GEOSCIENCES 09

Annual Conference
Oamaru, NZ

FIELD TRIP 10

WEST COAST STUDENT TRIP

Friday 20 November to Monday 23 November 2009

Leader: Dushan Jugum

Geology Dept, University of Otago

BIBLIOGRAPHIC REFERENCE:
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Field Trip notes by R. J. Norris, A. F. Cooper and V. G. Toy

Field Trip run by Dushan Jugum

Itinerary and route:

Friday 20th November

Leave airport: 8-9am (people have already booked to arrive at 7:30am so this is the best time)

Drive through Arthurs Pass and up the coast to just south of Westport then back along the coast to stay in Hokitika backpackers.

Things of interest: Arthurs Pass, Pancake Rocks and the Charleston Gneiss with pegmatites

Saturday 21st

Drive from Hokitika down the coast, stay at backpackers in Fox Glacier.

Things of interest: outcrops of the Alpine Fault and the Franz Josef Glacier

Sunday 22nd

Drive from Fox Glacier through Haast Pass and Lindis Pass to Mt Cook arrive late, backpackers.

Things of interest: Fox Glacier, beaches near Haast, Alpine Fault scarp, Haast Pass and Haast Schist

Monday 23rd

Drive from Mt Cook to Oamaru.

Things of interest: Mt Cook, Hooker and Tasman Glacier

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This field trip runs in the reverse direction from that guide.

INTRODUCTION

The field trip aims to examine the geological features and products of two plate collisional events in New Zealand's history. The first event saw the collision of the Torlesse and Caples terranes during the Rangitata Orogeny, the dynamo-thermal consequences of which were the formation of the Haast Schist. The inception of the Alpine Fault plate boundary in the mid-Cenozoic heralded the onset of the Kaikoura Orogeny, with the tempo of deformation increasing to the present day, where oblique collision between the Pacific and Australian plates results in uplift on the Alpine Fault and formation of the mountain range of the Southern Alps.

PREAMBLE

The Paleozoic-Mesozoic Rangitata Orogen may be divided broadly into two major assemblages of tectonostratigraphic terranes, the Hokonui Assemblage in the west and the Alpine Assemblage in the east. Each assemblage contains a number of terranes which may or may not have had original stratigraphic relationships with each other. The Hokonui Assemblage consists mainly of fragments of Permian-Jurassic volcanic arcs and arc-related sedimentary basins (Brook Street, Murihiku, Mitai/Dun Mountain terranes). It is generally weakly metamorphosed and only moderately deformed. The Alpine Assemblage is made up mainly of extremely thick sequences of greywacke and argillite with minor basic volcanics and cherts (Caples, Aspiring, Torlesse terranes). It is complexly deformed and metamorphosed up to amphibolite facies. The highest grade rocks crop out adjacent to the Alpine Fault where they have been exposed by recent uplift, but a broad axis of uplift extended through Otago during the late Mesozoic, exposing greenschist and epidote-amphibolite facies rocks as far east as Dunedin The part of the Alpine Assemblage exhibiting a metamorphic texture (i.e. cleavage or schistosity) is known as the Haast Schist, which includes the Otago Schists, Alpine Schists and Marlborough Schists.

The Haast Schist appears to be derived from at least three major lithologic associations. The eastern, and by far the largest, volume is derived from an extensive and very thick suite of Permian to Jurassic quartzofeldspathic sandstones and argillites, the Torlesse terrane. The western portion is derived from a ?Permian-Jurassic suite of volcanogenic sandstones and argillites, the Caples terrane. Between the two is the Aspiring terrane, a zone completely within the schist and dominated by pelitic schist, spilitic metavolcanics and cherts.

The first recognition of a systematic metamorphic zonation in the Haast Schist was by F.J. Turner (1933, 1938), who described a sequence of isograds along the Haast River. Rocks below the biotite zone were subdivided by Hutton and Turner (1936) into four textural zones based on the degree of schistosity development. Sub-greenschist facies metamorphic assemblages characterised by pumpellyite with or without prehnite were later described by Coombs (1960) and referred to the prehnite-pumpellyite and pumpellynite-actinolite facies.

The section exposed along the shores of Lake Hawea and its continuation along the Haast River is mainly within schist of the eastern portion derived from Torlesse quartzofeldspathic sediments. The composition of the original rocks is therefore fairly constant over a wide range of metamorphic and deformational states. The complete section takes us from rocks of pumpellyite-actinolite facies in which sedimentary features are still recognisable, to rocks of the oligoclase zone of the amphibolite facies which are best described as quartzofeldspathic gneisses in which all original features have been obliterated.

