{ sec}^{-1}$ (pers. comm. Takeshita and Heilbronner; in Wightman, 2005). It appears therefore, that GBS is likely in Phase B, as there are several exceptions that would allow GSS flow during conditions when experimental flow laws predict dislocation creep.

In short, I attribute the weak CPO fabrics in the strongly sheared quartz veins primarily to partial randomisation of those CPO fabrics inherited from Phase A during a Phase B deformation that included GBS under conditions of reduced differential stress. Completely randomised CPO fabrics only occur in the internal vein sections of 3 of the 17 shear zone samples examined. GBS is the most likely deformation mechanism for the complete fabric randomising; however, the remaining samples that still had a CPO fabric (although weak) may have undergone lesser amounts of GBS during this Phase B deformation. This may have been due to conditions not being met for GSS flow (grain size and strain-rate) or the period of time that conditions were favourable for GSS flow was not maintained for long enough in these shear zones for complete randomisation to occur. Calcite CPO fabrics that are much stronger than the quartz fabrics and do not show microstructural evidence for GBS (Chapters 4 and 6) and from flow laws (Fig. 6.5) are not estimated to have undergone GSS flow (where GBS occurs in calcite) during deformation in Phase B (Chapter 6). From the varied fabric strengths of sheared quartz vein samples it is clear that GBS in Phase B deformation affected individual shear zones and minerals differently.

7.2.3. Phase C: Static recrystallisation and grain growth

Grain growth and static recrystallisation of deformed veins defines Phase C of the shear zone deformation. This recrystallisation was probably driven by grain boundary area reduction (GBAR); a process that increases the mean grain size of a sample and overprints a deformation related grain shape fabric (GSF) with a equigranular-polygonal GSF. The temperature at which the coarsening took place may have been 300–400°C and would have decreased as the BDSZ is translated further up the Alpine Fault ramp towards the surface. The strain-rate and differential stress for Phase C could not have exceeded, $1 \times 10^{-14} \text{ sec}^{-1}$ and 22 MPa based on the final 126 μm recrystallised grain size, the Hirth et al. (2001) flow law and the palaeopiezometer of Twiss (1980). The coarsening of the equilibrium grain size for Phase C deformation is illustrated with a horizontal arrow in Fig. 7.6.

Static recrystallisation occurs when the strain-rate is so low (e.g. $1 \times 10^{-15} \text{ sec}^{-1}$) that significant creep and dynamic recrystallisation does not take place (Pfiffner and Ramsay, 1982; Stipp et al., 2002a). With ample fluid available along grain boundaries and in the crystal structure GBAR would be the main method of recovery during this static recrystallisation. This is a process of grain boundary migration where grain growth and straightening of grain boundaries occurs creating an equigranular-polygonal grain shape fabric (Passchier and Trouw, 1998). During GBAR the internal strain energy of a grain that is deformed during dislocation creep is recovered by preferential overgrowth of large grains that are relatively strain free (van der Pluijm and Marshak, 1997). Reduction of high internal energy grain boundaries between like grains and the increased development of low angle boundaries between unlike grains with lower internal energy boundaries promotes grain shape anisotropies in polymineralic veins during GBAR (Passchier and Trouw, 1998). Grain shape anisotropies observed in the Southern Alps samples between quartz and calcite and equigranular-polygonal grain shape fabrics in the deformed veins (both their internal and external sections, see Chapter 4) are evidence for this static grain growth during Phase C.

During static recrystallisation, CPO fabrics generated during dynamic recrystallisation are largely preserved (Heilbronner and Tullis, 2002) and subgrain and grain misorientation relationships are mostly unaffected by static

recrystallisation (Bestmann et al., 2005). These two experimental studies illustrate that the CPO patterns are only somewhat weakened, or diffused, during static recrystallisation and not lost completely. This recrystallisation is considered an additional CPO fabric weakening process in the Southern Alps samples. It is most likely responsible for the weakened CPO fabrics and diffused patterns across the entire shear zone, unlike GBS which localised fabric weakening in the most deformed sections of the sheared veins.

7.2.4. Phase D: Final increment of ductile strain during uplift

Microstructures preserved in the quartz and calcite microfabrics suggest relatively minor dynamic recrystallisation and dislocation creep took place in sheared quartz veins after the static recrystallisation of Phase C. Subgrain boundaries, grain boundary bulging, deformation lamellae, undulose extinction, fluid inclusion planes and calcite twinning are all evidence for this late stage dislocation creep and are classified as Regime 1 of Hirth and Tullis (1992). Some minor occurrences of core and mantle microstructures suggest that dynamic recrystallisation was able to occur, however it was not dominant. The oblique grain shape fabrics (GSF) observed in the infilling veins also record a deformation increment that was superimposed upon a previously annealed microstructure. These GSF's have a dextral west-side-up shear sense with a shear direction parallel to the moderately southwest pitching finite displacement vector (see Chapter 4).

Phase D deformation occurred in Regime 1 of Hirth and Tullis (1992) between temperatures of 280 and 400°C (as in Regime 1 deformation of natural rocks in Stipp et al., 2002b). Subgrain boundaries are uncommon, so temperatures were not as high as those required for Regime 2 of Hirth and Tullis (1992). I infer that the rocks were deforming towards the higher end of Regime 1 in Phase D. As a result of progressive cooling of the rocks, and if the strain-rate was maintained from Phase C, the Hirth et al. (2001) flow law for quartz suggests an increasing differential stress. This is represented by the Phase D arrow in Fig. 7.7a. This increase in differential stress is most likely the cause for these renewed dislocation creep microstructures. As seen in Fig. 7.7b, calcite was not able to undergo plastic creep as easily at these lower strain-rates and temperatures because of the high differential stress required to activate the {r} and {f} slip planes and would have been deforming dominantly by

Fig. 7.7. Flow behaviour of quartz (a) and calcite (b) for strain-rate of $1.0 \times 10^{-14} \text{sec}^{-1}$ for plastic creep (PC), grain size sensitive flow (GSS) and exponential creep (EC). PC flow law of the form $\dot{\epsilon} = A \cdot \sigma^n \cdot f_{\text{H}_2\text{O}}^n \cdot \exp(-Q/RT)$, GSS flow law of the form $\dot{\epsilon} = A \cdot \sigma^n \cdot d^m \cdot \exp(-Q/RT)$ for grain sizes of 100 μm , 10 μm , and 1 μm and EC flow law of the form $\dot{\epsilon} = A \cdot \exp(-Q/RT) \cdot \exp(C \cdot \sigma)$. Stress dependant recrystallised grain sizes of quartz (a) and of calcite from migration recrystallisation (b). Isotherms for 450°C and 250°C shown for reference. Isobars of 353 MPa and 203 MPa represent maximum differential stress where brittle Coulomb failure occurs (when $\lambda=0.6$) at 250 and 450°C respectively. Flow law parameters can be found in Table 7.1. Phase D arrow represents the decreasing temperature during final increment of ductile deformation in the Southern Alps sheared veins.

twinning and GSS flow as temperatures approached 280°C near the end of Phase D deformation.

The microstructures overprinting recrystallised grains in this deformation phase are not restricted to just the most deformed sections but are abundant throughout all parts of the sheared veins. This deformation was not renewed ductile displacement and shear of the veins but a broad deformation of the whole shear zone. However, the microstructures above only form oblique GSF's in the shear infilling veins (see Chapter 4). This implies that some shear deformation was focused into the shear infilling veins and that displacement in the finite shear direction was still occurring to a small extent in the BDSZ on the Alpine Fault ramp.

As dislocation creep is a process that can generate a preferred orientation of grains in a shear zone, the Phase D minimum shear strain estimates of ~ 1.5 from oblique GSF's (see Chapter 4) may be responsible for further weakening of quartz CPO fabrics imprinted during Phase A. This is due to this last increment of strain creating a new preferred orientation of quartz for slip in the [a] direction, not the [x] direction which generated the primary fabrics (see Chapter 5). The strain during this latter Phase D deformation, however, was not large enough to completely overprint the existing CPO fabrics (as in Strine and Wojtal, 2004), but may have been significant enough to weaken an existing CPO fabric.

7.2.5. Phase E: Semibrittle faulting of quartz and calcite twinning

The final deformation to affect the shear zones is inferred to have taken place near the s-BDTZ, at the end of the Phase D deformation path line in Fig. 7.7a. At shallower crustal levels and lower temperatures, the rock deformed by semibrittle fracturing rather than by plastic creep. A temperature of ~ 250 – 280 MPa is inferred from the transition of ductile to brittle deformation in Stipp et al. (2002b). A maximum differential stress of 202 MPa would have been required for brittle Coulomb failure at this temperature (assuming a $20^\circ\text{C}/\text{km}$ geothermal gradient and a minimum pore fluid pressure of $\lambda = 0.6$). However, if the fluid pressure was closer to lithostatic ($\lambda = 0.9$) then the differential stress required for brittle failure would only be 100 MPa. These estimates compare well with the temperature of $\sim 200^\circ\text{C}$ and maximum differential stress calculation of 189 MPa I have derived from calcite twin deformation microstructures in the shear zones (see Chapter 4).

Deformation lamellae and healed microcracks marked by planar alignments of fluid inclusions are consistent with the semibrittle flow and faulting regimes of Hirth and Tullis (1994). Microcracking occurs when internal dislocations rupture at grain boundaries to form brittle cracks and where internal grain dislocations are unable to climb. Recovery by plastic creep is thus hindered at these lower temperatures. Microcracks in the quartz, at the deformation temperature estimated, here would heal instantaneously on a geological time scale (Trepmann and Stöckhert, 2003). Microcracks that propagate across, instead of blunting against, grain boundaries reflect a shift from semibrittle flow to semibrittle fracturing. A decrease in temperature is inferred to have caused such a transition in the Southern Alps rocks (as in Hirth and Tullis, 1994).

Calcite at these temperatures can deform easily by e-twinning deformation. In the Southern Alps rocks these deformation microstructures are visible in most calcite grains and similar to the quartz fluid inclusion trails, the e-twins crosscut recrystallised grains and other microstructures formed during Phase C and D. The crosscutting relationship and the straight and planar aspect of the healed fractures and calcite twins indicate that they formed after the dislocation creep of Phase D. Semibrittle deformation in the shear zones is inferred to have ceased and the final microstructures frozen in when the Southern Alps rocks passed through the s-BDTZ on their way to the surface.

7.3. Conclusions

Exhumed arrays of brittle-ductile shears that have been exposed in the central Southern Alps of New Zealand near the Fox and Franz Josef glaciers have been studied by means of field-based structural mapping and optical microscopy of both microstructures and crystallographic preferred orientations (CPO) of quartz and calcite in sheared veins. The shears are exposed as arrays of systematically spaced shear zones in the host quartzofeldspathic Alpine Schist which has undergone deep embrittlement. By contrast, quartz-calcite veins in the schist have undergone variable brittle to ductile deformation that are the youngest ductile deformation features preserved in the Alpine schist. This study has documented the microstructural evolution of the shear zones from their incidence as backshears at the foot of the Alpine Fault ramp, where rocks of the Pacific Plate were uplifted and subjected to transiently high shear strain-rates, to their recrystallisation during later uplift and exhumation.

Field-based structural mapping of the shear zones at Sam Peak, Chancellor Ridge and Baumann Glacier has been used to determine 2 km width of the brittle-ductile shear array and to resolve the kinematics of the shears. The shears have a mean displacement of 9.9 cm ($n = 344$) and are spaced on average 25 cm apart ($n = 410$). The shear planes have a mean orientation of $221@89W \pm 1.1^\circ$ (95% confidence ellipse; $n = 780$) and have displaced the Alpine Schist and its veins in a dextral west-side-up sense that is antithetic to the dip-slip sense of the Alpine Fault. The shear displacement vector has been determined from the mineral fibre lineations that decorate the shear plane surfaces and from displaced marker veins, and is $226, 35 \pm 7^\circ$ ($n = 25$).

The quartz-calcite marker veins have undergone a mean finite ductile shear strain of 4.8 ± 0.3 ($n = 219$; 2σ). In the host quartzofeldspathic schist the shears occur as brittle fractures that are typically infilled by a syntectonically precipitated quartz-carbonate vein that has also been sheared. Shear spacing is in part controlled by the lithology of the Alpine Schist. Psammitic schist, for example, has more closely spaced shear zones than pelitic schist. While the shear zones in the psammitic schist accommodate much of the ramp related shearing, the pelitic schist

accommodates a greater proportion of the deformation by microshearing along foliation planes. The variably brittle to ductile expression of deformed marker veins is related in part to the vein thickness; thick veins are observed deform more ductilely and over wider deformation zones than thinner marker veins.

Five deformation phases have affected the sheared veins during their transport up the Alpine Fault ramp which were: 1) primary ductile shearing (triclinic flow with vertical extension); 2) grain boundary sliding accommodated by solid-state diffusion creep of the quartz in response to a drop in stress; 3) recrystallisation and grain growth; 4) renewed late-state dislocation creep; and 5) semibrittle deformation as the rocks pass through the brittle-ductile transition zone on their way to the surface.

Initial shear displacement and deep embrittlement of the schist occurred in the lower crust at temperatures of $450 \pm 50^\circ\text{C}$ (Wightman, 2005) at the base of the Alpine Fault ramp in response to up-ramping and transiently high strain-rates. A strain-rate of $3 \times 10^{-11} \text{ sec}^{-1}$ has been calculated for this deformation using the mean finite ductile shear strain, a ramping model where a shear is active for a time period estimated from that required for a 100 m width of rock to translate onto the Alpine Fault ramp and the convergent component of the PAC-AUS plate rotation (19.7 mm/yr normal to the mean shear plane from the DeMets et al., 1994 plate convergence vector). Using this strain-rate, and the Hirth et al. (2001) quartz flow law, the differential stress during ductile shearing is estimated to have been ~ 165 MPa. This is a differential stress at which the veins can undergo ductile deformation until fluid pressures reach near-lithostatic ($\lambda = 0.85$) and deep embrittlement occurs after Coulomb failure of the rock. Deformation inferred from flow law rheology at this differential stress is expected to occur by dislocation creep (a CPO generating process), and using a palaeopiezometer, the recrystallised grain size is expected to have been $\sim 8 \mu\text{m}$ for quartz and $\sim 25 \mu\text{m}$ for calcite.

Using a universal stage microscope, 89 quartz and 13 calcite crystallographic c-axis data sets were obtained for deformed veins in the shear zones. The c-axis CPO fabrics reveal that dislocation creep accompanied by dynamic recrystallisation was the chief agent of ductile strain during the initial and primary phase of vein deformation. The CPO fabrics for quartz (although weak) typically have CPO

patterns with a kinematic significance related to irrotational flow during this deformation.

As the shear zones were advected past the base of the Alpine Fault ramp away from the backshearing zone, the transiently high strain-rates are inferred to reduce to a minimum of $1 \times 10^{-14} \text{ sec}^{-1}$ and a low differential stress of $\sim 22 \text{ MPa}$. These conditions are calculated from the finite recrystallised grain size developed in the subsequent recrystallisation deformation phase which is assumed to represent these low stress conditions. At this low differential stress and inherited fine grain size, together with fluid in the shear zone, grain boundary sliding became a dominant deformation mechanism in some quartz veins. Evidence for this grain boundary sliding is found from some sheared veins from quartz CPO fabrics that were completely randomised in highly sheared parts of veins, probably as the result of this grain boundary sliding that was accompanied by solid-state diffusion creep of the quartz-calcite aggregate. In those same sheared veins, the calcite retains a very strong CPO fabric. Thus the calcite did not undergo significant grain boundary sliding or other fabric weakening processes, unlike the quartz grains surrounding it.

Recrystallisation occurred during the third deformation phase and was driven chiefly by grain boundary area reduction to achieve a finite mean diameter of $126 \mu\text{m}$ as grains equilibrate with the relatively lower differential stress. This recrystallisation and grain growth generated an equigranular-polygonal grain shape fabric that is retained in many vein samples and caused subsequent weakening of the quartz CPO fabrics across the shear zone. This deformation is inferred to have occurred at similar temperatures and strain-rates at the previous deformation phase.

These recrystallised grains were overprinted by a late-stage increment of dislocation creep accommodated shear and finally by semibrittle deformation during a period of increased differential stress levels experienced by the rocks at lower temperatures in the upper crust. The veins typically have microstructures such as grain boundary bulging, deformation lamellae, and minor subgrain boundaries that overprint the recrystallised fabric from the previous deformation phase. They were formed from a minimum shear strain of ~ 1.5 which is recorded by the obliquity of grain shape fabrics in the shear infilling veins. These microstructures are indicative of the low temperature Regime 1 of Hirth and Tullis (1992) and probably took place

at temperatures of 300–400°C. Quartz and calcite grain size palaeopiezometry yield low differential stresses of 16–65 MPa during this late-stage deformation.

The final phase of deformation involved micro-cracking of quartz and e-twinning of calcite during semibrittle deformation. This deformation occurred at differential stresses of <189 MPa and temperatures of 200–280°C that were determined from calcite twin palaeopiezometry and morphology, as well an assumed temperature for the natural brittle-plastic transition of quartz. The microstructures remnant from the last three phases were then frozen in as the rocks passed through the steady-state brittle-ductile transition zone (t-BDTZ) of the Southern Alps (8–10 km depth) on their way to being exhumed to the surface.

The CPO patterns in the quartz and calcite reveal that the principle extension direction was not sub-parallel to the southwest pitching shear direction, as would be expected for a case of simple shear. Instead the principal extension direction was consistently near-vertical. This unexpected result for these demonstrably sheared veins suggests that the deformation involved a three-dimensional transpressive strain and that the irrotational component of this general shear was preferentially imprinted into the resultant CPO pattern. This discordance between the mean CPO-derived finite extension direction of $235, 81 \pm 8^\circ$ (81° southwest pitch in the shear plane) and the shear displacement vector consistently recorded by the vein offsets and by the mineral fibre lineations (35° southwest pitch in the shear plane), is evidence for a triclinic symmetry to the flow.

The most remarkable aspect of the quartz CPO fabrics observed from sheared veins in this study is their weak intensity considering the high finite ductile shear strain known to exist in the veins. The complex triclinic strain may have played a role in this fabric weakening; however, grain boundary sliding during the second deformation phase is inferred to have dominantly weakened, and completely randomised some quartz CPO fabrics during shearing. The quartz fabrics were additionally weakened, although to a lesser degree, by subsequent grain growth recrystallisation and late-stage dislocation creep. Those veins with >5% calcite, have on average even weaker quartz CPO's, indicating that calcite may have aided in the grain boundary sliding deformation of quartz, and as indicated by microstructures in the veins, accommodated some of the slip by solid-state diffusion creep.

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Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	CH01	2002	2,276,932	5,739,683	-	1437	219	88												
MH	CH02	2002	2,276,886	5,740,055	-	1603			211	85					212	22				
MH	CH03	2002	2,276,666	5,739,975	-	1390	220	82	030	70										
MH	CH04-1	2002	2,276,189	5,740,303	-	1208	219	81	030	74					217	38				
MH	CH04-2	2002	2,276,189	5,740,303	-	1208	221	86	028	79					215	29				
MH	CH04-3	2002	2,276,189	5,740,303	-	1208	224	88												
MH	CH04-4	2002	2,276,189	5,740,303	-	1208	226	82												
MH	CH05-1	2002	2,276,052	5,740,437	-	1146	213	86	032	74										
MH	CH05-2	2002	2,276,052	5,740,437	-	1146	218	72												
MH	CH05-3	2002	2,276,052	5,740,437	-	1146	220	80												
MH	CH05-4	2002	2,276,052	5,740,437	-	1146	219	86	032	72					208	24				
MH	CH05-5	2002	2,276,052	5,740,437	-	1146	027	72												
MH	CH05-6	2002	2,276,052	5,740,437	-	1146	030	74	028	81										
MH	CH06	2002	2,275,974	5,740,568	-	1104	214	76												
MH	CH07-1	2003	2,277,105	5,740,078	-	1671	219	84	040	82										
MH	CH07-3	2003	2,277,105	5,740,078	-	1671	217	84												
MH	CH08-1	2003	2,276,764	5,740,046	-	1513	229	85												
MH	CH08-2	2003	2,276,764	5,740,046	-	1513	228	85												
MH	CH08-3	2003	2,276,764	5,740,046	-	1513	232	88												
MH	CH08-4	2003	2,276,764	5,740,046	-	1513	230	84												
MH	CH08-5	2003	2,276,764	5,740,046	-	1513	226	88												
MH	CH08-6	2003	2,276,764	5,740,046	-	1513	226	82												
MH	CH08-7	2003	2,276,764	5,740,046	-	1513	228	84												
MH	CH08-8	2003	2,276,764	5,740,046	-	1513	230	84												
MH	CH08-9	2003	2,276,764	5,740,046	-	1513	224	80												
MH	CH08-10	2003	2,276,764	5,740,046	-	1513	224	82												
MH	CH09-1	2003	2,277,249	5,740,071	-	1685	036	84												
MH	CH09-2	2003	2,277,249	5,740,071	-	1685	215	88												
MH	CH09-3	2003	2,277,249	5,740,071	-	1685	215	87												
MH	CH09-4	2003	2,277,249	5,740,071	-	1685	039	83	049	78										
MH	CH09-5	2003	2,277,249	5,740,071	-	1685	215	88												
MH	CH10-1	2003	2,277,373	5,740,071	-	1710	218	87	041	81										
MH	CH10-2	2003	2,277,373	5,740,071	-	1710	222	88												
MH	CH11-1	2003	2,277,675	5,740,243	-	1771	216	84	033	82	038	80								

Sample Site		Year	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field	of coll-	E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
	station #	ection					Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	CH12	2003	2,277,619	5,740,276	-	1770	215	82												
MH	CH13-1	2003	2,277,325	5,740,132	-	1710	218	84	034	80							223	38		
MH	CH13-2	2003	2,277,325	5,740,132	-	1710	038	89												
MH	CH14-1	2003	2,277,286	5,740,163	-	1689	217	88	032	76										
MH	CH14-2	2003	2,277,300	5,740,178	-	1689	215	87	032	75										
MH	CH14-3	2003	2,277,300	5,740,178	-	1689			034	76	038	70			218	34				
MH	CH14-4	2003	2,277,301	5,740,163	-	1695	217	86	042	70					220	40				
MH	CH14-5	2003	2,277,301	5,740,163	-	1695	217	88												
MH	CH14-6	2003	2,277,301	5,740,163	-	1695	215	85												
MH	CH14-7	2003	2,277,301	5,740,163	-	1695	215	88												
MH	CH14-8	2003	2,277,301	5,740,163	-	1695	216	86												
MH	CH14-9	2003	2,277,301	5,740,163	-	1695	216	86												
MH	CH14-10	2003	2,277,301	5,740,163	-	1695	216	88												
MH	CH15-1	2003	2,277,272	5,740,207	-	1665	217	82	027	75										
MH	CH15-2	2003	2,277,272	5,740,207	-	1665	219	85												
MH	CH15-3	2003	2,277,272	5,740,207	-	1665														
MH	CH15-4	2003	2,277,272	5,740,207	-	1665														
MH	CH16	2003	2,277,107	5,740,211	-	1618	221	85	034	74										
MH	CH17	2003	2,276,934	5,740,285	-	1551	218	86	035	78										
MH	CH18-1	2003	2,275,675	5,740,507	-	878			039	71										
MH	CH18-2	2003	2,275,675	5,740,507	-	878			025	78	036	60								
MH	CH19-1	2003	2,275,814	5,740,403	-	920	223	76	035	63										
MH	CH19-5	2003	2,275,814	5,740,403	-	920	220	82												
MH	CH20-1	2003	2,276,050	5,740,450	-	1183	215	87	029	77										
MH	CH20-2	2003	2,276,050	5,740,450	-	1183	218	88												
MH	CH20-3	2003	2,276,050	5,740,450	-	1183	208	81												
MH	CH21-1	2003b	2,276,064	5,740,293	-	1156	221	86	035	76										
MH	CH21-2	2003b	2,276,064	5,740,293	-	1156	224	88	032	70										
MH	CH21-3	2003b	2,276,064	5,740,293	-	1156	220	88	032	70										
MH	CH21-4	2003b	2,276,064	5,740,293	-	1156	218	87	036	75										
MH	CH22-1	2003b	2,276,050	5,740,450	-	1183	040	82	028	82										
MH	CH22-2	2003b	2,276,050	5,740,450	-	1183	038	88	036	70										
MH	CH23-1	2003b	2,275,985	5,740,544	-	1123	221	87	035	72										
MH	CH23-2	2003b	2,275,985	5,740,544	-	1123	216	78	028	70										

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	CH23-3	2003b	2,275,985	5,740,544	-	1123	220	79	029	68										
MH	CH24	2003b	2,276,129	5,740,351	-	1161	224	84	038	70										
MH	CH25-1	2003b	2,276,338	5,740,114	-	1264	220	85	036	65										
MH	CH25-2	2003b	2,276,338	5,740,114	-	1264	219	88	025	70										
MH	CH26-1	2003b	2,277,280	5,740,132	-	1666	213	85	028	71										
MH	CH26-2	2003b	2,277,280	5,740,132	-	1666	219	84	027	76										
MH	CH27-1	2003b	2,277,348	5,740,090	-	1704	222	88	027	75										
MH	CH27-2	2003b	2,277,348	5,740,090	-	1704	218	89	025	74										
MH	CH28	2003b	2,277,421	5,740,067	-	1698	222	86	027	75							223	12		
MH	CH29-1	2003b	2,277,802	5,739,908	-	1751	231	82	029	74										
MH	CH29-2	2003b	2,277,802	5,739,908	-	1751	218	85	028	80										
MH	CH30	2003b	2,277,114	5,740,287	-	1580	210	88	041	64										
MH	CH31-1	2003b	2,277,232	5,740,212	-	1641	216	86	037	67										
MH	CH32	2003b	2,276,924	5,739,676	-	1449	216	68	042	78										
MH	CH33	2003b	2,276,926	5,739,676	-	1452	218	84									223	41		
MH	CH34	2003b	2,276,924	5,739,671	-	1441	218	82	035	82										
MH	CH35	2003b	2,276,935	5,739,670	-	1450	216	80	042	78										
MH	CH36-1	2003b	2,276,962	5,739,676	-	1451	212	80												
MH	CH36-2	2003b	2,276,962	5,739,676	-	1451	196	82												
MH	CH36-3	2003b	2,276,962	5,739,676	-	1451	208	81												
MH	CH31-2	2003b	2,277,232	5,740,212	-	1641	220	65									239	35		
MH	CH31-3	2003b	2,277,232	5,740,212	-	1641	219	78									225	25		
MH	CH31-4	2003b	2,277,232	5,740,212	-	1641	210	82									214	25		

Appendix A-1. Structural field data collected on Chancellor Ridge. a - geologist collecting the data: MH - Matt Hill, TL - Timothy Little, RW - Ruth Wightman. Collection year and field season (a or b) within that year listed. b - Grid reference is in New Zealand map grid coordinates (metres). c - Accuracy of coordinates measured using a GPS unit ($\pm$ in meters). d - elevation given in meters above mean sea level. Alpine Fol refers to the Alpine Schist foliation and Myl fol refers to the Alpine Schist mylonitic foliation. Lineation subscripts refer to foliations or intersections: L₂₋₃ - intersection lineation between S₂ and S₃, L₄ - mineral fibre lineation decorating S₄ fault surfaces, and L_m - mineral stretching lineation on Alpine Schist mylonite foliation (S_m).

Sample Site		Year of coll- station #	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	SP01	2002	2,273,780	5,738,418	16	-			042	74					212	38				
MH	SP02	2002	2,273,686	5,738,406	12	-			028	62										
MH	SP03	2002	2,273,513	5,738,421	-	-			030	74					218	32				
MH	SP04	2002	2,273,385	5,738,506	8	1700			204	60					218	54				
MH	SP05	2002	2,273,235	5,738,374	6	-			026	80					222	50				
MH	SP06	2002	2,272,925	5,738,335	6	1680			039	60	182	62			221	22				
MH	SP07	2002	2,274,496	5,737,332	-	1860	228	62	217	89										
MH	SP08	2002	2,274,495	5,737,213	5	1865	034	62	026	82										
MH	SP09	2002	2,274,514	5,737,163	5	1865	202	52	205	76										
MH	SP10	2002	2,274,555	5,737,213	7	1875	182	64	204	73										
MH	SP11	2002	2,274,762	5,737,045	5	1900	196	40	213	64										
MH	SP12	2002	2,274,625	5,737,165	-	-	207	54	200	69										
MH	SP13	2002	2,274,525	5,737,220	-	-	210	66	212	82										
RW	RW29-1	2002	2,273,715	5,738,047	-	-					201	68								
RW	RW29-2	2002	2,273,715	5,738,047	-	-					207	50								
RW	RW29-3	2002	2,273,715	5,738,047	-	-					063	73								
RW	RW29-4	2002	2,273,715	5,738,047	-	-			041	90	101	16								
RW	RW30-1	2002	2,273,655	5,738,044	-	-			200	68										
RW	RW30-2	2002	2,273,655	5,738,044	-	-			201	68										
RW	RW31	2002	2,273,585	5,738,002	-	-			213	80	111	10			217	10				
RW	RW32-1	2002	2,273,439	5,738,035	-	-			210	72					225	38				
RW	RW32-2	2002	2,273,439	5,738,035	-	-														
RW	RW33	2002	2,273,325	5,737,971	-	-			213	87										
RW	RW34-1	2002	2,273,135	5,738,015	-	-			013	88	181	47								
RW	RW34-2	2002	2,273,135	5,738,015	-	-			037	84										
RW	RW35-1	2002	2,274,172	5,737,505	-	-	207	65			207	80								
RW	RW35-2	2002	2,274,172	5,737,505	-	-	205	62			210	84								
RW	RW35-3	2002	2,274,172	5,737,505	-	-	212	70			200	74								
RW	RW35-4	2002	2,274,172	5,737,505	-	-	207	55												
RW	RW35-5	2002	2,274,172	5,737,505	-	-	218	60												
RW	RW35-6	2002	2,274,172	5,737,505	-	-	212	74												
RW	RW35-7	2002	2,274,172	5,737,505	-	-	213	63												
RW	RW35-8	2002	2,274,172	5,737,505	-	-	207	64												
RW	RW35-9	2002	2,274,172	5,737,505	-	-	200	56			203	80								

Sample Site		Year	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field	of coll-	E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
	station #	ection					Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
RW	RW35-10	2002	2,274,172	5,737,505	-	-	197	64												
RW	RW35-11	2002	2,274,172	5,737,505	-	-	191	58												
RW	RW35-12	2002	2,274,172	5,737,505	-	-	188	60			211	72								
RW	RW35-13	2002	2,274,172	5,737,505	-	-	191	62												
RW	RW35-14	2002	2,274,172	5,737,505	-	-	206	64			193	68								
RW	RW36	2002	2,274,383	5,737,438	-	-	181	64												
RW	RW37	2002	2,274,302	5,737,456	-	-	179	64			202	78								
RW	RW38-1	2002	2,274,188	5,737,505	-	-	213	65			204	83								
RW	RW38-2	2002	2,274,188	5,737,505	-	-	207	64												
RW	RW38-3	2002	2,274,188	5,737,505	-	-	213	56												
TL	TJFA36-1	2002	2,273,840	5,738,296	-	-			043	78	132	55			211	40				
TL	TJFA36-2	2002	2,273,840	5,738,296	-	-					155	40								
TL	TJFA37	2002	2,273,843	5,738,156	-	1670			195	71	189	27			205	15				
TL	TJFA38	2002	2,273,855	5,737,949	-	1700			201	71	080	52			226	20				
TL	TJFA39	2002	2,273,928	5,737,901	-	1727			215	85	087	58			222	23				
TL	TJFA40	2002	2,274,236	5,737,567	-	1786			201	72	081	40			205	32				
TL	TJFA41	2002	2,274,321	5,737,492	-	1815	222	82	205	76					215	23				
TL	TJFA42-1	2002	2,274,079	5,737,423	-	1837	232	80												
TL	TJFA42-2	2002	2,274,079	5,737,423	-	-	227	87	203	64										
TL	TJFA42-3	2002	2,274,079	5,737,423	-	-	222	84												
TL	TJFA42-4	2002	2,274,079	5,737,423	-	-	218	70												
TL	TJFA42-5	2002	2,274,079	5,737,423	-	-	210	79												
TL	TJFA43	2002	2,274,409	5,737,321	-	1824	211	64	202	79										
TL	TJFA44-1	2002	2,274,436	5,737,312	-	1837	215	75	208	82					210	21				
TL	TJFA44-2	2002	2,274,436	5,737,312	-	-	210	68												
TL	TJFA46-1	2002	2,274,517	5,737,228	-	1865	211	75												
TL	TJFA46-2	2002	2,274,517	5,737,228	-	-	212	62												
TL	TJFA47	2002	2,274,502	5,737,234	-	1865	213	60	203	89										
TL	TJFA48	2002	2,274,461	5,737,285	-	1850	220	64									224	7		
TL	TJFA49-1	2002	2,274,356	5,737,408	-	1809	218	68	204	83					210	27				
TL	TJFA49-2	2002	2,274,356	5,737,408	-	-	209	63									220	20		
TL	TJFA49-3	2002	2,274,356	5,737,408	-	-	220	70												
TL	TJFA49-4	2002	2,274,356	5,737,408	-	-	210	70												
TL	TJFA50-1	2002	2,274,300	5,737,390	-	1815	209	67	198	74										

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geof ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
TL	TJFA50-2	2002	2,274,300	5,737,390	-	-	209	68												
TL	TJFA51-1	2002	2,274,266	5,737,416	-	1795	226	65									253	44		
TL	TJFA51-2	2002	2,274,266	5,737,416	-	1786	211	65												
TL	TJFA51-3	2002	2,274,266	5,737,416	-	1788	210	63									216	12		
TL	TJFA52-1	2002	2,274,288	5,737,385	-	1797	204	68												
TL	TJFA52-2	2002	2,274,288	5,737,385	-	-	212	60												
TL	TJFA52-3	2002	2,274,288	5,737,385	-	1787	215	65												
TL	TJFA53	2002	2,274,248	5,737,386	-	-	215	67	205	77										
TL	TJFA54	2002	2,274,210	5,737,380	-	1761	209	60	198	64				225	43					
TL	TJFA56	2002	2,274,197	5,737,210	-	1741	212	63	207	73										
TL	TJFA57	2002	2,274,246	5,737,177	-	1757	212	62												
TL	TJFA59	2002	2,274,341	5,737,202	-	1798	227	67												
TL	TJFA60-1	2002	2,274,352	5,737,202	-	1801	215	60												

Appendix A-2. Structural field data collected on Sam Peak. a - geologist collecting the data: MH - Matt Hill, TL - Timothy Little, RW - Ruth Wightman. Collection year and field season (a or b) within that year listed. b - Grid reference is in New Zealand map grid coordinates (metres). c - Accuracy of coordinates measured using a GPS unit ($\pm$ in meters). d - elevation given in meters above mean sea level. Alpine Fol refers to the Alpine Schist foliation and Myl fol refers to the Alpine Schist mylonitic foliation. Lineation subscripts refer to foliations or intersections: L₂₋₃ - intersection lineation between S₂ and S₃, L₄ - mineral fibre lineation decorating S₄ fault surfaces, and L_m - mineral stretching lineation on Alpine Schist mylonite foliation (S_m).

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	BM01-01	2004	2,280,390	5,745,031	8	1495	062	74												
MH	BM01-02	2004	2,280,390	5,745,031	8	1495	043	80												
MH	BM01-03	2004	2,280,390	5,745,031	8	1495			067	72										
MH	BM01-05	2004	2,280,390	5,745,031	8	1495	042	78												
MH	BM02-01	2004	2,280,528	5,745,097	9	1480	048	86												
MH	BM02-02	2004	2,280,528	5,745,097	9	1480					040	78								
MH	BM03-01	2004	2,280,760	5,745,004	6	1531	052	60												
MH	BM03-02	2004	2,280,760	5,745,004	6	1531	046	67												
MH	BM03-03	2004	2,280,760	5,745,004	6	1531	046	70												
MH	BM04-01	2004	2,280,815	5,744,895	6	1546	046	72												
MH	BM04-02	2004	2,280,815	5,744,895	6	1546	036	72												
MH	BM05-01	2004	2,280,956	5,744,858	9	1613	052	70												
MH	BM05-02	2004	2,280,956	5,744,858	9	1613	054	72												
MH	BM05-04	2004	2,280,956	5,744,858	9	1613	052	49												
MH	BM05-05	2004	2,280,956	5,744,858	9	1613	049	68												
MH	BM05-06	2004	2,280,956	5,744,858	9	1613	056	68												
MH	BM05-07	2004	2,280,956	5,744,858	9	1613	049	70												
MH	BM05-08	2004	2,280,956	5,744,858	9	1613					064	68								
MH	BM05-10	2004	2,280,956	5,744,858	9	1613	235	88												
MH	BM05-11	2004	2,280,956	5,744,858	9	1613	227	86												
MH	BM05-12	2004	2,280,956	5,744,858	9	1613	237	87												
MH	BM05-13	2004	2,280,956	5,744,858	9	1613	227	88												
MH	BM05-14	2004	2,280,956	5,744,858	9	1613	233	84												
MH	BM05-15	2004	2,280,956	5,744,858	9	1613	223	84	048	74										
MH	BM06	2004	2,281,063	5,744,840	16	1629	046	86												
MH	BM07-01	2004	2,281,277	5,744,898	5	1745					038	68								
MH	BM08	2004	2,281,306	5,744,853	6	1750					038	78								
MH	BM09-01	2004	2,281,304	5,744,565	50	1730					044	86			221	40				
MH	BM09-02	2004	2,281,304	5,744,565	50	1730					056	70								
MH	BM10-01	2004	2,281,178	5,744,490	50	1740	057	76												
MH	BM10-02	2004	2,281,178	5,744,490	50	1740					074	54								
MH	BM11-01	2004	2,281,162	5,744,633	8	1699	229	80												
MH	BM11-02	2004	2,281,162	5,744,633	8	1699	228	88												
MH	BM11-03	2004	2,281,162	5,744,633	8	1699	226	82												

Sample Site		Year	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field	of coll-	E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
	station #	ection					Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	BM12-01	2004	2,279,955	5,744,609	6	1728	046	82												
MH	BM12-02	2004	2,279,955	5,744,609	6	1728	054	80												
MH	BM12-03	2004	2,279,955	5,744,609	6	1728	044	78												
MH	BM12-05	2004	2,279,955	5,744,609	6	1728	048	86												
MH	BM13-01	2004	2,279,906	5,744,559	6	1746	042	74												
MH	BM13-02	2004	2,279,906	5,744,559	6	1746	043	76												
MH	BM13-04	2004	2,279,906	5,744,559	6	1746	039	78												
MH	BM14-01	2004	2,279,922	5,744,478	7	1780	045	82												
MH	BM14-02	2004	2,279,922	5,744,478	7	1780	048	78	038	83	050	70								
MH	BM14-03	2004	2,279,922	5,744,478	7	1780	041	82	045	68										
MH	BM14-04	2004	2,279,922	5,744,478	7	1780	045	82	038	84										
MH	BM14-05	2004	2,279,922	5,744,478	7	1780	046	80	038	83										
MH	BM14-06	2004	2,279,922	5,744,478	7	1780	234	84	038	83	045	68								
MH	BM15-01	2004	2,279,964	5,744,459	5	1823	046	86												
MH	BM15-02	2004	2,279,964	5,744,459	5	1823	048	78												
MH	BM16-01	2004	2,280,054	5,744,399	5	1877	228	82												
MH	BM16-02	2004	2,280,054	5,744,399	5	1877	045	77												
MH	BM16-03	2004	2,280,054	5,744,399	5	1877	052	70												
MH	BM16-04	2004	2,280,054	5,744,399	5	1877	048	74												
MH	BM16-05	2004	2,280,054	5,744,399	5	1877	045	70												
MH	BM17-01	2004	2,280,153	5,744,359	5	1940	046	73												
MH	BM17-02	2004	2,280,153	5,744,359	5	1940	043	88												
MH	BM17-03	2004	2,280,153	5,744,359	5	1940	231	88												
MH	BM17-04	2004	2,280,153	5,744,359	5	1940	055	86												
MH	BM17-05	2004	2,280,153	5,744,359	5	1940	040	72												
MH	BM18-01	2004	2,279,994	5,744,738	6	1744	050	76												
MH	BM18-05	2004	2,279,994	5,744,738	6	1744	044	88												
MH	BM19-01	2004	2,280,084	5,744,774	6	1761	047	83												
MH	BM19-02	2004	2,280,084	5,744,774	6	1761	058	78												
MH	BM20-01	2004	2,280,081	5,744,689	5	1737	046	83	036	70										
MH	BM20-02	2004	2,280,081	5,744,689	5	1737	046	80	221	89										
MH	BM20-03	2004	2,280,100	5,744,678	5	1750	048	77	221	89										
MH	BM20-04	2004	2,280,100	5,744,678	5	1750	048	77												
MH	BM20-05	2004	2,280,100	5,744,678	5	1750	049	88												