THE LAKE HAWEA SECTION - GENERAL DESCRIPTION

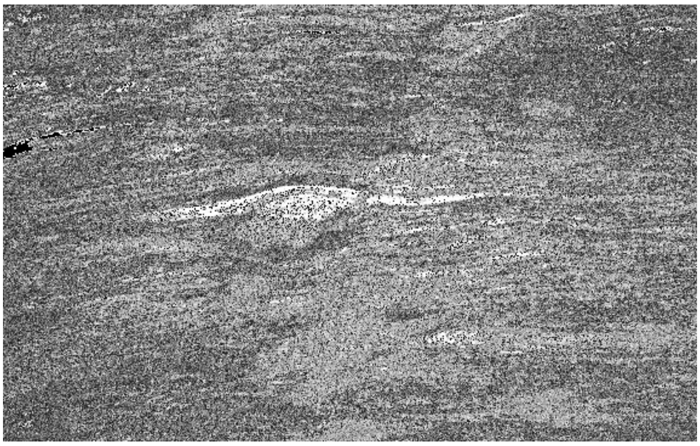
The shores of Lake Hawea, in particular the West Arm, expose a magnificent section within the Haast Schist, extending from textural zone IIB, pumpellyite-actinolite facies, to textural zone IV, greenschist facies (fig. 1). The main lithology is interbedded psammite and pelite, probably representing metamorphosed flysch. Graded bedding is recognisable at the lower grade (eastern) end of the section. Thick units of laminated pelite and pelitic conglomerate also occur, together with rare thin units of greenschist. The metamorphic mineral assemblage is in general quartz-albite-muscovite-chlorite-titanite with pumpellyite at the eastern end, epidote/clinozoisite at the western end and sporadic stilpnomelane and actinolite.

Two generations of early to syn-metamorphic structures and three generations of late to post metamorphic structures have been recognised. The earliest structures recognised are steeply plunging folds in bedding with a well-developed axial-surface cleavage. They are most clearly seen in the lower grade rocks along the west side of the lake, where fold vergence and graded bedding indicate their being part of the upper limb of a southward facing syncline with an amplitude of about 20 km. This structure is similar to steeply plunging folds described in greywackes further east by Spörli and Lillie (1974) and Ward and Spörli (1979). Accompanying the folds are thick quartz veins and pods developed parallel to the axial surface. Several other vein orientations were produced at the same time. With increasing metamorphic grade westward, metamorphic lamination is developed parallel to the cleavage by pressure solution and recrystallisation. The nature of this lamination is dependent on both the fine and gross lithological characters of the original rock. Deformed conglomerate horizons indicate increasing total strain westward, with constant volume strain ellipsoids for the pebbles of 2.6:1.35:0.3 near the top of TZIIB and 4:1:0.25 within TZIIIA (i.e. 75% shortening perpendicular to cleavage (Norris and Bishop 1990)).

The second generation of structures develop with increasing intensity westwards, from occasional buckles and kinkfolds with patchy development of crenulation cleavage, to an intense, differentiated, crenulation cleavage with bedding, early cleavage and early quartz veins all tightly folded. Refolded early folds are occasionally recognisable. The form of the later mesoscopic folds is largely governed by the buckling of the early quartz veins and pods which impart a gross mechanical heterogeneity to the rock. The quartz pods become much thinner in the textural zone IV schists, probably due to greater flattening during deformation. Pressure solution was important in developing the differentiated cleavage and the attenuated folds; quartz veining parallel to the cleavage increases in importance towards higher grade.

The second generation folds plunge southwards over most of the section but change to northward plunging across a narrow zone of folding and dislocation which trends north-south across the western end of the West Arm. The deformation related to this zone is referred to the third generation of structures; a similar north-south trending zone of deformation is found on the east side of Lake Hawea. Conjugate reclined folds on various scales characterise this generation; crenulation cleavage is locally developed and quartz veining is common. The fourth generation is widespread throughout the area and is mainly represented by shallow dipping conjugate kinkbands and zones of *en echelon* sigmoidal quartz gashes. Stress analysis for the third and fourth generations indicates a change from subhorizontal compression to subhorizontal extension, assuming no large change in attitude of the foliation (which is a fairly dubious assumption!). On the north side of the Neck, lamprophyre dykes dated regionally at 23-28 Ma (Adams and Cooper 1996) postdate kink folds of this folding phase.

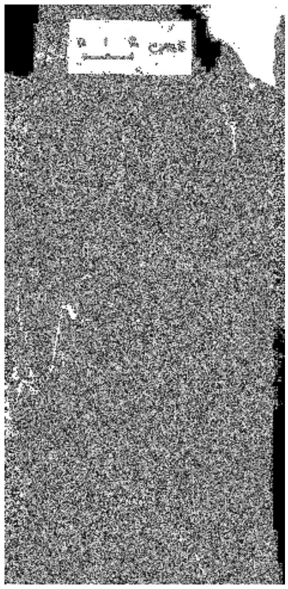
The fifth generation of structures consists of northeast- and southeast-trending fault zones containing contorted schists and welded breccia, often impregnated with Fe-rich carbonate. These structures are definitely Cenozoic as, elsewhere, they are associated with and cross lamprophyre dykes of known early Miocene age. Occasional low-angle eastward dipping thrust planes have been recorded; while they definitely post-date F_3 (Dingleburn) structures, their relationship with later generations and their regional significance is unknown.