Sample Site		Year	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field	of coll-	E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
	station #	ection					Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	BM20-06	2004	2,280,112	5,744,667	6	1759	048	76	221	89										
MH	BM21-02	2004	2,280,123	5,744,672	6	1764	056	80	215	84	053	60								
MH	BM22-01	2004	2,280,138	5,744,640	4	1773	051	73			045	60								
MH	BM22-02	2004	2,280,138	5,744,640	4	1773	049	74	039	80					219	19				
MH	BM22-03	2004	2,280,138	5,744,640	4	1773	045	85												
MH	BM22-04	2004	2,280,138	5,744,640	4	1773	044	86												
MH	BM22-05	2004	2,280,138	5,744,640	4	1773	047	73												
MH	BM23	2004	2,280,172	5,744,593	5	1812	048	85	226	86	052	72								
MH	BM24-01	2004	2,280,207	5,744,569	6	1826	051	80	025	85	018	88			218	33				
MH	BM24-02	2004	2,280,207	5,744,569	6	1826	222	88												
MH	BM25	2004	2,280,294	5,744,536	7	1887	053	82	045	80	202	72								
MH	BM27-01	2004	2,280,326	5,744,483	5	1929	047	75	210	82	197	76			218	36				
MH	BM27-02	2004	2,280,326	5,744,483	5	1929	050	85												
MH	BM28-01	2004	2,280,123	5,744,672	6	1764	062	88												
MH	BM28-02	2004	2,280,123	5,744,672	6	1764	225	82												
MH	BM28-03	2004	2,280,123	5,744,672	6	1764	225	82												
TL	BM01-01	2004	2,280,390	5,745,031	8	1537	226	83												
TL	BM01-02	2004	2,280,390	5,745,031	-	1537	046	78												
TL	BM01-03	2004	2,280,390	5,745,031	-	1537	044	73			045	61			224	27				
TL	BM02	2004	2,280,516	5,745,090	-	-	048	86												
TL	BM04-01	2004	2,280,836	5,744,894	-	1450	049	88												
TL	BM04-02	2004	2,280,836	5,744,894	-	1450	225	87												
TL	BM04-04	2004	2,280,836	5,744,894	-	1450					035	87			205	27				
TL	BM05-01	2004	2,280,959	5,744,858	-	1540	055	78	041	83					217	18				
TL	BM05-02	2004	2,280,959	5,744,858	-	1540	051	79												
TL	BM05-03	2004	2,280,959	5,744,858	-	1540	054	77												
TL	BM05-04	2004	2,280,959	5,744,858	-	1540	048	82												
TL	BM05-05	2004	2,280,959	5,744,858	-	1540	238	83												
TL	BM05-06	2004	2,280,959	5,744,858	-	1540	049	90												
TL	BM05-07	2004	2,280,959	5,744,858	-	1540					055	57								
TL	BM07	2004	2,281,277	5,744,898	-	-					034	72			216	13				
TL	BM08-01	2004	2,281,236	5,744,785	-	1675					038	78			214	33				
TL	BM08-02	2004	2,281,236	5,744,785	-	1675					043	69								
TL	BM08-03	2004	2,281,236	5,744,785	-	1675					050	73								

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
TL	BM09-01	2004	2,281,304	5,744,565	-	1672			057	85					212	40				
TL	BM09-02	2004	2,281,304	5,744,565	-	1672			065	62										
TL	BM10	2004	2,281,178	5,744,490	-	1681	057	76			074	54								
TL	BM11	2004	2,281,154	5,744,643	-	1604	230	76			041	84								
TL	BM12-01	2004	2,279,946	5,744,628	-	-			045	72	053	58			209	28				
TL	BM12-02	2004	2,279,946	5,744,628	-	-	047	82												
TL	BM12-03	2004	2,279,946	5,744,628	-	-	045	78												
TL	BM13-01	2004	2,279,924	5,744,576	-	1730														
TL	BM13-02	2004	2,279,924	5,744,576	-	1730	225	86												
TL	BM13-03	2004	2,279,924	5,744,576	-	1730	048	80												
TL	BM13-04	2004	2,279,924	5,744,576	-	1730	044	79												
TL	BM13-05	2004	2,279,924	5,744,576	-	1730	044	78												
TL	BM13-06	2004	2,279,924	5,744,576	-	1730			044	89	055	64			217	17				
TL	BM14-01	2004	2,279,935	5,744,472	-	1820			039	83	051	65			209	26				
TL	BM14-02	2004	2,279,935	5,744,472	-	1820	046	82												
TL	BM14-03	2004	2,279,935	5,744,472	-	1820	047	83												
TL	BM14-05	2004	2,279,935	5,744,472	-	1820	047	83									219	49		
TL	BM14-06	2004	2,279,935	5,744,472	-	1820	047	83									213	63		
TL	BM14-07	2004	2,279,935	5,744,472	-	1820	046	80												
TL	BM15-01	2004	2,279,963	5,744,458	-	1830	047	83												
TL	BM15-02	2004	2,279,963	5,744,458	-	1830	050	87												
TL	BM15-03	2004	2,279,963	5,744,458	-	1830			041	80	047	52			214	22				
TL	BM16-01	2004	2,280,044	5,744,379	-	1850	053	80									214	61		
TL	BM16-02	2004	2,280,044	5,744,379	-	1850			044	77	204	68			210	41				
TL	BM16-03	2004	2,280,044	5,744,379	-	1850			032	83	219	52			212	32				
TL	BM16-04	2004	2,280,044	5,744,379	-	1850	056	80												
TL	BM16-05	2004	2,280,044	5,744,379	-	1850	044	77												
TL	BM17-01	2004	2,280,150	5,744,345	-	1940	059	79												
TL	BM17-02	2004	2,280,150	5,744,345	-	1940	047	88												
TL	BM17-03	2004	2,280,150	5,744,345	-	1940			035	82	132	30			216	17				
TL	BM18-01	2004	2,279,987	5,744,727	-	1760			033	84	138	28			214	30				
TL	BM18-02	2004	2,279,987	5,744,727	-	1760					064	51								
TL	BM18-03	2004	2,279,987	5,744,727	-	1760	048	90												
TL	BM18-04	2004	2,279,987	5,744,727	-	1760	049	84												

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
TL	BM18-05	2004	2,279,987	5,744,727	-	1760	048	88												
TL	BM20-01	2004	2,280,103	5,744,674	-	1750	045	82												
TL	BM20-02	2004	2,280,103	5,744,674	-	1750	228	88									239	80		
TL	BM20-03	2004	2,280,103	5,744,674	-	1750	055	82												
TL	BM20-05	2004	2,280,103	5,744,674	-	1750			041	88	045	68			218	26				
TL	BM20-06	2004	2,280,103	5,744,674	-	1750					045	72								
TL	BM20-07	2004	2,280,103	5,744,674	-	1750	048	84												
TL	BM21-01	2004	2,280,122	5,744,678	-	1760					053	64			206	24				
TL	BM21-02	2004	2,280,122	5,744,678	-	1760	045	76			053	60								
TL	BM21-03	2004	2,280,122	5,744,678	-	1760	045	78												
TL	BM21-05	2004	2,280,122	5,744,678	-	1760	048	77									233	21		
TL	BM21-06	2004	2,280,122	5,744,678	-	1760	056	84												
TL	BM22-01	2004	2,280,140	5,744,695	-	1780	053	85	041	75	065	38			216	19				
TL	BM23	2004	2,280,170	5,744,593	-	1810			040	79	062	63			210	24				
TL	BM24-01	2004	2,280,196	5,744,597	-	1830			217	85	202	69			209	20				
TL	BM24-02	2004	2,280,196	5,744,597	-	1830	055	82												
TL	BM25	2004	2,280,302	5,744,523	-	1890	052	80	044	75	128	20			220	22				
TL	BM26	2004	2,280,305	5,744,482	-	1900			225	88	072	39			221	20				
TL	BM27	2004	2,280,320	5,744,472	-	1930			044	78	190	60			212	34				
RW	BM01-01	2004	2,280,390	5,745,031	-	1495	046	84	056	73										
RW	BM01-02	2004	2,280,390	5,745,031	-	1495	048	82												
RW	BM05-01	2004	2,280,956	5,744,858	-	1613	056	78												
RW	BM05-02	2004	2,280,956	5,744,858	-	1613	061	84												
RW	BM05-03	2004	2,280,956	5,744,858	-	1613	240	84												
RW	BM05-04	2004	2,280,956	5,744,858	-	1613	035	87			058	68								
RW	BM05-05	2004	2,280,956	5,744,858	-	1613	253	72												
RW	BM07	2004	2,281,277	5,744,898	-	1745					038	78								
RW	BM09	2004	2,281,304	5,744,565	-	1730			074	66					238	32				
RW	BM11	2004	2,281,162	5,744,633	-	1699	222	86												
RW	BM12-01	2004	2,279,955	5,744,609	-	1728	055	83									231	32		
RW	BM12-02	2004	2,279,955	5,744,609	-	1728	057	82			060	64								
RW	BM13-01	2004	2,279,906	5,744,559	-	1746	235	89												
RW	BM14-01	2004	2,279,922	5,744,478	-	1780	050	78												
RW	BM14-02	2004	2,279,922	5,744,478	-	1780	047	85												

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
RW	BM14-03	2004	2,279,922	5,744,478	-	1780	045	82												
RW	BM15-01	2004	2,279,964	5,744,459	-	1823	239	88												
RW	BM15-02	2004	2,279,964	5,744,459	-	1823	050	82												
RW	BM16-01	2004	2,280,054	5,744,399	-	1877	055	84												
RW	BM16-02	2004	2,280,054	5,744,399	-	1877	225	87												
RW	BM17	2004	2,280,153	5,744,359	-	1940	053	85												
RW	BM18-01	2004	2,279,994	5,744,738	-	1744	231	88	042	77	152	44								
RW	BM18-02	2004	2,279,994	5,744,738	-	1744	045	83												
RW	BM18-03	2004	2,279,994	5,744,738	-	1744	209	84												
RW	BM19-01	2004	2,280,084	5,744,774	-	1761	041	82												
RW	BM19-02	2004	2,280,084	5,744,774	-	1761	240	82												
RW	BM19-03	2004	2,280,084	5,744,774	-	1761	230	88												
RW	BM20-01	2004	2,280,081	5,744,689	-	1737	233	82												
RW	BM20-02	2004	2,280,081	5,744,689	-	1737	041	80												
RW	BM20-03	2004	2,280,081	5,744,689	-	1737	227	78												
RW	BM22-01	2004	2,280,138	5,744,640	-	1773	056	78			076	50								
RW	BM22-02	2004	2,280,138	5,744,640	-	1773	237	88												
RW	BM23	2004	2,280,172	5,744,593	-	1812	048	82	057	70	065	62								
RW	BM24	2004	2,280,207	5,744,569	-	1826	057	90												
RW	BM25-01	2004	2,280,294	5,744,536	-	1887	230	82	026	74										
RW	BM25-02	2004	2,280,294	5,744,536	-	1887	229	87												

Appendix A-3. Structural field data collected on Baumann Glacier. a - geologist collecting the data: MH - Matt Hill, TL - Timothy Little, RW - Ruth Wightman. Collection year and field season (a or b) within that year listed. b - Grid reference is in New Zealand map grid coordinates (metres). c - Accuracy of coordinates measured using a GPS unit ($\pm$ in meters). d - elevation given in meters above mean sea level. Alpine Fol refers to the Alpine Schist foliation and Myl fol refers to the Alpine Schist mylonitic foliation. Lineation subscripts refer to foliations or intersections: L₂₋₃ - intersection lineation between S₂ and S₃, L₄ - mineral fibre lineation decorating S₄ fault surfaces, and L_m - mineral stretching lineation on Alpine Schist mylonite foliation (S_m).

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	HM02-1	2002	2,273,760	5,747,622	-	315							057	34						
MH	HM02-2	2002	2,273,760	5,747,622	-	315							053	46					077	32
MH	HM03-1	2002	2,273,889	5,747,623	-	325							046	39					095	35
MH	HM03-2	2002	2,273,889	5,747,623	-	325							045	37					097	33
MH	HM04-1	2002	2,274,099	5,747,608	-	415							048	28					094	18
MH	HM04-2	2002	2,274,099	5,747,608	-	415							044	26					104	20
MH	HM05-1	2002	2,273,843	5,747,610	-	295							059	27					117	23
MH	HM05-2	2002	2,273,843	5,747,610	-	295							058	33						
MH	HM06-1	2002	2,273,909	5,747,537	-	313							042	30					104	34
MH	HM06-2	2002	2,273,909	5,747,537	-	-							049	29					108	31
MH	HM06-3	2002	2,273,909	5,747,537	-	-													112	24
MH	HM06-4	2002	2,273,909	5,747,537	-	-													101	26
MH	HM07	2002	2,274,011	5,747,467	-	-							043	22					113	27
MH	HM08	2002	2,274,040	5,747,448	-	-							042	31					088	20
TL	2-11	2002	2,273,890	5,747,630	-	-							046	39					095	35
TL	2-12-1	2002	2,274,117	5,747,616	-	-							048	28						
TL	2-12-2	2002	2,274,117	5,747,616	-	-							088	27						
TL	2-12-3	2002	2,274,117	5,747,616	-	-							029	22					092	24
TL	2-13-1	2002	2,273,909	5,747,537	-	-							049	29					033	28
TL	2-13-2	2002	2,273,909	5,747,537	-	-													101	26
TL	2-13-3	2002	2,273,909	5,747,537	-	-													112	24
TL	2-14	2002	2,274,041	5,747,446	-	-							032	37					157	30
TL	2-15	2002	2,274,010	5,747,466	-	-							039	30					092	22
MH	HM01	2004	2,273,722	5,747,569	50	275							061	32						

Appendix A-4. Structural field data collected in Hare Mare Creek. a - geologist collecting the data: MH - Matt Hill, TL - Timothy Little. Collection year and field season (a or b) within that year listed. b - Grid reference is in New Zealand map grid coordinates (metres). c - Accuracy of coordinates measured using a GPS unit ($\pm$ in meters). d - elevation given in meters above mean sea level. Alpine Fol refers to the Alpine Schist foliation and Myl fol refers to the Alpine Schist mylonitic foliation. Lination subscripts refer to foliations or intersections: L₂₋₃ - intersection lineation between S₂ and S₃, L₄ - mineral fibre lineation decorating S₄ fault surfaces, and L_m - mineral stretching lineation on Alpine Schist mylonite foliation (S_m).

Sample Site		Year of coll- ection	Grid reference ^b				Structural plane measured: (right hand rule)								Lineations measured:					
Geol ^a	Field station #		E	N	Ac. ^c	Elevation ^d	B-D shear (S ₄)		Alpine fol. (S ₃)		Alpine fol. (S ₂)		Myl. fol. (S _m)		L ₂₋₃		L ₄		L _m	
							Strike	Dip	Strike	Dip	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge	Trend	Plunge
MH	FJ02	2002	2,280,850	5,749,464	-	231			042	78					211	34				
MH	FJ04	2002	2,280,808	5,748,981	-	222			042	78										
MH	FJ05	2002	2,280,954	5,748,339	-	209			042	72					204	42				
MH	FJ07	2002	2,281,034	5,748,112	-	261			040	83										
MH	FJ08-1	2002	2,281,021	5,748,082	-	274					042	78								
MH	FJ08-2	2002	2,281,021	5,748,082	-	274														
MH	FJ09	2002	2,281,016	5,747,832	-	252			040	76	040	76			199	55				
TL	02-01-01	2002	2,281,061	5,748,126	-	-			038	71					192	52				
TL	02-02	2002	2,281,039	5,748,111	-	-					042	78			212	38				
TL	02-03	2002	2,281,021	5,748,082	-	-					039	87			216	48				
TL	02-04	2002	2,280,954	5,747,997	-	-					042	82			207	62				
TL	02-05	2002	2,281,045	5,747,850	-	-					038	81			204	56				
TL	02-06	2002	2,281,024	5,747,826	-	-					038	75			195	56				
TL	02-07	2002	2,281,065	5,747,761	-	-					039	84			212	51				
TL	02-08	2002	2,281,103	5,747,766	-	-					040	83			212	48				
TL	02-09	2002	2,281,124	5,747,720	-	-					036	81								
TL	02-10	2002	2,281,205	5,747,692	-	-					037	84			207	59				

Appendix A-5. Structural field data collected in Waiho River Valley. a - geologist collecting the data: MH - Matt Hill, TL - Timothy Little. Collection year and field season (a or b) within that year listed. b - Grid reference is in New Zealand map grid coordinates (metres). c - Accuracy of coordinates measured using a GPS unit ($\pm$ in meters). d - elevation given in meters above mean sea level. Alpine Fol refers to the Alpine Schist foliation and Myl fol refers to the Alpine Schist mylonitic foliation. Lination subscripts refer to foliations or intersections: L₂₋₃ - intersection lination between S₂ and S₃, L₄ - mineral fibre lination decorating S₄ fault surfaces, and L_m - mineral stretching lination on Alpine Schist mylonite foliation (S_m).

le-ductile shear survey data.

ns data collected from transects through continuous arrays of spaced
t Chancellor Ridge and Baumann Glacier. Orientation and spacing data
collected from three survey sites at Chancellor Ridge (CH01, CH02 and
site at Baumann Glacier (BM-)). Data for these surveys was measured
glaciated Alpine Schist outcrops and every shear zone visible that
normal transect line was measured. An additional survey (BM-f) was
data collected across the Baumann Glacier field area and combined to
us (not along a continuous transect line) data set.

been assigned a number within the survey for use with the measured data. The data were processed using software by Little (1997) which calculated the shear displacement (net-slip) and the net-slip pitch. This pitch was 30° as determined from the orientations of mineral inclusions deformed along the fault surfaces and piercing points. The net-slip data has been filtered and any nodes with a marker within 5° of the shear plane (within 5° of the net-slip pitch) were removed to avoid trigonometrically unstable net-slip calculations. From the net-slip data, the shear strain has been calculated.

contains:

- B-1. Data collected in the field and calculated net-slip for nodes in Survey CH01.
- B-2. Data collected in the field and calculated net-slip for nodes in Survey CH02.
- B-3. Data collected in the field and calculated net-slip for nodes in Survey CH03.
- B-4. Data collected in the field and calculated net-slip for nodes in Survey CH04.
- B-5. Data collected in the field and calculated net-slip for nodes in Survey CH05.
- B-6. Finite ductile shear strains calculated for nodes at all five survey sites.
- B-7. Finite ductile shear strains calculated for nodes at all five survey sites, and for the shear zones at each site.
- B-8. Plots of the distribution of the markers in the shear zone at each of the five survey sites.
- B-9. Plots of the distribution of the marker veins in the shear zone at each of the five survey sites.
- B-10. Plots of the shear zone samples used for CPO analysis.
- B-11. Plots of ductile deformation characteristics against marker vein thickness for Chancellor Ridge survey sites.

Transect: Chancellor Ridge Survey 1 (CH01)

Survey length: 67.01 m Average finite ductile shear strain: 2.0 $2\sigma = 0.75$
 Nodes: 47 Average shear displacement (net-slip): 5.5 $2\sigma = 1.9$

Location of first node^a: E 2,276,050 N 5,740,450
 Elevation of first node^b: 1132 m
 Bearing of survey line:
 124, 14° Nodes 1-7
 102, 25° Nodes 8-23
 120, 18° Nodes 24-35
 122, 24° Nodes 36-47

Surveyed by: Matt Hill (2003)

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
1	220	85	014	73	0.00	3	9	1.0	4.4	0.32	3.6
2	223	84	196	89	2.73	3	8	0.7	4.2	0.64	4.3
3	213	87	013	72	1.39	2	18	1.4	7.9	0.37	4.9
4	215	88	179	76	1.47	3	6	0.4	3.5	0.14	5.2
5	213	77	186	85	2.50	2	6	0.4	3.4	0.26	2.8
6	218	80	003	72	1.66	3	14	1.5	13.2	0.17	12.0
7	216	85	189	75	2.69	3	12	1.0	9	0.22	13.9
8	210	82	193	82	0.97	1	9	0.4	3.5	0.14	-
9	217	87	-	-	2.05	-	-	-	-	-	-
10	217	87	-	-	2.40	-	-	-	-	-	-
11	219	85	194	76	0.44	3	10	1.3	3.5	0.09	4.5
12	219	84	020	72	3.45	2	2	0.0	4.4	0.00	3.7
13	216	87	191	79	1.07	2	7	0.2	10.5	0.05	13.9
14	220	82	203	89	0.96	5	7	0.4	4.5	0.11	4.5
15	217	82	018	69	1.34	4	3	0.4	4.5	0.11	-
16	216	84	015	68	0.51	3	5	0.5	3.2	0.38	2.3
17	211	87	194	85	0.55	1	4	0.3	3.4	0.26	-
18	212	80	022	68	0.45	4	6	0.5	7.2	0.10	2.1
19	217	80	019	75	0.17	1	5	0.3	4.5	0.07	0.5
20	218	85	026	74	1.33	1	3	0.0	6.6	0.00	-
21	215	84	012	62	0.51	1	4	0.0	1.3	0.00	-
22	222	85	012	78	0.34	2	5	0.8	2.5	0.60	2.3
23	222	86	-	-	0.80	-	-	-	-	-	-
24	217	88	008	70	0.79	1	13	1.1	8.5	0.44	7.5
25	037	88	-	-	3.12	-	-	-	-	-	-
26	035	82	-	-	0.79	-	-	-	-	-	-
27	217	86	-	-	0.72	-	-	-	-	-	-
28	214	88	-	-	1.85	-	-	-	-	-	-
29	028	85	-	-	3.27	-	-	-	-	-	-
30	212	84	-	-	0.46	-	-	-	-	-	-
31	215	88	-	-	0.89	-	-	-	-	-	-
32	214	82	-	-	0.68	-	-	-	-	-	-
33	034	87	-	-	1.02	-	-	-	-	-	-
34	039	75	-	-	0.37	-	-	-	-	-	-
35	215	88	-	-	2.06	-	-	-	-	-	-
36	025	86	-	-	1.05	-	-	-	-	-	-
37	031	85	-	-	2.92	-	-	-	-	-	-
38	032	83	-	-	1.65	-	-	-	-	-	-
39	030	86	-	-	2.11	-	-	-	-	-	-

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
40	212	87	-	-	1.90	-	-	-	-	-	-
41	220	83	015	76	1.76	1	30	0.5	8.8	0.43	7.8
42	220	85	018	78	0.62	4	16	0.9	5.9	0.36	4.7
43	218	82	-	-	0.22	-	-	-	-	-	-
44	216	80	010	70	0.27	3	25	1.3	3.3	0.58	2.3
45	221	86	-	-	0.24	-	-	-	-	-	-
46	220	88	-	-	0.44	-	-	-	-	-	-
47	224	84	-	-	0.58	-	-	-	-	-	-

Appendix B-1. Data collected for Chancellor Ridge structural survey 01(CH01) from an array of shears in the brittle-ductile shear zone (BDSZ). a - Survey location listed in New Zealand Grid coordinates (metres). b - Elevation is in metres above mean sea level. c - marker thickness not listed where the Alpine Foliation was used as the displacement marker (<1 mm thick). d - Ductile / total separation ratio was calculated from the ductile separation of the marker veins and the total measured separation of the vein across the survey (brittle-ductile separation). e - The net-slip (shear displacement) is calculated for a net-slip pitch (displacement vector) of 30° in the fault plane. Net-slip has been filtered for shear zones that have a marker vein that intercepts the shear plane at a pitch that is within 5° of the the net-slip pitch. Shear plane and marker vein orientations are listed in right-hand-rule notation.

Transect: Chancellor Ridge Survey 2 (CH02)

Survey length: 5.1 m Average finite ductile shear strain: 7.6 $2\sigma = 3.7$
 Nodes: 100 Average shear displacement (net-slip): 15.2 $2\sigma = 8.24$

Location of first node^a: E 2,277,114 N 5,740,287

Elevation of first node^b: 1579 m

Bearing of survey line: 120, 15°

Surveyed by: Matt Hill, Ruth Wightman and Kate Wilson (2003)

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
1	207	88	045	77	0.000	1.0	-	0.0	4.5	0.00	13.4
2	212	89	045	77	0.087	1.0	-	0.0	1.2	0.00	5.5
3	212	86	045	77	0.039	1.0	-	0.0	0.5	0.00	3.9
4	211	89	045	77	0.068	1.0	-	0.0	0.3	0.00	1.2
5	214	86	200	88	0.020	1.0	1.0	0.0	1.0	0.00	0.8
6	210	89	040	65	0.058	1.0	2.0	0.2	2.5	0.12	11.5
7	214	85	040	75	0.010	1.0	-	0.0	1.1	0.00	3.7
8	213	88	035	70	0.029	1.0	-	0.1	3.0	0.07	4.5
9	213	88	035	70	0.088	1.0	-	0.0	5.2	0.00	7.9
10	205	88	018	81	0.097	1.0	8.0	0.1	20.0	1.00	-
11	208	89	032	72	0.039	1.0	3.0	0.2	2.1	1.00	4.9
12	210	87	051	69	0.127	1.0	-	0.0	1.2	0.00	6.9
13	214	89	192	86	0.184	2.0	15.0	0.1	30.0	0.27	-
14	204	88	044	77	0.039	0.5	-	0.0	1.9	0.00	5.0
15	209	87	044	77	0.029	1.0	-	0.0	6.0	0.00	26.5
16	211	75	039	70	0.030	0.5	-	0.0	0.4	0.00	1.0
17	207	87	059	71	0.117	0.5	-	0.0	0.4	0.00	1.0
18	214	89	059	71	0.010	1.0	-	0.0	2.8	0.00	8.3
19	218	88	059	71	0.010	0.5	-	0.0	0.2	0.00	0.8
20	215	89	059	71	0.010	1.0	-	0.0	3.4	0.00	10.6
21	213	89	059	71	0.010	0.5	-	0.0	0.7	0.00	2.0
22	210	87	059	71	0.020	1.0	-	0.1	3.0	0.50	8.2
23	209	89	145	52	0.058	1.0	4.0	0.3	1.5	0.60	4.5
24	210	86	037	71	0.039	1.0	4.0	0.0	1.0	0.00	3.2
25	210	87	037	71	0.049	0.5	2.0	0.0	0.8	0.00	2.7
26	216	87	046	70	0.010	0.5	-	0.0	1.5	0.00	9.7
27	212	88	046	70	0.010	0.5	-	0.0	0.2	0.00	-
28	212	88	046	70	0.005	0.5	-	0.0	0.5	0.00	-
29	206	87	039	71	0.034	0.5	-	0.0	0.8	0.00	-
30	212	86	043	75	0.049	1.0	-	0.0	5.0	0.00	-
31	209	89	041	66	0.029	1.0	-	0.0	0.3	0.00	2.4
32	211	88	041	69	0.029	0.5	-	0.0	0.6	0.00	3.8
33	211	87	036	75	0.020	0.5	6.0	0.2	2.0	0.05	5.8
34	210	86	071	54	0.010	0.5	6.0	0.0	2.0	0.00	10.8
35	212	87	102	67	0.010	0.5	6.0	0.0	0.2	0.00	0.3
36	208	85	102	67	0.015	0.5	5.0	0.2	1.8	0.22	3.1
37	211	86	043	68	0.025	0.5	-	0.0	0.5	0.00	3.8
38	213	89	043	68	0.010	0.5	-	0.0	0.3	0.00	1.8
39	218	88	045	69	0.039	4.0	-	0.0	19.0	0.00	58.6
40	208	89	-	-	0.029	0.5	-	-	-	-	-
41	202	89	032	63	0.010	0.5	-	0.0	2.2	0.00	8.4
42	203	88	181	85	0.019	0.5	2.0	0.0	1.2	0.00	1.4

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
43	210	89	030	65	0.107	1.0	1.0	0.0	4.8	0.00	5.1
44	210	87	030	65	0.020	0.5	1.0	0.0	2.6	0.00	2.8
45	208	89	041	66	0.010	0.5	-	0.0	0.3	0.00	-
46	206	88	041	64	0.068	0.5	-	0.0	2.5	0.00	-
47	207	88	041	64	0.019	1.0	-	0.0	0.3	0.00	-
48	211	89	041	64	0.019	3.0	-	0.0	13.0	0.00	52.8
49	209	89	061	66	0.068	1.0	3.0	0.2	6.0	0.08	18.2
50	212	89	061	66	0.010	0.5	3.0	0.1	0.7	0.29	2.4
51	027	79	041	62	0.081	1.0	-	0.2	10.5	0.03	10.7
52	212	89	041	66	0.039	0.5	-	0.0	0.2	0.00	0.8
53	210	89	039	64	0.019	0.5	-	0.0	1.1	0.00	3.8
54	033	82	039	64	0.018	1.0	-	0.2	2.0	0.15	2.0
55	219	89	039	64	0.019	0.5	-	0.0	0.8	0.00	0.8
56	030	84	039	64	0.028	0.5	-	0.0	0.3	0.00	0.3
57	212	87	042	69	0.020	2.0	-	0.0	1.5	0.00	8.5
58	214	80	042	69	0.080	0.5	-	0.0	0.2	0.00	0.5
59	213	84	044	60	0.030	5.0	-	0.0	18.0	0.00	54.3
60	217	89	044	60	0.077	1.0	-	0.0	0.6	0.00	1.3
61	209	88	186	81	0.058	0.5	10.0	0.5	3.0	0.33	4.3
62	207	89	045	67	0.034	0.5	-	0.0	1.0	0.00	-
63	221	87	040	61	0.053	0.5	-	0.0	0.2	0.00	0.2
64	204	89	063	52	0.164	1.0	5.0	0.3	0.6	1.00	4.0
65	207	82	265	80	0.030	1.0	5.0	0.3	1.2	0.83	0.9
66	213	88	045	62	0.068	0.5	-	0.0	0.9	0.00	4.5
67	209	88	059	65	0.078	1.0	8.0	0.5	7.5	0.07	28.4
68	215	82	278	85	0.010	1.0	3.0	0.0	1.0	0.00	0.9
69	208	85	236	78	0.049	1.0	12.0	0.0	1.4	0.00	0.8
70	209	86	043	61	0.098	10.0	-	0.0	6.0	0.00	33.3
71	211	87	324	66	0.098	0.5	8.0	0.4	1.2	1.00	0.6
72	210	85	038	67	0.010	1.0	5.0	0.1	2.5	0.20	7.7
73	206	89	057	78	0.261	1.0	12.0	0.3	0.4	1.00	0.7
74	209	84	196	78	0.119	1.0	12.0	1.0	7.5	1.00	13.2
75	206	86	043	62	0.029	1.0	9.0	0.5	3.0	1.00	-
76	212	86	043	62	0.020	1.0	9.0	0.3	4.5	0.44	16.8
77	210	88	041	65	0.136	1.0	8.0	0.2	2.5	0.04	13.1
78	208	88	045	63	0.049	1.0	-	0.0	0.8	0.00	-
79	208	89	040	68	0.053	0.5	-	0.0	0.4	0.00	-
80	207	89	040	68	0.005	0.5	-	0.0	0.4	0.00	-
81	205	88	040	68	0.005	0.5	-	0.0	0.5	0.00	-
82	210	86	032	63	0.142	0.5	1.5	0.1	1.2	0.50	1.7
83	209	86	040	69	0.010	1.0	-	0.0	1.3	0.00	9.0
84	210	88	039	64	0.068	2.0	-	0.0	3.0	0.00	10.3
85	214	84	031	68	0.197	1.0	3.0	0.2	1.8	0.06	1.5
86	210	88	031	68	0.019	1.0	10.0	0.5	5.0	0.16	6.6
87	020	76	037	40	0.052	0.5	5.0	0.3	1.1	0.64	1.2
88	212	84	230	77	0.049	3.0	2.0	0.4	32.0	0.03	16.8
89	209	89	020	58	0.029	0.5	-	0.0	2.5	0.00	1.3
90	207	89	020	58	0.078	1.0	-	0.0	20.0	0.00	12.9
91	212	88	-	-	0.078	30.0	-	-	-	-	-
92	030	67	046	61	0.063	1.0	-	0.0	5.0	0.00	5.0
93	208	89	038	67	0.087	2.0	-	0.0	32.0	0.00	181.0
94	210	88	060	66	0.029	5.0	5.0	0.6	2.2	0.09	6.8

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule) Strike	(right hand rule) Dip	(right hand rule) Strike	(right hand rule) Dip		Infilling vein (mm)	Marker (mm) ^c				
95	209	87	002	75	0.020	2.0	3.0	0.0	3.3	0.00	2.2
96	210	87	034	70	0.039	1.0	-	0.0	2.8	0.00	6.7
97	208	85	038	71	0.039	10.0	-	0.0	26.0	0.00	177.2
98	207	82	038	71	0.050	2.0	-	0.0	34.0	0.00	225.4
99	212	88	034	65	0.029	15.0	-	0.0	22.0	0.00	38.9
100	217	88	014	62	0.019	1.0	2.0	0.3	0.3	0.67	-

Appendix B-2. Data collected for Chancellor Ridge structural survey 02 (CH02) from an array of shears in the brittle-ductile shear zone (BDSZ). a - Survey location listed in New Zealand Grid coordinates (metres). b - Elevation is in metres above mean sea level. c - marker thickness not listed where the Alpine Foliation was used as the displacement marker (<1 mm thick). d - Ductile / total separation ratio was calculated from the ductile separation of the marker veins and the total measured separation of the vein across the survey (brittle-ductile separation). e - The net-slip (shear displacement) is calculated for a net-slip pitch (displacement vector) of 30° in the fault plane. Net-slip has been filtered for shear zones that have a marker vein that intercepts the shear plane at a pitch that is within 5° of the net-slip pitch. Shear plane and marker vein orientations are listed in right-hand-rule notation.

Transect: Chancellor Ridge Survey 3 (CH03)

Survey length: 27.11 m Average finite ductile shear strain: 3.9 $2\sigma = 1.2$
 Nodes: 155 Average shear displacement (net-slip): 8.9 $2\sigma = 2.8$

Location of first node^a: E 2,277,232 N 5,740,212

Elevation of first node^b: 1636 m

Bearing of survey line: 129, 32°

Surveyed by: Matt Hill, Ruth Wightman and Kate Wilson (2003)

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
1	212	89	235	80	0.000	7.0	9.0	1.2	16.5	0.42	10.5
2	216	89	050	76	0.102	1.0	-	0.0	8.5	0.00	24.3
3	033	80	045	71	0.052	5.0	12.0	2.0	20.0	0.20	41.2
4	219	87	042	63	0.173	1.0	-	0.0	2.5	0.96	3.2
5	220	87	042	63	0.030	1.0	-	0.0	0.5	0.00	0.6
6	223	86	042	63	0.013	2.0	-	0.0	0.5	0.00	0.4
7	222	87	050	55	0.068	3.0	-	0.0	0.5	0.00	0.9
8	216	86	050	55	0.079	0.5	-	0.0	1.0	0.00	3.3
9	217	80	050	55	0.046	1.0	-	0.3	4.0	0.05	10.6
10	218	81	043	48	0.100	2.0	-	0.0	0.5	0.00	0.5
11	216	82	043	48	0.064	2.0	-	0.3	0.5	0.40	0.6
12	215	88	051	53	0.026	0.5	-	0.0	0.7	0.00	2.5
13	220	84	062	54	0.062	1.0	-	0.0	2.0	0.00	-
14	220	87	062	54	0.009	5.0	-	0.0	1.3	0.00	-
15	217	88	050	53	0.052	2.0	-	0.0	3.0	0.00	73.5
16	035	86	210	85	0.089	1.0	30.0	0.0	1.8	0.00	-
17	037	86	210	85	0.032	2.0	26.0	0.4	0.8	0.25	4.9
18	218	80	032	50	0.064	2.0	2.0	0.0	0.9	0.00	0.6
19	217	82	055	50	0.054	2.0	2.0	0.0	1.5	0.00	5.1
20	212	85	056	57	0.045	1.0	1.0	0.2	0.5	0.60	-
21	216	84	052	58	0.009	0.5	2.0	0.3	2.4	0.38	11.4
22	035	82	230	85	0.038	0.5	3.0	0.3	6.2	0.11	2.7
23	039	82	230	85	0.008	1.5	3.0	0.7	5.0	0.50	1.7
24	039	85	190	79	0.039	1.5	3.0	0.0	2.0	0.00	3.9
25	220	83	222	80	0.080	2.0	30.0	1.5	22.0	0.41	-
26	214	85	012	73	0.098	1.0	4.0	0.7	5.3	0.75	1.6
27	215	80	240	77	0.139	2.0	4.0	0.4	6.7	0.16	6.0
28	217	76	058	72	0.047	2.0	2.0	0.0	0.3	0.00	-
29	222	82	058	72	0.063	2.0	3.0	0.0	0.5	0.00	-
30	216	88	058	72	0.078	18.0	-	-	-	-	-
31	217	80	041	53	0.064	2.0	3.0	0.4	2.6	0.31	0.0
32	040	62	068	73	0.029	0.5	2.0	0.1	2.5	0.12	2.5
33	034	66	068	73	0.017	0.5	-	-	-	-	-
34	217	80	043	76	0.101	0.5	7.0	0.3	21.5	0.02	12.5
35	038	64	359	82	0.110	2.0	1.0	0.0	21.5	0.00	30.0
36	041	72	032	70	0.025	1.0	1.0	0.0	0.3	0.00	0.3
37	215	82	039	72	0.182	1.0	6.0	0.5	6.5	0.38	1.5
38	219	88	180	82	0.051	0.5	15.0	0.3	16.5	0.03	-
39	221	85	180	82	0.070	2.0	15.0	1.0	8.0	0.75	-
40	224	83	069	67	0.071	1.0	2.0	0.3	1.5	0.60	7.4
41	219	81	230	82	0.564	1.0	5.0	0.0	1.5	0.00	-
42	220	84	230	82	0.009	1.0	2.0	0.2	4.5	0.22	4.7

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
43	223	87	051	58	0.077	1.5	5.0	0.4	1.7	0.18	1.8
44	041	67	018	63	0.073	2.0	1.0	0.0	1.0	0.00	1.0
45	219	83	018	63	0.072	1.0	1.0	0.0	0.5	0.00	-
46	036	64	210	87	0.184	2.0	1.5	0.0	1.2	0.00	1.1
47	215	89	176	73	0.060	1.0	8.0	0.4	0.2	1.00	0.3
48	220	86	211	75	0.462	0.5	2.0	0.0	0.6	0.00	3.1
49	236	77	165	57	0.059	1.0	6.0	0.2	1.8	0.33	3.6
50	229	81	240	79	0.219	1.0	3.0	0.0	9.0	0.00	8.8
51	042	82	052	74	0.404	1.0	1.0	0.3	0.2	1.00	0.5
52	222	89	231	76	0.117	1.0	7.0	0.6	10.5	0.14	-
53	210	83	040	63	0.100	0.5	1.0	0.0	0.7	0.00	1.2
54	212	86	224	88	0.053	0.5	4.0	0.4	1.4	0.07	1.8
55	032	62	224	56	0.020	0.5	1.0	0.2	1.6	0.19	0.1
56	040	72	085	70	0.013	1.0	-	0.2	0.3	1.00	0.4
57	031	71	085	70	0.019	0.5	5.0	0.0	1.0	0.00	1.3
58	214	84	240	83	0.009	0.5	3.0	0.0	2.0	0.00	2.2
59	215	82	106	55	0.009	1.0	3.0	0.3	2.7	0.26	5.9
60	214	88	332	78	0.242	1.0	16.0	0.7	13.0	0.35	12.9
61	218	85	222	88	0.185	5.0	4.0	0.0	3.0	0.00	6.5
62	220	83	241	87	0.268	1.0	2.0	0.4	0.5	1.00	0.6
63	242	87	154	82	0.067	1.0	3.0	0.3	0.6	0.50	0.8
64	212	84	040	51	0.045	0.5	1.0	0.0	0.6	0.00	0.7
65	215	80	045	68	0.111	3.0	4.0	0.6	0.3	1.00	0.7
66	212	82	052	67	0.100	15.0	10.0	1.8	18.5	0.57	-
67	214	84	043	64	0.072	1.0	2.0	0.4	0.2	1.00	0.1
68	213	82	043	64	0.009	0.5	2.0	0.3	0.1	1.00	0.1
69	210	86	198	88	0.009	4.0	1.0	0.0	0.5	0.00	0.5
70	221	85	011	52	0.035	10.0	5.0	1.2	3.0	0.33	-
71	224	88	059	74	0.059	1.0	8.0	0.0	0.2	0.00	0.8
72	041	64	206	79	0.046	0.5	7.0	0.5	4.0	0.18	9.9
73	214	88	206	79	0.017	0.5	10.0	0.0	0.5	0.00	1.5
74	213	87	206	79	0.017	1.0	10.0	0.0	2.3	0.00	7.2
75	213	83	230	80	0.136	1.0	3.0	0.0	1.1	0.00	1.2
76	215	85	232	82	0.213	2.0	1.0	0.3	0.7	0.14	0.7
77	040	65	234	78	0.011	1.0	3.0	0.0	3.8	0.00	2.7
78	218	88	010	45	0.257	2.0	2.0	0.0	2.0	0.00	1.8
79	215	80	226	87	0.166	4.0	3.0	1.0	13.5	0.22	25.1
80	217	76	232	82	0.482	15.0	7.0	2.0	23.0	0.15	36.1
81	216	82	346	68	0.200	1.0	10.0	1.5	7.0	1.00	4.7
82	212	82	254	80	0.420	0.5	7.0	0.5	6.8	0.35	6.6
83	217	85	260	77	0.451	6.0	4.0	0.7	10.5	0.10	8.0
84	214	81	050	63	0.312	1.0	-	0.0	1.7	0.00	8.0
85	216	78	223	80	0.355	3.0	4.0	0.4	4.5	0.11	6.3
86	216	79	339	63	0.195	1.0	17.0	0.7	5.7	1.00	5.0
87	214	83	228	80	0.045	1.0	5.0	0.6	6.0	0.75	6.2
88	213	85	224	84	0.027	1.0	1.0	0.0	5.0	0.00	5.5
89	214	88	043	55	0.069	2.0	24.0	1.5	11.0	0.18	21.1
90	215	88	043	55	0.190	0.5	13.0	1.2	2.5	0.12	3.7
91	212	83	225	75	0.208	0.5	7.0	0.5	3.0	0.60	2.6
92	215	80	225	75	0.046	11.0	10.0	1.3	5.5	0.27	5.0
93	032	68	352	62	0.082	1.0	7.0	0.4	0.4	1.00	0.4
94	032	82	352	62	0.011	1.0	5.0	0.3	0.3	1.00	0.3