(a) F1 fold in bedding with S1 axial plane cleavage (b) Deformed conglomerate with granitoid and sst clasts

c) F2 folds in D1 quartz veins and S1. cleavage

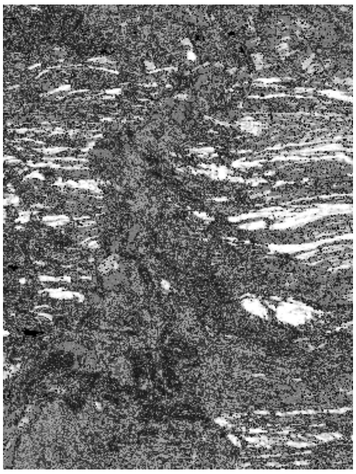
(d) F2 folds in psammites and pelites



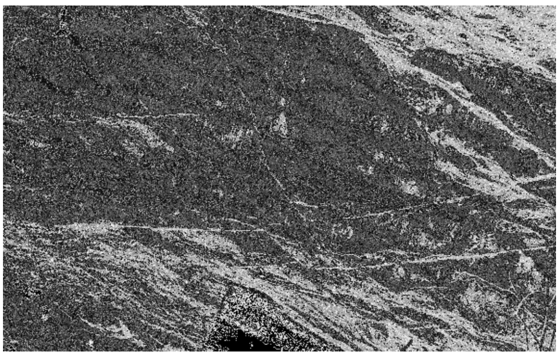
(e) Differentiated S2 crenulation

(f) conjugate F3 folds

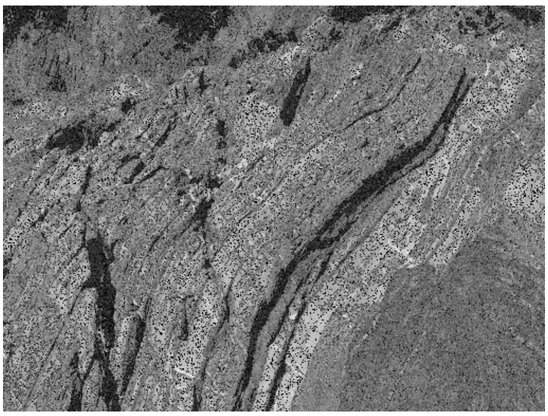
(g) F3 folds with axial plane S3



(h) crosscutting lamprophyre dyke



(i) F4 kink folds



(j) F4 folds with quartz gashes

THE HAAST RIVER SECTION - GENERAL DESCRIPTION

Along the lower Haast River the road cuts obliquely across the isograd-isotect trend, and from east to west is exposed a progressive metamorphic sequence of chlorite (textural zone IV), biotite, garnet, and oligoclase zones. At Haast River, the earliest folding phase folds a well-developed quartz-albite lamination, suggesting a correlation with F_2 at Lake Hawea. These structures have been refolded by F_3 structures which have an almost identical style to F_2 structures described for the Lake Hawea section. Thus it would appear as if an extra phase of syn-metamorphic folding appears in the higher grade schists. A similar sequence is described in the Mt Aspiring area by Craw (1985). If we assume progressive non-coaxial deformation of the schist during metamorphism, then it is to be expected that the more highly strained higher-grade schists will exhibit a greater complexity of ductile deformation phases than the lower-grade schists. Detailed mapping of greenschist horizons and the sense of vergence of mesoscopic folds define the hinge zone of a macroscopic antiformal F_3 fold opening to the SE in biotite and garnet zone schists of the eastern Haast River area (fig. 2; Cooper 1974). Both biotite and garnet porphyroblasts show random orientation with respect to S_2 and S_3 surfaces indicating that the metamorphic maximum post-dated both folding phases (Grindley 1963; Cooper 1974).