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
95	212	80	322	71	0.246	0.5	6.0	0.0	0.3	0.00	0.3
96	218	84	263	84	0.151	3.0	3.0	0.0	8.0	0.00	8.3
97	217	78	133	78	0.056	0.5	6.0	0.2	0.8	0.50	0.8
98	214	82	133	78	0.046	0.5	6.0	0.3	1.7	0.82	1.9
99	220	86	028	68	0.122	1.0	3.0	0.2	0.4	0.50	0.1
100	218	84	255	60	0.027	1.0	6.0	0.6	2.4	0.63	1.7
101	217	82	018	72	0.318	2.0	6.0	1.1	32	0.44	17.1
102	210	86	231	76	0.009	0.5	1.0	0.0	2.5	0.00	2.1
103	213	80	223	80	0.009	2.0	4.0	0.0	6	0.00	6.8
104	219	78	230	78	0.014	0.5	13.0	0.6	11	0.35	12.5
105	212	82	222	78	0.123	2.0	12.0	1.5	15.5	0.68	13.5
106	214	82	347	52	0.155	0.5	5.0	0.4	11.2	0.12	8.4
107	214	85	038	60	0.142	1.0	-	0.0	8.5	0.00	10.2
108	212	78	038	60	0.009	0.5	-	0.0	0.9	0.00	1.4
109	208	87	038	60	0.009	1.0	-	0.0	1.9	0.00	5.1
110	210	88	038	60	0.104	2.0	1.0	0.5	13	0.08	28.7
111	212	82	332	61	0.091	8.0	6.0	1.0	4	0.25	0.0
112	213	84	054	55	0.018	1.0	-	0.0	5.5	0.00	45.4
113	216	87	355	69	0.052	1.0	13.0	0.7	14.5	0.14	12.2
114	215	84	011	64	0.251	1.0	6.0	1.2	9	0.78	-
115	218	83	056	57	0.799	0.5	-	0.0	0.8	0.00	2.8
116	210	87	338	64	0.087	1.0	7.0	3.0	1.5	0.67	1.1
117	219	84	210	85	0.302	2.0	5.0	0.0	7.4	0.00	8.1
118	223	82	021	88	0.161	2.0	2.0	0.0	0.4	0.00	0.4
119	227	85	230	63	0.043	1.0	6.0	0.6	1.2	1.00	1.0
120	040	65	059	60	0.442	2.0	4.0	0.4	8	0.38	12.4
121	213	89	229	84	0.094	0.5	2.0	0.3	0.7	1.00	0.7
122	214	80	048	79	0.111	1.0	2.0	0.0	9.6	0.00	-
123	210	79	039	70	0.252	0.5	3.0	0.0	1.5	0.00	5.2
124	036	74	053	58	0.392	1.0	-	0.0	24	0.00	97.6
125	223	82	056	65	0.419	1.0	3.0	0.0	13	0.00	41.6
126	216	81	079	59	0.284	2.0	1.0	4.0	35	0.09	100.8
127	211	86	125	64	0.309	1.0	6.0	0.0	1	0.00	1.8
128	212	88	052	64	0.069	1.0	12.0	0.0	2.8	0.00	-
129	213	81	222	89	0.110	1.0	2.0	0.4	1.8	0.83	4.1
130	217	82	205	71	0.245	0.5	2.0	0.3	6	0.22	14.9
131	218	85	016	71	0.110	1.0	7.0	0.5	8.5	0.65	6.4
132	220	85	163	69	0.022	1.0	15.0	0.4	3.8	0.53	5.5
133	036	85	059	70	0.238	0.5	22.0	0.4	0.2	1.00	0.3
134	217	76	196	68	0.558	1.0	11.0	0.8	1.5	0.47	1.4
135	202	75	120	52	0.266	0.5	17.0	0.0	1.5	0.00	3.0
136	212	81	296	54	0.405	3.0	14.0	1.2	2	1.00	2.0
137	204	88	250	79	0.284	1.0	4.0	0.0	0.8	0.00	0.8
138	216	81	186	76	0.092	1.0	3.0	5.0	4	1.00	5.4
139	219	79	152	83	0.314	2.0	3.0	0.0	2	0.00	2.2
140	208	89	328	67	0.540	1.0	20.0	1.5	13	0.62	11.6
141	210	82	062	67	0.658	1.0	10.0	0.6	26	0.33	66.1
142	215	87	053	66	0.366	3.0	7.0	1.0	14.5	0.34	-
143	209	84	098	45	0.306	1.0	4.0	0.0	3	0.33	5.4
144	217	85	098	45	0.283	50.0	-	-	-	-	-
145	212	83	189	83	0.172	2.0	5.0	0.5	8.5	0.12	9.9
146	210	79	192	72	0.084	2.0	13.0	1.0	8.5	0.24	13.2

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
147	215	85	344	77	0.160	0.5	10.0	0.6	4.5	0.62	4.5
148	210	82	249	46	0.375	1.0	12.0	0.9	15	0.27	14.7
149	211	77	181	83	0.425	1.0	4.0	0.0	11.4	0.00	11.5
150	206	85	181	83	0.027	1.0	4.0	0.0	23	0.00	25.7
151	205	82	202	79	0.036	2.0	3.0	0.6	4.8	1.00	8.2
152	208	77	329	58	0.019	1.0	3.0	0.5	7.6	0.07	7.5
153	205	76	329	58	0.645	3.0	-	-	-	-	-
154	212	78	329	58	0.244	30.0	-	-	-	-	-
155	222	85	245	88	0.524	2.0	8.0	1.1	3.2	0.88	-

Appendix B-3. Data collected for Chancellor Ridge structural survey 03 (CH03) from an array of shears in the brittle-ductile shear zone (BDSZ). a - Survey location listed in New Zealand Grid coordinates (metres). b - Elevation is in metres above mean sea level. c - marker thickness not listed where the Alpine Foliation was used as the displacement marker (<1 mm thick). d - Ductile / total separation ratio was calculated from the ductile separation of the marker veins and the total measured separation of the vein across the survey (brittle-ductile separation). e - The net-slip (shear displacement) is calculated for a net-slip pitch (displacement vector) of 30° in the fault plane. Net-slip has been filtered for shear zones that have a marker vein that intercepts the shear plane at a pitch that is within 5° of the net-slip pitch. Shear plane and marker vein orientations are listed in right-hand-rule notation.

Transect: Baumann Glacier Survey 1 (BM01)

Survey length: 19.54 Average finite ductile shear strain: 5.5 $2\sigma = 1.1$
 Nodes: 111 Average shear displacement (net-slip): 11.3 $2\sigma = 2.8$

Location of first node^a: E 2,280,123 N 5,744,672
 Elevation of first node^b: 1740 m
 Bearing of survey line:
 312, 23° Nodes 1-34
 330, 26° Nodes 35-56
 320, 17° Nodes 57-86
 324, 68° Nodes 87-109

Surveyed by: Tim Little, Julie Vry, Ruth Wightman and Matt Hill (2004)

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
0	044	73	063	62	0.000	-	5.0	0.0	3.0	0.00	6.2
1	046	80	345	80	0.389	-	17.0	0.6	4.0	0.35	4.3
2	229	88	018	66	0.081	-	12.0	3.0	8.3	0.34	6.1
3	039	70	175	69	0.170	-	15.0	0.3	2.7	0.78	6.9
4	047	66	175	69	0.040	-	15.0	0.3	2.0	0.50	4.3
5	052	69	175	69	0.039	-	10.0	0.2	2.7	0.07	5.0
6	049	70	182	81	0.317	-	4.0	0.2	7.2	0.03	12.1
7	048	78	175	80	0.176	-	20.0	0.5	46.5	0.16	-
8	042	80	175	80	0.117	1.0	25.0	1.8	7.5	1.00	11.6
9	049	80	071	60	0.261	-	5.0	0.3	1.2	0.67	3.8
10	046	74	023	79	0.040	2.0	4.0	0.4	18.5	0.03	-
11	049	78	195	84	0.117	-	2.0	0.0	1.0	0.00	1.6
12	045	84	014	77	0.115	-	5.0	1.0	72.0	0.04	70.3
13	050	80	024	80	0.251	-	15.0	2.0	6.0	0.33	6.5
14	050	82	338	88	0.057	5.0	10.0	1.0	5.0	1.00	5.4
15	050	80	027	83	0.174	-	15.0	0.8	4.5	1.00	-
16	054	77	018	80	0.222	-	5.0	1.0	2.5	1.00	2.7
17	049	79	017	75	0.408	-	2.0	0.2	1.5	0.67	1.6
18	045	78	062	66	0.373	0.5	4.0	0.0	5.4	0.00	9.2
19	049	73	198	81	0.030	1.0	6.0	1.0	9.0	0.28	13.9
20	045	79	007	74	0.117	0.5	12.0	0.2	6.5	0.08	6.8
21	047	78	204	89	0.166	5.0	4.0	0.3	49.0	0.01	66.9
22	045	80	197	80	0.039	-	8.0	0.5	13.0	0.27	20.1
23	042	79	312	77	0.049	1.0	15.0	1.5	18.0	0.39	18.8
24	050	79	066	62	0.194	4.0	2.0	0.0	23.5	0.02	50.7
25	047	74	150	82	0.673	0.5	13.0	0.9	2.5	1.00	3.0
27	053	77	334	80	0.339	-	2.0	0.4	4.8	1.00	5.0
28	048	70	170	80	0.020	-	7.0	0.7	3.5	1.00	4.5
29	051	76	345	71	0.039	-	15.0	0.6	10.0	0.40	10.3
30	048	77	335	76	0.020	-	20.0	1.5	17	0.09	17.9
32	050	79	335	76	0.087	0.5	17.5	3.8	14.0	0.25	14.6
33	051	82	176	80	0.038	0.5	10.0	1.0	6.0	0.58	6.9
34	045	72	087	62	0.040	1.0	20.0	2.0	25	0.12	33.6
35	233	87	102	71	0.026	0.5	4.0	1.0	3.0	0.67	5.0
36	055	79	020	64	0.067	1.0	7.0	0.6	3.3	0.94	2.8
37	051	72	014	74	0.118	-	8.0	0.0	3.3	0.00	3.7
38	231	72	200	71	0.071	0.5	25.0	1.5	16.5	0.21	-
39	055	75	215	70	0.078	0.5	4.0	1.3	8.0	0.20	-
40	233	87	195	63	0.017	0.5	9.0	0.5	8.5	0.29	18.3

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
41	042	74	207	78	0.688	0.5	13.0	1.8	9.0	0.44	-
42	055	72	190	82	0.059	1.0	6.0	0.8	6.0	0.33	9.9
43	232	81	167	66	0.130	-	8.0	0.6	3.8	0.47	5.9
44	231	86	-	-	0.026	-	-	-	-	-	-
45	230	84	-	-	0.292	-	-	-	-	-	-
46	231	70	206	70	0.089	1.0	8.0	1.2	9.5	0.53	-
47	228	77	190	70	0.364	-	2.0	0.1	5.6	0.05	7.8
48	234	84	210	74	0.295	1.0	4.0	0.8	2.0	1.00	3.1
49	229	78	210	74	0.046	1.0	3.0	1.5	5.0	1.00	6.8
50	229	86	-	-	0.076	-	-	-	-	-	-
51	223	89	202	81	0.102	2.0	2.0	0.4	4.0	0.38	6.1
52	051	76	196	64	0.803	0.5	14.0	1.5	16.7	0.10	62.2
53	051	79	-	-	0.124	3.0	-	-	-	-	-
54	231	64	355	56	0.012	0.5	5.0	0.3	3.5	0.29	3.2
55	231	68	344	60	0.138	0.5	5.0	0.7	2.5	1.00	2.4
56	225	69	344	60	0.013	1.0	5.0	0.4	1.3	1.00	1.2
57	042	83	-	-	0.302	-	-	-	-	-	-
58	039	81	301	71	0.156	-	10.0	0.8	5.0	0.40	4.3
59	042	82	192	83	0.039	-	6.0	1.0	6.0	1.00	10.4
60	053	71	007	68	0.020	-	7.0	0.0	3.0	0.00	2.9
61	048	80	012	62	0.149	-	8.0	0.8	5.0	0.40	3.6
62	043	79	012	62	0.030	-	20.0	0.0	10.0	0.00	6.9
63	046	70	358	68	0.379	-	5.0	0.0	2.0	0.00	1.9
64	044	76	358	68	0.010	-	3.0	0.2	1.0	1.00	0.9
65	229	84	166	62	0.405	-	6.0	0.8	7.0	0.29	12.8
66	042	73	181	80	0.020	-	10.0	1.0	2.5	1.00	4.8
67	043	76	181	80	0.030	-	10.0	0.3	3.5	0.80	6.3
68	044	78	181	80	0.010	-	5.0	0.0	0.7	0.00	1.2
69	233	83	178	74	0.055	1.0	10.0	0.6	1.5	1.00	2.1
70	047	75	198	80	0.459	0.5	13.0	0.0	10.5	0.00	26.2
71	046	88	032	88	0.125	1.5	20.0	3.0	8.5	0.76	9.6
72	049	74	-	-	0.270	-	-	-	-	-	-
73	052	74	297	61	0.380	1.0	20.0	2.3	9.5	0.68	6.7
74	043	80	-	-	0.374	5.0	-	-	-	-	-
75a	232	85	303	89	0.213	-	14.0	1.2	9.0	1.00	10.3
75b	047	77	350	68	0.219	5.0	17.0	0.0	40.0	0.00	35.8
76	044	70	305	84	0.030	0.5	14.0	0.5	9.0	0.22	9.1
77	233	87	343	78	0.056	1.0	3.0	0.4	7.8	0.38	7.5
78	222	77	-	-	0.103	-	-	-	-	-	-
79	048	69	312	88	0.309	1.0	7.0	0.4	9.8	0.18	10.6
80	045	68	058	70	0.109	7.0	6.0	0.0	33.5	0.00	34.6
83	050	74	187	80	0.050	1.0	2.0	0.0	3.7	0.00	6.7
84	043	77	-	-	0.050	-	-	-	-	-	-
85	051	73	-	-	0.230	10.0	-	-	-	-	-
86	051	70	282	78	0.180	-	15.0	0.6	3.0	1.00	2.4
87	048	83	339	80	0.082	5.0	12.0	1.1	7.7	0.48	7.6
88	049	82	332	72	0.030	2.0	10.0	0.6	3.5	1.00	3.6
89	048	87	081	78	0.172	4.0	25.0	3.0	7.4	1.00	10.3
90	046	88	059	76	0.153	-	15.0	1.3	7.5	0.53	26.7
91	054	88	290	85	0.207	0.5	13.0	5.0	11.0	0.05	11.9
92	225	81	082	80	0.046	1.0	8.0	7.0	13.0	1.00	20.9
93	055	78	122	70	0.095	2.0	10.0	1.4	6.0	1.00	8.3

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
94	047	81	090	82	0.072	0.5	10.0	1.0	13.0	0.08	-
95	051	84	055	72	0.117	-	8.0	1.3	4.3	1.00	15.0
96	052	86	074	69	0.123	0.5	10.0	1.0	5.0	0.60	11.2
97	045	78	001	87	0.244	3.0	5.0	1.5	32.5	0.09	-
98	049	79	167	45	0.212	-	13.0	1.5	6.0	1.00	23.2
99b	048	78	173	82	0.006	-	20.0	0.4	3.5	0.14	5.1
99a	053	84	332	78	0.028	1.0	10.0	0.8	5.0	0.60	4.8
100	050	79	332	78	0.016	-	20.0	0.2	11.0	0.05	10.7
101a	050	79	129	48	0.076	1.0	20.0	0.5	2.5	1.00	6.8
101b	042	76	108	60	0.035	-	20.0	0.6	7.5	0.20	13.5
102a	049	75	154	61	0.096	-	8.0	0.0	2	0.00	4.1
102b	045	82	005	81	0.005	2.0	25.0	2.4	8	1.00	7.5
103	044	80	005	81	0.147	1.0	35.0	1.0	6	1.00	5.9
104	050	55	193	80	0.042	0.5	7.0	0.5	6	1.00	15.0
105	051	85	022	79	0.082	0.5	5.0	0.4	3	1.00	2.2
106a	044	87	192	79	0.042	1.0	13	0.7	2.5	1.00	3.9
106b	047	86	192	79	0.013	0.5	13	0.7	3	0.67	4.7
107	048	72	062	67	0.096	0.5	5	0.0	2	0.00	2.3
108	050	89	065	78	0.062	2.0	10.0	0.0	5.5	0.00	14.1
109	050	85	183	89	0.145	2.0	3.0	0.4	4.7	1.00	-

Appendix B-4. Data collected for Baumann Glacier structural survey 01 (BM01) from an array of shears in the brittle-ductile shear zone (BDSZ). a - Survey location listed in New Zealand Grid coordinates (metres). b - Elevation is in metres above mean sea level. c - marker thickness not listed where the Alpine Foliation was used as the displacement marker (<1 mm thick). d - Ductile / total separation ratio was calculated from the ductile separation of the marker veins and the total measured separation of the vein across the survey (brittle-ductile separation). e - The net-slip (shear displacement) is calculated for a net-slip pitch (displacement vector) of 30° in the fault plane. Net-slip has been filtered for shear zones that have a marker vein that intercepts the shear plane at a pitch that is within 5° of the net-slip pitch. Shear plane and marker vein orientations are listed in right-hand-rule notation.

Transect: Baumann Glacier Field Surveys (BM-f)

Survey length: - Average finite ductile shear strain: 4.9 $2\sigma = 1.4$
 Nodes: 22 Average shear displacement (net-slip): 13.5 $2\sigma = 4.4$

Location of first node^a:

Elevation of first node^b:

Bearing of survey line:

Surveyed by: Matt Hill (2004)

Varied shear locations where node = field station number from Appendix 1.
 This data was collected from individual and small arrays of brittle-ductile shears
 found in the Baumann Glacier brittle-ductile shear zone.

Node	Shear plane		Marker plane		Spacing from adjacent shear plane (m)	Thickness of:		Ductile deformation width (cm)	Total separation (cm)	Ductile/total separation ratio ^d	Calculated net slip (cm) ^e
	(right hand rule)		(right hand rule)			Infilling vein (mm)	Marker (mm) ^c				
	Strike	Dip	Strike	Dip							
BM01	062	74	194	86	-	-	8.0	2.0	25.5	0.24	36.6
BM03	046	70	192	82	-	-	8.0	1.0	4.5	0.22	9.1
BM04	036	72	102	86	-	-	10.0	1.0	12.0	0.08	7.2
BM05	054	72	078	78	-	5.0	9.0	4.0	28.5	0.46	29.5
BM12a	044	74	027	84	-	4.0	12.0	1.4	13.0	0.58	22.7
BM12b	048	86	201	71	-	1.0	11.0	1.8	10.0	0.60	24.4
BM13	043	76	195	75	-	-	6.0	1.0	12.0	0.25	20.2
BM15	049	78	180	64	-	-	10.0	1.5	4.0	1.00	8.6
BM16a	052	70	028	64	-	-	5.0	1.0	6.8	0.66	6.4
BM16b	048	74	028	64	0.090	-	5.0	0.6	7.0	0.36	5.7
BM16c	045	70	196	84	-	2.0	10.0	0.8	14.0	0.21	23.8
BM17a	046	73	004	62	-	-	18.0	1.2	4.2	0.76	3.7
BM17b	231	88	198	74	-	-	14.0	1.6	6.2	1.00	10.8
BM17c	053	86	198	74	0.088	-	5.0	0.5	3.3	1.00	6.6
BM18a	050	76	198	70	-	1.0	7.0	1.0	20.5	0.14	26.7
BM18b	050	76	210	74	-	1.0	5.0	0.8	7.5	0.40	-
BM18c	050	76	202	84	-	1.0	3.0	0.5	9.5	0.11	10.9
BM19	058	78	196	88	-	-	9.0	1.0	6.5	0.51	4.0
BM20a	048	70	025	83	-	-	9.0	1.6	8.0	1.00	14.7
BM20b	049	88	025	83	0.085	-	9.0	1.4	2.0	1.00	1.7
BM22a	047	73	354	75	-	-	8.0	0.8	4.7	0.85	5.1
BM22b	047	73	007	65	0.160	-	10.0	0.7	4.5	0.56	4.4

Appendix B-5. Data collected for Baumann Glacier structural survey 2 (BM-f) from shear zones in the brittle-ductile shear zone (BDSZ). a - Survey location listed in New Zealand Grid coordinates (metres). b - Elevation is in metres above mean sea level. c - marker thickness not listed where the Alpine Foliation was used as the displacement marker (<1 mm thick). d - Ductile / total separation ratio was calculated from the ductile separation of the marker veins and the total measured separation of the vein across the survey (brittle-ductile separation). e - The net-slip (shear displacement) is calculated for a net-slip pitch (displacement vector) of 30° in the fault plane. Net-slip has been filtered for shear zones that have a marker vein that intercepts the shear plane at a pitch that is within 5° of the net-slip pitch. Shear plane and marker vein orientations are listed in right-hand-rule notation. This data is an augmented data set created from individual shear zone measurements across the Baumann Glacier field area and not from a continuous transect line. Node number refer to field sites in Appendix A.

Appendix B-6. Histogram plots of finite ductile shear strain calculated from transect survey data at Chancellor Ridge. Shear strains are calculated from a shear displacement with a net-slip pitch of 30° from the southwest. Where not data is present, the node may have been brittlely offset, a marker may not have been present, or the data may have been filtered from the survey (filtering of any nodes which had an intersection of the shear and marker planes $\pm 5^\circ$ of the net-slip pitch was made).

Appendix B-7. Histogram plots of finite ductile shear strain calculated from transect survey data at Baumann Glacier (a & b) and for the sheared vein samples used for CPO analysis (c). Shear strains are calculated from a shear displacement with a net-slip pitch of 30° from the southwest. Where not data is present, the node may have been brittlely offset, a marker may not have been present, or the data may have been filtered from the survey (filtering of any nodes which had an intersection of the shear and marker planes $\pm 5^\circ$ of the net-slip pitch was made).

Appendix B-8. Pitches of the intersection of the marker (qtz-cal vein or bedding) in the shear plane. Positive values are pitching from the SW and negative values are pitching from the NE. a. Pitches of markers in shear planes for survey CH01. b. Pitches of markers in shear planes for survey CH02. c. Pitches of markers in shear planes for survey CH03.

Appendix B-9. Pitches of the intersection of the marker (qtz-cal vein or bedding) in the shear plane. Positive values are pitching from the SW and negative values are pitching from the NE. a. Pitches of markers in shear planes for survey BM01. b. Pitches of markers in shear planes for survey BM-f. c. Pitches of markers in shear planes for shears that have undergone CPO analysis.

Appendix B-10. Ductile deformation width and ductile / total ratio separation ratio against marker vein thickness for Chancellor Ridge surveys.

Appendix B-11. Ductile deformation width and ductile / total ratio separation ratio against marker vein thickness for Baumann Glacier surveys.

Sample number		Sample area ^c		Grain D ^d (μ m)	Minerals in the: (abbreviations as in Kretz, 1983)		Estimated content			Fabric strength ranking ^e			Obl. GSF $\angle^f$		R ⁱ
Field ^a	VUW ^b				Alpine Schist	Sheared veins	% Qtz	% Cal	% Mica	GBM	SGR	GSF	-p cut ^g	-st cut ^h	
MHCH01	39380	-	Schist	95	Qtz, Bt, Ms, Chl, Ep, Pl, Ilm, Ttn, opaques	Qtz, Bt, Ms, Chl	98	0	2	1	1	0	-	-	-
MHCH02	39381	-	Infilling	116	Qtz, Cal, Bt, Chl, Ms, Ep, opaques	Qtz, Cal, Chl, Ms	98	1	1	1	2	2	-	0	-
MHCH03	39382	-	Schist	118	Qtz, Bt, Cal, Ep, Ms, Chl, opaques	Qtz, Cal	60	38	2	2	1	1	-	0	-
MHCH04	39383	-	Infilling	126	Qtz, Bt, Ms, Cal, Chl, Pl, Ep, opaques	Qtz, Ms, Cal, Chl	95	4	1	3	2	1	-	45	-
MHCH05	39384	-	Schist	-	Qtz, Bt, Ms, Chl, Ttn, Ep, Pl	-	-	-	-	-	-	-	-	-	-
MHCH06	39385	-	Infilling	140	Qtz, Cal, Ms, Cal, Bt, Pl, Chl, opaques	Qtz, Cal, Ms	95	4	1	1	2	3	25	30	2.08
MHCH07	39386	-	Infilling	138	Qtz, Cal, Chl, Ms	Qtz, Cal, Chl, Ms	90	7	3	2	2	3	32	45	2.70
MHCH08	39387	-	Infilling	400	Qtz, Cal, Bt, Ms, Pl, Chl	Qtz, Cal, Ms	60	39	1	1	1	2	-	0	-
MHCH09	39388	-	Schist	-	Qtz, Cal, Ms, Bt, Pl, Ep, Chl, opaques	Qtz, Cal, Ms	50	49	1	-	-	2	-	0	-
MHCH10	39389	-	Infilling	157	Qtz, Cal, Ms, Chl, Bt	Qtz, Cal, Ms, Chl	95	3	2	3	2	2	36	37	2.27
MHCH11	39390	-	External	90	Qtz, Cal, Bt, Ep, Pl	Qtz, Cal	-	-	-	1	1	2	-	0	-
MHCH12	39391	A	Infilling	143	Qtz, Cal, Ms, Chl, Bt	Qtz, Cal, Ms, Chl	93	5	2	3	2	3	25	30	2.13
MHCH12	-	B	Infilling	-	Qtz, Cal, Ms, Chl, Bt	Qtz, Cal, Ms, Chl, Bt	-	-	-	3	2	2	-	25	-
MHCH13	39392	-	Schist	-	Bt, Ms, Qtz, Cal, Chl, Pl	-	-	-	-	-	-	-	-	-	-
MHCH14	39394	-	Infilling	155	Qtz, Chl, Cal, Bt, Ms	Qtz, Chl, Cal, Ms	79	20	1	2	2	2	20	20	2.08
MHCH15	39395	-	Infilling	170	Cal, Qtz, Ms, Bt, opaques	Qtz, Cal, Ms	70	28	2	2	2	2	-	36	-
MHCH16	39396	-	Schist	-	Qtz, Cal, Pl, Ms, Bt, Chl, Ilm, Po, Ep	-	-	-	-	-	-	-	-	-	-
MHCH17	39397	B	Internal	178	-	Qtz, Cal, Ms	90	8	2	1	1	0	-	-	-
MHCH17	-	C	Infilling	150	-	Qtz, Cal, Ms	58	40	2	3	1	1	-	0	-
MHCH17	-	A	External	208	Qtz, Cal, Bt, Pl, Ms	Qtz, Cal, Ms	90	8	2	1	1	0	-	-	-
MHCH18	39398	-	Infilling	139	Qtz, Cal, Bt, Ms, Pl, Ep, Chl, opaques	Qtz, Cal	90	7	3	3	1	2	-	0	-
MHCH19	39399	B	Internal	111	-	Qtz, Cal, Ms, Chl	94	5	1	2	2	2	-	Fol	-
MHCH19	-	C	Infilling	125	-	Qtz, Cal, Ms, Chl	-	-	-	1	1	0	-	0	-
MHCH19	-	A	External	111	Qtz, Cal, Ms, Ep, Chl	Qtz, Cal, Ms, Chl	-	-	-	2	2	2	-	Fol	-
MHCH20	39400	A	External	118	Qtz, Cal, Bt, Ms, Ep, Chl, Ttn, Pl, Po, opaques	Qtz, Cal, Chl	-	-	-	1	1	3	-	Fol	-
MHCH20	-	B	Internal	-	-	Qtz, Cal, Chl	-	-	-	-	-	-	-	-	-
MHCH20	-	C	Internal	149	-	Qtz, Cal, Chl	-	-	-	1	2	2	-	0	-
MHCH20	-	E	External	116	-	Qtz, Cal, Chl	-	-	-	2	3	3	-	Fol	-
MHCH20	-	F	Internal	-	-	Qtz, Cal, Chl	-	-	-	-	-	-	-	-	-
MHCH20	-	G	Internal	76	-	Qtz, Cal, Chl	-	-	-	-	-	-	-	-	-
MHCH20	-	H	External	90	-	Qtz, Cal, Chl	-	-	-	-	-	-	-	-	-
MHCH20	-	I	Internal	135	-	Qtz, Cal, Chl	-	-	-	2	2	2	-	0	-
MHCH20	-	J	Internal	122	-	Qtz, Cal, Chl	-	-	-	2	2	2	-	0	-
MHCH20	-	K	Internal	142	-	Qtz, Cal, Chl	-	-	-	-	-	-	-	Fol	-
MHCH20	-	L	External	142	-	Qtz, Cal, Chl	-	-	-	3	3	3	-	Fol	-
MHCH20	-	O	Internal	52	-	Qtz, Cal, Chl	50	50	0	-	-	-	-	-	-

Sample number		Sample area ^c		Grain D ^d (μ m)	Minerals in the: (abbreviations as in Kretz, 1983)		Estimated content			Fabric strength ranking ^e			Obl. GSF $\angle^f$		R ⁱ
Field ^a	VUW ^b				Alpine Schist	Sheared veins	% Qtz	% Cal	% Mica	GBM	SGR	GSF	-p cut ^g	-st cut ^h	
MHCH21	39401	A	Infilling	145	Qtz, Cal, Ms, Bt, Ttn, opaques	Qtz, Cal, Ms	60	38	2	1	3	1	-	0	-
MHCH21	-	B	External	149	-	Qtz, Cal, Ms	-	-	-	2	2	1	-	Fol	-
MHCH22	39402	B	Internal	113	Qtz, Bt, Chl, Ms, Ep, Ttn, Pl	Qtz, Cal, Chl	-	-	-	2	1	3	-	25	1.85
MHCH22	-	C	Infilling	38	-	Qtz, Chl	75	0	25	0	1	3	-	0	1.67
MHCH22	-	A	External	92	-	Qtz, Cal, Chl	-	-	-	3	3	2	-	Fol	-
MHCH23	39403	-	Infilling	167	Chl, Qtz, Cal, Bt, Ms, Pl, opaques	Qtz, Cal, Chl	90	9	1	2	2	2	-	30	-
MHCH24a	39404	-	Infilling	151	Chl, Qtz, Cal, Ms, Bt, Pl, Chl	Qtz, Chl, Cal, Ms	90	8	2	1	1	1	-	0	-
MHCH24b	-	-	Infilling	123	Qtz, Cal, Chl, Ms, Bt, Pl, Ep, Ttn, opaques	Qtz, Chl, Cal, Ms	90	7	3	1	1	1	-	0	-
MHCH24c	-	B	Internal	-	Qtz, Cal, Ms, Chl, Pl, Bt, Ep, Ttn	Qtz, Chl, Cal, Ms	90	9	1	1	2	2	-	Fol	-
MHCH24c	-	C	Internal	108	-	Qtz, Chl, Cal, Ms	-	-	-	1	2	0	-	-	-
MHCH24c	-	D	Infilling	134	-	Qtz, Chl, Cal, Ms	70	28	2	0	2	1	-	0	-
MHCH24c	-	A	External	133	-	Qtz, Chl, Cal, Ms	-	-	-	2	3	2	-	Fol	-
MHCH25	39405	D	Internal	144	Qtz, Cal, Bt, Ms, Chl, Ep, Ttn, Pl, sulphides	Qtz, Cal, Ms	90	8	2	0	1	2	-	0	-
MHCH25	-	B	Internal	120	-	Qtz, Cal, Ms	-	-	-	0	1	2	-	0	-
MHCH25	-	C	External	124	-	Qtz, Cal, Ms	-	-	-	3	2	0	-	-	-
MHCH25	-	A	External	130	-	Qtz, Cal, Ms	-	-	-	3	2	0	-	-	-
MHFJ01a	39406	-	Chert	189	Qtz, Cal, Ms, Bt	-	94	5	1	2	2	3	-	10	-
MHFJ01b	-	-	Chert	-	Qtz, Cal, Ms, Bt	-	-	-	-	-	-	-	-	-	-
MHFJ02a	39407	-	Chert	159	Grt, Qtz, Ms, Bt, Cal	-	-	-	-	1	2	3	-	0	-
MHFJ02b	-	-	Chert	113	Qtz, Cal, Ms, Bt	-	93	1	6	2	2	2	-	0	-
MHFJ03	39408	-	Chert	110	Grt, Qtz, Bt, Ms, Cal, opaques, Chl	-	90	5	5	3	1	2	-	0	-
MHHM01a	39409	Mylonitic Chert	76	Grt, Bt, Hbl, Pl, Qtz, Ms	-	85	0	-	-	2	3	3	-	0	-
MHHM01b	-	Mylonitic Chert	86	Qtz, Grt, Bt, Ms, Pl, Hbl	-	85	0	-	-	2	3	3	-	0	-
MHSP04	39410	-	Schist	-	Qtz, Ms, Bt, Chl, Gr, Ill, Ttn, Grt, Ep	-	-	-	-	-	-	-	-	-	-
MHSP06	39411	-	Schist	-	Bt, Chl, Ms, Grt, Qtz, opaques, Ttn, Ill	-	-	-	-	-	-	-	-	-	-
MHSP07	39412	-	Schist	-	Qtz, Cal, Chl, Bt, Ms, Pl	-	-	-	-	-	-	-	-	-	-
MHSP08	39413	-	Schist	-	Bt, Gr, Ms, Qtz, Cal, Chl, Ttn, opaques	-	-	-	-	-	-	-	-	-	-
MHSP09	39414	-	Infilling	138	-	Qtz, Cal, Chl, Ms	60	30	10	1	2	0	-	-	-
MHSP10	39415	-	Schist	-	Qtz, opaques, sulphides, Bt, Ms, Chl, Gr	-	-	-	-	-	-	-	-	-	-
MHSP11	39416	-	Infilling	138	Qtz, Bt, Ms, Chl, Ttn, Ep	Qtz, Ms, Chl	90	0	10	2	2	2	-	40	-
RW35b	39431	-	Infilling	133	-	Qtz, Ms	95	0	5	1	1	2	-	0	-
TJFA43	39432	-	Infilling	143	Qtz, Cal, Ms, Chl, Bt, Ep, Ttn	Qtz, Cal, Ms, Chl	50	45	5	2	1	2	-	0	-
TJFA47	39433	-	Infilling	127	Qtz, Cal, Ms, Chl, Bt, Ep	Qtz, Cal, Ms, Chl	50	45	5	2	2	1	-	0	-
TJFA50	39434	A	External	-	Qtz, Cal, Ms, Bt, sulphides, Ttn, Ep, Pl	Qtz, Cal, Ms	94	5	1	-	-	-	-	-	-
TJFA50	-	B	External	-	-	Qtz, Cal, Ms	-	-	-	-	-	-	-	-	-
TJFA52	39435	-	Infilling	145	-	Qtz, Ms, Cal	97	1	2	1	2	2	-	0	-

Sample number		Sample area ^c		Grain D ^d (μ m)	Minerals in the: (abbreviations as in Kretz, 1983)		Estimated content			Fabric strength ranking ^e			Obl. GSF $\angle^f$		R ⁱ
Field ^a	VUW ^b				Alpine Schist	Sheared veins	% Qtz	% Cal	% Mica	GBM	SGR	GSF	-p cut ^g	-st cut ^h	
TJFA56	39436	B	Internal	200	Qtz, Ms, Chl, Pl, Bt, Ttn	Qtz, Ms, Chl	98	0	2	1	2	0	-	-	-
TJFA56	-	A	External	194	-	Qtz, Ms, Chl	98	0	2	3	1	1	-	Fol	-
MHBM01	39417	-	Infilling	75	Qtz, Cal, Ms, Chl, Ttn, Ep, Pl, Bt, opaques	Qtz, Cal, Ms, Chl	60	35	5	3	1	2	-	0	-
MHBM02	39418	-	Infilling	1015	Qtz, Cal, Ms, Chl, Bt, Ep, Pl, Ttn, opaques	Qtz, Cal, Ms, Chl	70	28	2	3	3	2	-	38	-
MHBM03	39419	B	Internal	-	Qtz, Cal, Ms, Chl, Pl, Bt, Ep, Ttn	Qtz, Cal, Ms	-	-	-	-	-	-	-	-	-
MHBM03	-	C	Internal	157	-	Qtz, Cal, Ms	60	35	5	1	1	1	-	0	-
MHBM03	-	D	Infilling	149	-	Qtz, Cal, Ms	60	36	4	1	2	2	-	0	-
MHBM03	-	A	External	176	-	Qtz, Cal, Ms	90	8	2	1	1	2	-	Fol	-
MHBM04	39420	B	Internal	113	Qtz, Cal, Ms, Bt, opaques, Pl	Qtz, Cal, Ms	98	1	1	0	1	0	-	-	-
MHBM04	-	A	External	138	-	Qtz, Cal, Ms	-	-	-	0	1	2	-	Fol	-
MHBM05	39421	C	Internal	130	Cal, Qtz, Ms, Bt, Ttn, Ep, Pl	Qtz, Cal, Ms	88	10	2	1	1	0	-	-	-
MHBM05	-	B	External	-	-	Qtz, Cal, Ms	-	-	-	-	-	-	-	-	-
MHBM05	-	A	External	156	-	Qtz, Cal, Ms	88	10	2	1	2	1	-	Fol	-
MHBM06	39422	-	Infilling	155	Qtz, Cal, Ms, Bt, Pl, opaques	Qtz, Cal, Ms	85	10	5	3	3	2	30	35	2.33
MHBM07	39423	-	Infilling	137	-	Qtz, Cal, Ms	97	2	1	2	2	2	22	30	1.85
MHBM08	39424	-	Infilling	1440	-	Qtz, Cal, Ms	60	35	5	2	2	1	-	0	-
MHBM09	39425	B	Internal	117	Qtz, Ms, Cal, Bt, Ep, Ttn, Pl	Qtz, Cal, Ms	99	1	0	1	1	1	-	0	-
MHBM09	-	A	External	160	-	Qtz, Cal, Ms	97	1	2	2	2	2	-	Fol	-
MHBM10	39426	B	Internal	166	Qtz, Cal, Ms, Bt, Chl, Ep, Pl, Ttn	Qtz, Cal, Ms, Bt, Chl	90	7	3	1	0	0	-	-	-
MHBM10	-	A	External	149	-	Qtz, Cal, Ms, Bt, Chl	95	4	1	3	3	2	-	Fol	-
MHBM10	-	C	External	149	-	Qtz, Cal, Ms, Bt, Chl	-	-	-	3	3	2	-	Fol	-
MHBM11	39427	B	Internal	173	Bt, Chl, Ttn, Ep, Pl, Qtz, Cal, Ms	Qtz, Cal, Ms	90	8	2	2	1	0	-	-	-
MHBM11	-	A	External	170	-	Qtz, Cal, Ms	90	9	1	2	2	2	-	Fol	-
MHBM12	39428	B	Internal	60	Qtz, Cal, Ms, Chl, Bt, Ep, Ttn, Pl	Qtz, Cal, Ms, Chl	80	10	10	2	1	2	-	0	-
MHBM12	-	C	Infilling	82	-	Qtz, Cal, Ms, Chl	60	35	5	2	1	2	-	0	-
MHBM12	-	A	External	176	-	Qtz, Cal, Ms, Chl	70	28	2	1	1	2	-	Fol	-
MHBM13	39429	B	Internal	106	Qtz, Cal, Ms, Bt, Ep, Pl, Ttn, Chl	Qtz, Cal, Ms	95	5	0	2	1	1	-	0	-
MHBM13	-	A	External	208	-	Qtz, Cal, Ms	95	3	2	2	2	0	-	-	-
MHBM13	-	C	Internal	109	-	Qtz, Cal, Ms	95	5	0	1	0	2	-	0	-
MHBM13	-	D	External	145	-	Qtz, Cal, Ms	95	3	2	2	1	0	-	-	-
MHBM14b	39430	A	Infilling	1504	-	Qtz, Cal, Ms, Chl	70	26	4	2	1	2	-	0	-
MHBM14b	-	B	Infilling	95	-	Qtz, Cal, Ms, Chl	70	26	4	1	2	1	-	0	-

Appendix D. Quartz CPO fabrics measured from sheared quartz-carbonate veins collected in the brittle-ductile shear zone (BDSZ).

Crystallographic orientations of quartz c-axes have been measured using a universal-stage microscope in various locations throughout individual shear zones. This appendix combines schematic illustrations of the sheared veins that have been sampled for this crystallographic research with the crystallographic preferred orientation (CPO) fabric plots and CPO patterns as well as fabric strength data. Sample locations can be found by cross-referencing the sample numbers with data in Appendix C. All structural orientations and the finite ductile shear strain for the deformation are listed with each sample in this appendix. Sixteen veins were sampled and are illustrated in Appendixes D-1 to D-16. Some of these figures have been reproduced in Figs. 5.6 and 6.2 although samples have been re-labelled in those figures. Field sample numbers are presented for each cartoon in these two figures and are able to be cross-referenced with this appendix.

Shear zone schematic illustrations include the sheared vein, the Alpine Schist host rock and shear infilling vein material where present. They are scale drawings of the actual samples collected and stored in the Victoria University of Wellington rock collection (see Appendix C for collection numbers). The drawings are made from rock surface cuts perpendicular to the shear zone and either parallel to the strike or the mineral fibre lineation measured on the shear plane (as noted on the cartoon). Each drawing is also labelled with the top side of the sample and the north or down-dip end of the section. The Alpine Schist foliation is drawn as an intersection lineation on the surface of the rock cut. Locations of crystallographic analyses are noted by letters in the location where the measurements were made (in an area of $\sim 10\text{mm}^2$). Orientations of all the planes (and the [x] direction of the most highly deformed CPO fabric plots) are shown on a stereogram for each sample.

CPO fabric plots are shown in a rotated reference frame (x-y-z). This reference frame and the rotation process are outlined in Chapter 5. CPO fabrics are presented in both scatter pole figures and contour plots of pole density with the Alpine Schist annotated onto samples external to the ductile shear deformation. CPO patterns (see Chapter 5) are plotted onto scatter plots to illustrate the inferred skeletal outlines. All CPO fabric plots are on equal area, lower hemisphere, stereographic projections.

Data for each of the CPO fabric is listed in a table which includes: the orientation of the shear plane (x-y plane) in the plot, the pitch of [x] from the southwest and eigenvector ratios.

c-axis CPO	A	B	C	D
X-Y Plane	048@78E	048@78E	048@78E	048@78E
X (Pitch from S)	55°	68°	80°	90°
S1/S3	1.56	1.51	1.60	1.09
S1/S2	1.22	1.26	1.25	1.02
S2/S3	1.28	1.20	1.27	1.07
Finite ductile shear strain		>6.3		
Shear plane (S)		048@78 SE		
Vein orientation (V)		020@76 SE		
Alpine foliation (F)		038@83 SE		
Thin section plane (T)		228@12 NW

Appendix D-1. Sample MHB03. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar. CPO patterns show a progressive shift from an inherited fabric in the schist to a cleft girdle CPO pattern in the sheared section of the vein (CPO C). The infilling vein has a random CPO pattern and has a low S₁/S₃ ratio. Quartz CPO derived stretching direction with a pitch of 89° has been assigned to this sample from the calcite CPO data (Appendix I) (of the same sample) as the stretching direction is more clearly defined by the calcite than the quartz.

c-axis CPO	A	B
X-Y Plane	041@82 E	041@82 E
X (Pitch from S)	73°	68°
S1/S3	2.069	1.799
S1/S2	1.078	1.290
S2/S3	1.919	1.394
Finite ductile shear strain	>2.6	
Shear plane (S)	041@82 SE	
Vein orientation (V)	006@78 E	
Alpine foliation (F)	045@68 SE	
Thin section plane (T)	221@08 NW

Appendix D-2. Sample MHB04. Sheared quartz-carbonate vein within Alpine Schist. Most attenuated section of the vein not recovered during sampling and finite ductile shear strain is based only on offset of sample recovered. CPO fabric (A) shows a single girdle pattern perpendicular to the Alpine Schist foliation. CPO fabric (B) measured from in the sheared section of the vein does not show a change into the shear zone other than a weaker CPO fabric and a more diffused CPO pattern compared with CPO fabric (A). CPO fabric (B) also shows a decrease in the S_2/S_3 ratio confirming the weaker girdle fabric. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B	C
X-Y Plane	045@82E	045@82E	045@82E
X (Pitch from S)	67°	65°	90°
S1/S3	1.72	1.46	1.53
S1/S2	1.18	1.02	1.30
S2/S3	1.46	1.43	1.18
Finite ductile shear strain		3.2	
Shear plane (S)		045@82 SE	
Vein orientation (V)		193@83 W	
Alpine foliation (F)		038@84 SE	
Thin section plane (T)		225@08 NW

Appendix D-3. Sample MHB05. Sheared quartz-carbonate vein with Alpine Schist that shows a progressive reorganisation of c-axes into the sheared section of the vein. CPO (C) shows a cleft girdle CPO pattern which has been developed from the Type II CPO patterns found in CPO fabrics (A) and (C). CPO fabric (B) weakens from CPO fabric (A) with CPO fabric (C) having a strong fabric and a different stretching direction [x]. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B
X-Y Plane	046@83E	046@83E
X (Pitch from S)	88°	90°
S1/S3	2.16	1.62
S1/S2	1.21	1.39
S2/S3	1.78	1.17
Finite ductile shear strain	>4.1	
Shear plane (S)	046@83 SE	
Vein orientation (V)	192@76 W	
Alpine foliation (F)	036@70 E	
Thin section plane (T)	226@07 NW

Appendix D-5. Sample MHB09. Section of a sheared quartz-carbonate vein found in Alpine Schist that shows randomising of the CPO fabric in the sheared section of the vein recovered. CPO fabric (A) shows a strong single gride CPO pattern outside the shear zone which is not found in the sheared section of the vein in CPO fabric (B). CPO pattern in fabric (A) shows a perpendicular relationship to the Alpine Schist foliation plane. Finite ductile shear strain calculated from field observation of offset. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B	C
X-Y Plane	046@80W	046@80W	046@80W
X (Pitch from S)	90°	85°	90°
S1/S3	1.80	2.05	2.35
S1/S2	1.11	1.31	1.02
S2/S3	1.62	1.56	2.30

Finite ductile shear strain

Shear plane (S)

Vein orientation (V)

Alpine foliation (F)

Thin section plane (T)

4.5

046@80 NW

346@72 NE

221@89 NW

Appendix D-5. Sample MHBM10. Sheared quartz-carbonate vein with ductile offset only and brittle cracks that have propagated along the vein schist boundary. CPO fabrics (A) and (C) both show a broad single girdle perpendicular to the Alpine Foliation plane. CPO fabric (B) in the sheared section of the vein shows a deviation from the CPO patterns in the unsheared section to a diffused cleft girdle CPO pattern. Brittle crack tips do not break through the sheared vein and instead propagate along the vein schist boundary. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B
X-Y Plane	048@77E	048@77E
X (Pitch from S)	78°	90°
S1/S3	1.686	1.473
S1/S2	1.222	1.087
S2/S3	1.379	1.355
Finite ductile shear strain		>5.9
Shear plane (S)		048@77 SE
Vein orientation (V)		019@78 E
Alpine foliation (F)		221@89 NW
Thin section plane (T)		228@13 NW

Appendix D-6. Sample MHBM11. Sheared quartz-carbonate vein in the Alpine Schist with a CPO fabric that weakens with shearing. CPO fabric (A) shows a diffused single girdle CPO pattern which weakens to a random CPO pattern in CPO fabric (B) in the sheared section of the vein. The most attenuated section of the sheared vein was not recovered during sampling. The finite ductile shear strain is calculated only for section of the vein where the CPO fabric was measured. Contours are calculated using a counting circle of 15 with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B	C
X-Y Plane	048@76E	048@76E	048@76E
X (Pitch from S)	73°	90°	73°
S1/S3	1.675	2.175	1.363
S1/S2	1.173	1.431	1.254
S2/S3	1.428	1.519	1.087
Finite ductile shear strain	5.0		
Shear plane (S)	048@76 SE		
Vein orientation (V)	208@86 W		
Alpine foliation (F)	221@89 NW		
Thin section plane (T)	228@14 NW

— Brittle fracture
— Shear Infilling Vein
— Sheared Vein
— Alpine Schist
'A' CPO Analysis

Appendix D-7. Sample MHBM12. Sheared quartz-carbonate vein with brittle-ductile shear and a shear infilling vein section. CPO fabric (A) in the unsheared section of the vein contains a CPO pattern not related to the shear plane offsetting the vein. This unrelated CPO pattern is not seen the sheared section of the vein where CPO fabric (B) shows a diffused cleft girdle CPO pattern or in CPO fabric (C) from the infilling vein section which has a random CPO fabric. Contours are calculated using a counting circle of 15 with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B	C	D
X-Y Plane	056@80E	056@80E	056@80E	056@80E
X (Pitch from S)	73°	80°	86°	68°
S1/S3	2.12	1.66	2.03	2.08
S1/S2	1.44	1.35	1.34	1.32
S2/S3	1.47	1.23	1.51	1.57
Finite ductile shear strain	3.1			
Shear plane (S)	056@80 SE			
Vein orientation (V)	014@80 E			
Alpine foliation (F)	215@84 NW			
Thin section plane (T)	236@10 NW

Appendix D-8. Sample MHBM13. Quartz-carbonate vein that has undergone brittle-ductile deformation. CPO fabrics (A) and (D) both show single girdle or weak Type 1 CPO patterns that are perpendicular to the Alpine Foliation plane. The sheared ductile sections of the veins which have been separated by brittle offset have had CPO fabrics (B) and (C) measured in them and show CPO patterns that are perpendicular to the shear zone and have what is best described as cleft girdles. The CPO patterns could also be interpreted as a diffused single girdle in which case a weak asymmetry could be inferred with a top-to-the-right sense of shear on the CPO fabrics. This shear sense translates into a dextral-west-side-up sense of shear in the rock sample. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B	C
X-Y Plane	038@88E	038@88E	038@88E
X (Pitch from S)	82°	82°	90°
S1/S3	1.61	2.08	1.50
S1/S2	1.01	1.41	1.13
S2/S3	1.59	1.47	1.33

Finite ductile shear strain

Shear plane (S)

Vein orientation (V)

Alpine foliation (F)

Thin section plane (T)

Appendix D-9. Sample MHCH17. Sheared quartz-carbonate vein in the Alpine Schist which has undergone brittle-ductile deformation and had precipitation of an infilling vein against the shear plane. CPO fabric (A) shows a cleft girdle CPO pattern perpendicular to the Alpine Schist foliation. This CPO pattern changes to a Type II pattern in CPO fabric (B) in the sheared section of the vein. The infilling vein has a random CPO pattern. Contours are calculated using a counting circle of 15 with concentration out of the total points indicated by percentage on the scale bar.

Appendix D-10. MHCH19. CPO fabrics (A) and (B) have been assigned different CPO patterns of small circles and cleft girdles respectively based on the absence of c-axis poles parallel to the y-axis of the CPO fabric plot. The CPO fabrics, apart from this subtle absence of c-axis poles, are very similar and may both be related to the deformation that offsets the vein. The sheared vein cartoon clearly illustrates that the deformation is dominantly brittle which explains why CPO fabric (B) is so weak as it not undergone very much ductile deformation. CPO fabric shows a weak Type 1 CPO pattern (C) perpendicular to the shear plane. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

Appendix D-11. Sample MHCH20G. Sheared quartz-carbonate vein that has undergone brittle-ductile deformation. Five CPO fabrics were measured across the sheared vein with asymmetric CPO patterns found in the sheared sections of the vein. CPO fabrics (A) and (H) from the unsheared sections show diffused single girdle CPO patterns perpendicular to the Alpine Foliation. These CPO patterns change to asymmetric Type I CPO patterns in the sheared sections of the vein (CPO fabrics B, C and G). Sense of shear is top-to-the-left on the CPO fabric plots and is dextral-west-side-up in the rock. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar. Net-slip vector calculated from two plane intersection method in Chapter 4.

4.4
222@86 NW
002@82 E
027@75 SE
042@04 SE

Finite ductile shear strain
Shear plane (S)
Vein orientation (V)
Alpine foliation (F)
Thin section plane (T)

c-axis CPO	E	F	I	J	O	K	L
X-Y Plane	222@86W	222@86W	222@86W	222@86W	222@86W	222@86W	222@86W
X (Pitch from S)	110°	65°	85°	110°	80°	90°	90°
S1/S3	1.52	1.94	1.52	1.35	2.31	1.55	1.31
S1/S2	1.26	1.49	1.10	1.17	1.11	1.32	1.23
S2/S3	1.21	1.30	1.38	1.16	2.08	1.18	1.06

Appendix D-12. Sample MHCH20W. Sheared quartz-carbonate vein from the same sample and shear as sample MHCH20G (see Fig. 4.h.d for whole sample cartoon). Random CPO fabrics (E), (L) and (K) are found in the unheated section of the vein. This lack of CPO fabric was not expected considering the visible ductile folding that the unheated section of the vein had undergone. CPO fabrics (F), (I) and (J) all show similar CPO patterns about the z-pole. The CPO fabrics have notable high concentrations of c-axes in the positions on the CPO fabric that plunge ~45° from the north and south ends of the z-axis. CPO fabric (O) was measured on 50-80 µm quartz grains in a calcite matrix and showed a strong cleft girdle CPO pattern. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar. Net-slip vector used to calculate finite ductile shear strain was calculated from the two plane intercept method in Chapter 4.

c-axis CPO	A	B	C
X-Y Plane	219@89W	219@89W	219@89W
X (Pitch from S)	110°	90°	105°
S1/S3	2.60	1.96	2.35
S1/S2	1.51	1.75	1.31
S2/S3	1.72	1.12	1.79
Finite ductile shear strain	13.8		
Shear plane (S)	219@89 NW		
Vein orientation (V)	012@71 E		
Alpine foliation (F)	027@75 W		
Thin section plane (T)	039@01 SE

Appendix D-13. Sample MHCH22. Sheared quartz-carbonate vein that has undergone ductile and brittle deformation with a later precipitation of an infilling quartz-chlorite vein along the brittle shear plane fracture. CPO fabric (A) shows a strong Type II girdle which changes to a small circle CPO pattern in CPO fabric (B). The infilling section CPO fabric shows cleft girdle that is strong compared with other infilling vein samples. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

Appendix D-14. Sample MHCH24c. Sheared quartz-carbonate vein that has undergone brittle-ductile deformation and had an infilling vein precipitated along the shear plane. CPO fabrics (A) and (B) from the unsheared section of the vein show diffused small circle CPO patterns which are weakened in the sheared section of the vein where the vein is the most attenuated has a random CPO fabric. The stronger CPO pattern in fabric (B) may be related to the veins deformation but after further shearing the CPO fabric (C) is randomised. The infilling vein after 900 measured c-axis orientation measurements shows a random CPO fabric. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B	C	D
X-Y Plane	216@80W	216@80W	216@80W	216@80W
X (Pitch from S)	90°	90°	90°	90°
S1/S3	1.41	1.85	1.50	2.04
S1/S2	1.22	1.65	1.11	1.51
S2/S3	1.15	1.12	1.35	1.35
Finite ductile shear strain B	6.7			
Finite ductile shear strain D	6.4			
Shear plane (S)	216@80 NW			
Vein orientation (V)	017@80 E			
Alpine foliation (F)	042@78 SE			
Thin section plane (T)	036@10 SE			

— Brittle fracture
— Sheared Vein
— Alpine Schist
'A' CPO Analysis

Appendix D-15. Sample MHCH25. Sheared quartz-carbonate vein in Alpine Schist that has undergone ductile deformation with a brittle crack propagating along the vein schist boundary but not penetrating through the vein. CPO fabrics (A) and (C) from unsheared sections of the vein show random CPO patterns. A CPO of c-axes is developed in the sheared sections of the vein (CPO fabrics B and D) with a small circle CPO pattern in one shear zone and a cleft girdle in the other shear zone. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

c-axis CPO	A	B
X-Y Plane	212@63W	212@63W
X (Pitch from S)	37°	67°
S1/S3	1.73	1.70
S1/S2	1.52	1.36
S2/S3	1.14	1.25
Finite ductile shear strain		3.8
Shear plane (S)		212@63 NW
Vein orientation (V)		195@70 W
Alpine foliation (F)		207@73 NW
Thin section plane (T)		032@27 SE

Appendix D-16. Sample TJFA56. Sheared quartz-carbonate vein from the Sam Peak that shows brittle-ductile deformation. The unsheared section of this vein has a CPO fabric with a small circle CPO pattern in mirror symmetry to the Alpine Schist foliation. The most attenuated section of the sheared vein has a weaker CPO fabric and shows a diffused Type 1 CPO pattern with a weak asymmetry. The sense of shear is top-to-the-left on the CPO fabric plot and translates to a dextral-west-side-up sense of shear in the rock sample. Contours are calculated using a counting circle of 1σ with concentration out of the total points indicated by percentage on the scale bar.

Appendix E-1. Crystallographic preferred orientations of quartz c-axes in the shear infilling vein samples on Chancellor Ridge. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-2. Crystallographic preferred orientations of quartz c-axes in the shear infilling vein samples on Chancellor Ridge and Sam Peak (6 fabric plots below horizontal division). Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-3. Crystallographic preferred orientations of quartz c-axes in the shear infilling vein samples at Baumann Glacier. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-4. Crystallographic preferred orientations of quartz c-axes from the highly deformed internal sections of the sheared veins on Chancellor Ridge. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-5. Crystallographic preferred orientations of quartz c-axes from the highly deformed internal sections of the sheared veins on Chancellor Ridge, Sam Peak and at Baumann Glacier. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-6. Crystallographic preferred orientations of quartz c-axes from the highly deformed internal sections of the sheared veins at Baumann Glacier. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-7. Crystallographic preferred orientations of quartz c-axes of chert samples from the non-mylonitic Alpine Schist and the Alpine Schist mylonite. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and (except MHHM01a-d which was calculated using a 3σ counting circle) are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-9. Crystallographic preferred orientations of quartz c-axes from the less deformed external sections of the sheared veins on Chancellor Ridge, Sam Peak and at Baumann Glacier. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix E-10. Crystallographic preferred orientations of quartz c-axes from the less deformed external sections of the sheared veins at Baumann Glacier. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 1σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix D. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most deformed part of the vein.

Appendix F. Hare Mare Creek Alpine Fault mylonite quartz c-axis CPO, microstructural and field measurements.

a. Quartz c-axis poles plotted on an equal area, lower hemisphere, stereographic projection. Contours were calculated using a counting circle of 3σ and are plotted as lines of equal concentration percentage. Light shades represent low concentration and dark shades represent high concentrations of c-axes. Percent measurements are shown on the graduated scale bar. Contour and scatter plots are paired for complete and objective fabric interpretations. [x] has been determined from rotation in the x-y plane from down dip ($P=90^\circ$ NE) to the best fit extension direction [x] ($P=34^\circ$ NE). Shear sense has been interpreted from a single girdle CPO pattern with an internal asymmetry. Fabric data can be found in Table 5.1 and rotation methods in Fig. 5.4. Crystallographic measurements were made using a universal stage and were from a chert band parallel to the dominant mylonitic foliation.

b. Stereographic projection of Alpine Fault mylonite planes, poles and shear directions from Hare Mare Creek in this study. Plate convergence vector from NUVEL-1A (DeMets et al., 1994). Mean ductile shear direction from Little et al. (2002b). CPO shear direction (star) and shear sense from CPO pattern (this Appendix a) with mineral stretching lineation on that sample (empty square) plotted for comparison. Uncertainties are for a 95% confidence ellipse about the mean line or pole to the mean plane. Quartz c-axis CPO-derived stretching direction is coincident with the mineral stretching lineation on the Alpine Fault mylonite sample measured. Mineral lineations and foliation collected in this study are plotted. Sample locations can be found in Appendix B. Spread of mineral stretching lineations is consistent with those measured by Sibson et al. (1979) and Sibson et al. (1981). These stretching lineations represent the stretching direction during triclinal deformation (Jiang et al., 2001) of the mylonite during uplift.

Appendix G. a. Crystallographic preferred orientation of quartz c-axes from euhedral quartz grains in photographs (b) and (c). Contours plotted for equal percent of total points and calculated using the Kamb contouring method and a 3σ counting circle. Reference system for CPO fabric plot has the z-pole normal to the vein wall with the x- and y-poles perpendicular in the vein wall plane. x-pole direction is unspecified as sample was not orientated in a geographic reference frame. b. Photograph of the unorientated sample used, and euhedral quartz crystals that have growth out from the vein wall are clearly visible. Photograph courtesy Mr. D. P. M. Mason with New Zealand 5 cent piece for scale. c. Microphotograph of thin section made for quartz c-axis orientation measurement from sample in (b) in an orientation where the thin section is normal to the wall rock. Orientation axes shown are the same as those for the CPO fabric plot in (a) and wall rock and quartz crystals are labeled for reference.

Appendix H. Data for quartz and calcite CPO fabrics measured across the brittle-ductile shear zone (BDSZ).

The appendix contains the data related to the location, orientation and fabric strength of the c-axis CPO fabric plots in Appendices E, F, G, I and J. Samples are identified by both their field number (a) and their Victoria University of Wellington Collection number (c) for cross-referencing with other data in this thesis and are also identified by the section of the shear zone the CPO fabric was measured from (vein section; b). The finite ductile shear strain (γ) is listed where known for a samples shear zone (d). The orientation of the quartz or calcite CPO-derived [x] direction (e) is presented and all values are for pitches in the shear plane orientation given for each sample.

CPO fabric have been assigned CPO patterns (f) and these are listed according to the pattern codes and methods in Chapter 5. Fabric strength data is also listed in this Appendix in the form of eigenvalues, fabric strength rankings (g), and fabric intensities (I). The calculation methods and use of the eigenvalue ratios can be found in Chapter 5.

Sample number			Section of shear zone analysed	γ	Shear plane orientation		Pitch of [x] from SW ^e	CPO pattern ^f	Fabric strength ranking ^g	Count of c-axes	Eigenvalues			Eigenvalue ratios			Fabric inten- sity (<i>I</i>)
Field ^a	Vein sctn ^b	VUW ^c			Strike	Dip					S ₁	S ₂	S ₃	S ₁ /S ₃	S ₁ /S ₂	S ₂ /S ₃	
MHCH01		39380	Schist		219	84	-	-	-	-	-	-	-	-	-	-	
MHCH02		39381	Infilling		215	88	60	CG	1	300	0.42	0.32	0.26	1.66	1.32	1.25	0.11
MHCH03		39382	Schist		218	87	-	-	-	-	-	-	-	-	-	-	
MHCH04		39383	Infilling		039	88	4	CG	2	300	0.39	0.35	0.26	1.54	1.13	1.36	0.08
MHCH05		39384	Schist		216	84	-	-	-	-	-	-	-	-	-	-	
MHCH06		39385	Infilling		218	84	7	C	4	300	0.47	0.28	0.26	1.82	1.67	1.09	0.20
MHCH07		39386	Infilling		217	88	90	SC	1	300	0.38	0.35	0.26	1.46	1.09	1.34	0.06
MHCH08		39387	Infilling		215	87	5	CG	2	300	0.42	0.34	0.24	1.73	1.25	1.38	0.12
MHCH09		39388	Schist		-	-	-	-	-	-	-	-	-	-	-	-	
MHCH10		39389	Infilling		217	86	8	C	3	300	0.44	0.32	0.23	1.92	1.37	1.40	0.17
MHCH11		39390	External		217	82	80	T1	4	300	0.49	0.31	0.20	2.43	1.60	1.52	0.32
MHCH12	A	39391	Infilling		221	85	18	T2	3	300	0.45	0.32	0.23	1.97	1.44	1.37	0.19
MHCH12	B		Infilling		221	85	18	C	3	300	0.47	0.28	0.25	1.90	1.66	1.15	0.21
MHCH13		39392	Schist		-	-	-	-	-	-	-	-	-	-	-	-	
MHCH14		39394	Infilling		218	88	7	R	0	300	0.38	0.34	0.28	1.35	1.09	1.23	0.04
MHCH15		39395	Infilling		208	81	165	CG	3	300	0.46	0.31	0.23	2.01	1.52	1.32	0.21
MHCH16		39396	Schist		-	-	90	-	-	-	-	-	-	-	-	-	
MHCH17	B	39397	Internal	7.7	038	88	82	T2	3	300	0.46	0.32	0.22	2.08	1.41	1.47	0.21
MHCH17	C		Infilling		038	88	90	R	0	300	0.39	0.35	0.26	1.50	1.13	1.33	0.07
MHCH17	A		External		038	88	82	CG	3	300	0.38	0.38	0.24	1.61	1.01	1.59	0.10
MHCH18		39398	Infilling		-	-	-	-	-	-	-	-	-	-	-	-	
MHCH19	B	39399	Internal	0	219	84	100	CG	3	300	0.41	0.35	0.25	1.65	1.18	1.40	0.10
MHCH19	C		Infilling		219	84	77	T1	2	500	0.43	0.33	0.25	1.71	1.31	1.31	0.12
MHCH19	A		External		219	84	95	SC	3	300	0.42	0.33	0.25	1.69	1.25	1.35	0.11
MHCH20	A	39400	External		222	86	60	SG-2	4	300	0.42	0.37	0.21	1.96	1.15	1.71	0.17
MHCH20	B		Internal	6.9	222	86	60	SG-2	3	300	0.41	0.35	0.24	1.75	1.17	1.49	0.12
MHCH20	C		Internal	6.9	222	86	70	SG-2	3	300	0.42	0.32	0.26	1.62	1.29	1.26	0.10
MHCH20	E		External		222	86	110	R	0	300	0.41	0.32	0.27	1.52	1.26	1.21	0.07
MHCH20	F		Internal	6.9	222	86	65	SC	3	300	0.46	0.31	0.24	1.94	1.49	1.30	0.19
MHCH20	G		Internal	6.9	222	86	70	SG-2	4	300	0.40	0.37	0.23	1.73	1.10	1.58	0.12
MHCH20	H		External		222	86	60	SG-2	4	300	0.44	0.36	0.21	2.14	1.23	1.74	0.21

Sample number			Section of shear zone analysed	γ	Shear plane orientation		Pitch of [x] from SW ^e	CPO pattern ^f	Fabric strength ranking ^g	Count of c-axes	Eigenvalues			Eigenvalue ratios			Fabric intensi- ty (<i>I</i>)
Field ^a	Vein sctn ^b	VUW ^c			Strike	Dip					S ₁	S ₂	S ₃	S ₁ /S ₃	S ₁ /S ₂	S ₂ /S ₃	
MHCH20	I		Internal	4.4	222	86	85	SC	3	300	0.39	0.35	0.26	1.52	1.10	1.38	0.07
MHCH20	J		Internal	4.4	222	86	110	SC	4	300	0.38	0.33	0.28	1.35	1.17	1.16	0.04
MHCH20	K		Internal	4.4	222	86	90	R	0	300	0.42	0.32	0.27	1.55	1.32	1.18	0.09
MHCH20	L		External		222	86	90	R	1	300	0.39	0.32	0.30	1.31	1.23	1.06	0.03
MHCH20	O		Internal	4.4	222	86	80	CG	4	300	0.43	0.39	0.19	2.31	1.11	2.08	0.25
MHCH21	A	39401	Infilling		218	89	100	R	1	300	0.41	0.34	0.25	1.60	1.21	1.32	0.09
MHCH21	B		External		218	89	80	SG-2	2	300	0.39	0.36	0.25	1.60	1.09	1.47	0.09
MHCH22	B	39402	Internal	13.8	219	89	90	SC	4	300	0.48	0.27	0.25	1.96	1.75	1.12	0.25
MHCH22	C		Infilling		219	89	105	CG	4	300	0.46	0.35	0.19	2.35	1.31	1.79	0.26
MHCH22	A		External		219	89	110	T2	3	300	0.49	0.32	0.19	2.60	1.51	1.72	0.34
MHCH23		39403	Infilling		218	84	40	C	1	300	0.42	0.32	0.26	1.61	1.32	1.22	0.10
MHCH24 All	I All	39404	Infilling		218	82	90	SG-2	1	900	0.41	0.33	0.26	1.55	1.22	1.27	0.08
MHCH24a			Infilling		218	82	105	R	1	300	0.41	0.34	0.26	1.59	1.22	1.31	0.09
MHCH24b			Infilling		218	82	90	R	0	300	0.42	0.32	0.26	1.59	1.28	1.25	0.09
MHCH24c	B		Internal	6.8	218	82	70	SC	4	300	0.43	0.31	0.26	1.64	1.40	1.17	0.11
MHCH24c	C		Internal	6.8	218	82	90	R	0	300	0.40	0.32	0.28	1.44	1.23	1.17	0.06
MHCH24c	D		Infilling		218	82	120	R	0	300	0.40	0.34	0.25	1.61	1.17	1.37	0.09
MHCH24c	A		External		218	82	85	SC	2	300	0.40	0.34	0.26	1.52	1.20	1.27	0.07
MHCH25	D	39405	Internal	6.4	216	80	90	CG	3	300	0.46	0.31	0.23	2.04	1.51	1.35	0.22
MHCH25	B		Internal	6.7	216	80	90	SC	4	300	0.47	0.28	0.25	1.85	1.65	1.12	0.20
MHCH25	C		External		216	80	90	R	0	300	0.39	0.35	0.26	1.50	1.11	1.35	0.07
MHCH25	A		External		216	80	90	R	1	300	0.40	0.32	0.28	1.41	1.22	1.15	0.05
MHFJ01a		39406	Chert		048	75	25	T2	4	300	0.46	0.34	0.20	2.36	1.37	1.73	0.27
MHFJ01b			Chert		048	75	40	SG-2	3	300	0.43	0.39	0.18	2.35	1.11	2.11	0.26
MHFJ02a		39407	Chert		-	-	-	-	-	-	-	-	-	-	-	-	-
MHFJ02b			Chert		-	-	-	-	-	-	-	-	-	-	-	-	-
MHFJ03		39408	Chert		035	75	60	T2	3	300	0.41	0.36	0.23	1.79	1.13	1.59	0.13
MHHM01a		39409	Mylonitic Chert		061	32	146	SG-3	5	300	0.69	0.28	0.03	21.09	2.48	8.50	1.65
MHHM01b			Mylonitic Chert		061	32	-	-	-	-	-	-	-	-	-	-	-
MHSP04		39410	Schist		-	-	-	-	-	-	-	-	-	-	-	-	-
MHSP06		39411	Schist		-	-	-	-	-	-	-	-	-	-	-	-	-

Sample number			Section of shear zone analysed	γ	Shear plane orientation		Pitch of [x] from SW ^e	CPO pattern ^f	Fabric strength ranking ^g	Count of c-axes	Eigenvalues			Eigenvalue ratios			Fabric inten- sity (<i>I</i>)
Field ^a	Vein sctn ^b	VUW ^c			Strike	Dip					S ₁	S ₂	S ₃	S ₁ /S ₃	S ₁ /S ₂	S ₂ /S ₃	
MHSP07		39412	Schist		-	-	-	-	-	-	-	-	-	-	-	-	
MHSP08		39413	Schist		-	-	-	-	-	-	-	-	-	-	-	-	
MHSP09		39414	Infilling		202	52	90	R	0	300	0.36	0.35	0.29	1.23	1.02	1.21	
MHSP10		39415	Schist		-	-	-	-	-	-	-	-	-	-	-	-	
MHSP11		39416	Infilling		206	48	105	T2	3	300	0.43	0.36	0.21	2.00	1.19	1.68	
RW35b		39431	Infilling		206	64	30	SC	3	300	0.42	0.31	0.26	1.59	1.34	1.19	
TJFA43		39432	Infilling		211	64	45	R	0	300	0.38	0.35	0.26	1.46	1.09	1.33	
TJFA47		39433	Infilling		213	60	43	R	0	300	0.38	0.32	0.30	1.26	1.16	1.09	
TJFA50	A	39434	External		206	65	47	SC	3	300	0.43	0.30	0.26	1.64	1.45	1.14	
TJFA50	B		External		206	65	37	SC	3	300	0.39	0.31	0.30	1.32	1.27	1.03	
TJFA52		39435	Infilling		200	65	110	T2	2	300	0.49	0.30	0.22	2.21	1.64	1.35	
TJFA56	B	39436	Internal	3.8	212	63	67	SG-2	2	300	0.43	0.32	0.25	1.70	1.36	1.25	
TJFA56	A		External		212	63	37	SC	3	300	0.45	0.29	0.26	1.73	1.52	1.14	
MHBM01		39417	Infilling		223	84	90	R	0	300	0.38	0.35	0.27	1.40	1.08	1.29	
MHBM02		39418	Infilling		-	-	-	-	-	-	-	-	-	-	-	-	
MHBM03	B	39419	Internal	6.3	048	78	68	CG	3	300	0.41	0.32	0.27	1.51	1.26	1.20	
MHBM03	C		Internal	6.3	048	78	80	CG	3	300	0.41	0.33	0.26	1.60	1.25	1.27	
MHBM03	D		Infilling		048	78	90	R	0	300	0.35	0.34	0.32	1.09	1.02	1.07	
MHBM03	A		External		048	78	55	T2	2	300	0.41	0.33	0.26	1.56	1.22	1.28	
MHBM04	B	39420	Internal	2.6	041	82	68	SG-2	2	300	0.43	0.33	0.24	1.80	1.29	1.39	
MHBM04	A		External		041	82	73	SG-2	3	300	0.41	0.38	0.20	2.07	1.08	1.92	
MHBM05	C	39421	Internal	3.2	045	82	90	CG	3	300	0.41	0.32	0.27	1.53	1.30	1.18	
MHBM05	B		External		045	82	65	T2	2	300	0.38	0.37	0.26	1.46	1.02	1.43	
MHBM05	A		External		045	82	67	T2	3	300	0.41	0.35	0.24	1.72	1.18	1.46	
MHBM06		39422	Infilling		046	80	90	R	0	300	0.36	0.36	0.28	1.30	1.02	1.28	
MHBM07		39423	Infilling		040	72	45	R	0	300	0.39	0.35	0.26	1.48	1.12	1.32	
MHBM08		39424	Infilling		044	88	90	C	2	300	0.44	0.33	0.23	1.95	1.34	1.45	
MHBM09	B	39425	Internal	4.1	046	83	90	R	0	300	0.43	0.31	0.26	1.62	1.39	1.17	
MHBM09	A		External		046	83	88	SG	2	300	0.44	0.36	0.20	2.16	1.21	1.78	
MHBM10	B	39426	Internal	4.5	046	80	85	SG	3	300	0.44	0.34	0.22	2.05	1.31	1.56	
MHBM10	A		External		046	80	90	SG	3	300	0.41	0.37	0.23	1.80	1.11	1.62	

Sample number			Section of shear zone analysed	γ	Shear plane orientation		Pitch of [x] from SW ^e	CPO pattern ^f	Fabric strength ranking ^g	Count of c-axes	Eigenvalues			Eigenvalue ratios			Fabric intensi- sity (<i>I</i>)
Field ^a	Vein sctn ^b	VUW ^c			Strike	Dip					S ₁	S ₂	S ₃	S ₁ /S ₃	S ₁ /S ₂	S ₂ /S ₃	
MHBM10	C		External		046	80	90	SG	3	300	0.42	0.41	0.18	2.35	1.02	2.30	0.28
MHBM11	B	39427	Internal	5.9	048	77	90	R	1	300	0.38	0.35	0.26	1.47	1.09	1.36	0.06
MHBM11	A		External		048	77	78	SG-3	3	300	0.41	0.34	0.25	1.69	1.22	1.38	0.11
MHBM12	B	39428	Internal	5	048	76	90	CG	3	300	0.46	0.32	0.21	2.18	1.43	1.52	0.24
MHBM12	C		Infilling		048	76	73	R	0	300	0.40	0.32	0.29	1.36	1.25	1.09	0.05
MHBM12	A		External		048	76	73	T2	3	300	0.41	0.35	0.24	1.68	1.17	1.43	0.10
MHBM13	B	39429	Internal	3.1	056	80	80	CG	3	300	0.43	0.32	0.26	1.66	1.35	1.23	0.11
MHBM13	A		External		056	80	73	SG-3	3	300	0.46	0.32	0.22	2.12	1.44	1.47	0.22
MHBM13	C		Internal	3.1	056	80	86	CG	4	300	0.45	0.33	0.22	2.03	1.34	1.51	0.19
MHBM13	D		External		056	80	68	SG-3	3	300	0.45	0.34	0.22	2.08	1.32	1.57	0.20
MHBM14b	A	39430	Infilling		225	82	92	C	3	300	0.46	0.29	0.25	1.79	1.57	1.14	0.17
MHBM14b	B		Infilling		225	82	105	SG	2	300	0.40	0.36	0.23	1.74	1.11	1.57	0.12
MHCH17	C	as above	Calcite Infilling		038	88	86	C	5	300	0.65	0.29	0.06	10.96	2.26	4.85	1.34
MHCH17	B	as above	Calcite Sheared	7.7	038	88	82	CG	5	300	0.65	0.29	0.06	10.17	2.26	4.51	1.31
MHCH17	A	as above	Calcite Unsheared		038	88	-	CG	5	300	0.57	0.34	0.09	6.45	1.67	3.87	0.87
MHCH20	C	as above	Calcite Sheared	6.8	222	86	90	CG	5	300	0.64	0.26	0.10	6.63	2.50	2.65	1.19
MHCH20	A	as above	Calcite Unsheared		222	86	-	C	5	300	0.64	0.29	0.07	9.18	2.24	4.10	1.25
MHCH20	J	as above	Calcite Sheared	4.4	222	86	82	CG	5	300	0.63	0.30	0.07	8.88	2.13	4.17	1.20
MHCH12b	A	as above	Calcite Infilling		221	85	-	C	5	300	0.63	0.24	0.14	4.52	2.67	1.70	1.00
MHCH12b	B	as above	Calcite Infilling		221	85	-	CG	5	300	0.63	0.27	0.10	6.45	2.30	2.80	1.10
MHCH14		as above	Calcite Infilling		218	88	-	C	5	300	0.63	0.23	0.14	4.40	2.74	1.61	1.00
TJFA47		as above	Calcite Infilling		213	60	-	C	5	300	0.65	0.24	0.11	6.02	2.77	2.17	1.22
MHSP09		as above	Calcite Infilling		216	46	-	C	5	300	0.77	0.16	0.07	11.25	4.87	2.31	2.20
MHBM03	B	as above	Calcite Infilling		048	78	-	C	5	300	0.73	0.15	0.11	6.62	4.76	1.39	1.82
MHBM03	A	as above	Calcite Sheared	6.3	048	78	89	CG	5	300	0.65	0.27	0.08	8.18	2.36	3.47	1.25
MH-EHD		39453	Euhedral Qtz	-	-	-	-	C	5	300	0.65	0.20	0.15	4.46	3.26	1.37	1.16

c-axis CPO	A	B
X-Y Plane	048@78E	048@78E
X (Pitch from S)	89	89
S1/S3	8.18	6.62
S1/S2	2.36	4.76
S2/S3	3.47	1.39
Finite ductile shear strain	>6.3	
Shear plane (S)	048@78 SE	
Vein orientation (V)	020@76 SE	
Alpine foliation (F)	038@83 SE	
Thin section plane (T)	228@12 NW

Appendix I-1. MHB03Cal. This sample has CPO fabrics measured from the internal and shear infilling vein sections (external section did not contain enough calcite for a crystallographic measurement). CPO fabric plot (A) has been interpreted as a cleft girdle because of its concentrations towards the y-axis which are unseen in plots such as CPO fabric (B) which is domain about the z-pole. Contours are calculated using a counting circle of 3 σ with plotted for equal point density. Schematic cartoons, fabric strengths and CPO fabric plots as in Appendix D.

c-axis CPO	A	B	C
X-Y Plane	038@88E	038@88E	038@88E
X (Pitch from S)	94°	82°	86°
S1/S3	6.45	10.17	10.96
S1/S2	1.67	2.26	2.26
S2/S3	3.87	4.51	4.85
Finite ductile shear strain		7.7	
Shear plane (S)		038@88 SE	
Vein orientation (V)		016@87 SE	
Alpine foliation (F)		036@70 E	
Thin section plane (T)		218@02 NW

Appendix I-2. MHCH17Cal. This sample has three CPO fabrics measured from the external and internal deformed vein sections and from the shear infilling vein. The three CPO fabric plots are all very similar however CPO fabric (C) does not have the c-axis poles orientated about the y-axis like the sheared vein fabric plots. The [x] direction found that defines the calcite CPO-derived stretching direction in CPO fabric plot (B) matches the quartz CPO-derived stretching direction (see Appendix D). Contours are calculated using a counting circle of 3σ with plotted for equal point density. Schematic cartoons, fabric strengths and CPO fabric plots as in Appendix D.

c-axis CPO	A	C	J	Finite ductile shear strain - White	4.4
				Finite ductile shear strain - Green	6.8
X-Y Plane	222@86W	222@86W	222@86W	Shear plane (S)	222@86 NW
X (Pitch from S)	78°	90°	82°	Vein orientation (VW) - White	002@82 E
S1/S3	9.18	6.63	8.88	Vein orientation (VG) - Green	104@64 S
S1/S2	2.24	2.50	2.13	Alpine foliation (F)	027@75 SE
S2/S3	4.10	2.65	4.17	Thin section plane (T)	042@04 SE

Appendix I-3. MHCH20Cal. This sample has two deformed veins on the same shear zone and calcite CPO fabric measurements were made from the internal sections of both veins with one external measurement from green veins external section. The two internal section samples (most sheared part of the vein) show cleft girdles whereas the external vein sample has a domainal concentration. Contours are calculated using a counting circle of 3σ with plotted for equal point density. Schematic cartoons, fabric strengths and CPO fabric plots as in Appendix D.

Appendix J-1. Crystallographic preferred orientations of calcite c-axes in the shear infilling vein samples on Chancellor Ridge, Sam Peak and at Baumann Glacier. Scatter and contour plots are on equal area, lower hemisphere, stereographic projections in the x-y-z reference frame (see Chapter 5). Contours were calculated using a 3σ counting circle and are plotted as lines of equal point concentration. Eigenvector ratios and fabric plot orientations can be found in Appendix H. CPO fabric plots are labelled by their field sample numbers and annotated with the thin-section orientation they were measured from (e.g. -st or -d; see Chapter 4). A second annotation to the sample number (e.g. A, B, C etc.) is the location of the sample in the sheared vein schematic illustrations in Appendix I. Where identified, internal asymmetries are illustrated on fabrics and the Alpine Schist foliation plane is plotted on fabrics external to the most

Cloud at sunset infilling the Fox Glacier valley behind the historic Chancellor Hut
- an evening roost for the local Kea (New Zealand Mountain Parrot).