Further west the dominant foliation is folded by broad, open, subhorizontal macroscopic F_4 structures designated the Haast Antiform, Thomas Synform, and Mount Victor Fold Belt (Grindley et al. 1959; Cooper 1974). On a regional scale these structures fold the isograds causing repetition of garnet and oligoclase metamorphic zones (fig. 2). Tightly appressed mesoscopic fold hinges exhibit strained quartz and feldspar and bent flakes of mica on a microscopic scale, attesting to late-metamorphic deformation. Cooper et al. (1987) have suggested that the north-south trending F_4 structures, which appear to be associated with the intrusion of east-west lamprophyre dykes of early Miocene age, formed as en-echelon folds in a dextral strike slip regime along the Alpine Fault at the time of its inception as a through-going transform fault. A post-F_4 suite of east-west faults are spatially related to the occurrence of F_5 kink or chevron folds. The major structure of this phase, the Burke Fault, is in turn truncated by a NE-striking fault, probably associated with the Moonlight Fault system (White, S.J., 1996, pers, comm.), again with associated kink folds (F_6). Metamorphically the greenschist-epidote amphibolite-amphibolite facies transition has been investigated by Turner (1933), Mason (1962), and Cooper (1971;1972). The epidote-amphibolite facies effectively represents a transitional zone in which albite and actinolite characteristic of lower grades coexist with, but suffer progressive depletion to, oligoclase and hornblende, typical phases of the amphibolite facies. Oligoclase zone gneisses with, further north, concordant partial melt granite-pegmatite sheets (Wellman 1955; Wallace 1974) are truncated to the west by the Alpine Fault.

K-Ar ages of schist micas from Haast River (Mason 1961; Hurley et al. 1962; Adams and Gabites 1985) range from 8 m.y. or less, adjacent to the fault (oligoclase zone) to around 150 m.y. 25 km further east (chlorite zone) (fig 3), the variation being ascribed to differential uplift along the Alpine Fault, or to frictional heating during the Cenozoic (Sheppard et al. 1975; Scholz et al. 1979). There is evidence for excess radiogenic ^{40}Ar in schist minerals near to the Alpine Fault (Gabites & Adams, 1978; Chamberlain et al. 1995). Ages from schists of central and eastern Otago, sufficiently distant from the Alpine Fault to be unaffected by argon loss or redistribution through uplift, range from 133-141 m.y. (Mason 1961; Hurley et al. 1962; Harper and Landis 1967) to as high as 200 m.y. on the lowest grade rocks (Adams et al. 1985) suggesting a Jurassic age of Rangitata metamorphism. The very young K-Ar ages from specimens close to the Alpine

Fault, coupled with results from fission track dating of apatite and zircon in schists (Kamp et al. 1989), indicate uplift of the Alpine Schists occurred only recently. Kamp et al. suggest that uplift was underway by about 7 m.y. at Haast River, and by 5 m.y. in the north, at Arthur's Pass.

The schists are crosscut in the Haast-Wanaka area by a swarm of lamprophyre intrusions (Turner 1933; Mason 1962; Grindley 1963; Cooper 1971, 1986). Intrusives, taking the form of dykes paralleling the ac joint system of the F_3 folding and sills paralleling the otherwise dominant foliation, are restricted to a roughly linear belt up to 25 km wide, extending from the Paringa River area southwards to the Shotover River, a distance of 100 km (fig. 4). The age of the dykes has been a matter of some debate. K-Ar dates on dyke minerals and whole rocks from the Haast area are highly discordant, with in general higher K minerals giving younger ages, and lower K minerals and whole rocks giving older ages, ranging from late Miocene to Precambrian (Wellman and Cooper 1971; Adams, C., unpubl. data). In the Haast River area, and in the western Matukituki River, the range of dates from 15-846 Ma clearly indicates a major redistribution of argon; the occurrence of excess radiogenic argon (as has been demonstrated in schist minerals) is highly likely. In contrast, Rb-Sr whole rock isochron ages at Haast River, a U-Pb zircon age on a dyke at Burke River, and K-Ar ages from eastern dykes in the swarm near L. Wanaka (distant from the Alpine Fault) yield consistent late Oligocene-early Miocene ages (Cooper et al. 1987, Adams and Cooper 1996)

At Haast River the dyke swarm is lithologically diverse, with a broad spectrum of consanguineous intrusives ranging from feldspar-free damkjernitic lamprophyre, through dominant camptonitic lamprophyre to tinguaite, trachyte and carbonatite (Cooper 1971, 1986). The latter are markedly enriched in the characteristic trace element suite Ba, Sr, Nb, R.E.E. and Th, exhibit extensive fenite contact zones with the host schist, and have oxygen and carbon isotope ratios typical of magmatic carbonatites (Blattner and Cooper 1974).

Geophysical evidence (Garrick and Hatherton 1973) has revealed the presence of a reflecting surface at 2-3 km depth restricted to the area of known dyke swarm outcrop in the Haast Valley. This surface has been interpreted as the top of the source magma chamber, an hypothesis compatible with the occurrence of gabbro and syenitic xenoliths in dykes and the diversity of dyke compositions arising through differentiation. A pronounced magnetic anomaly ascribed to the magma chamber north of Haast River (Woodward and Hatherton 1975) is absent further south along the swarm. Here the dyke swarm is composed solely of lamprophyres (occasionally enclosing lherzolite xenoliths) attesting rapid magmatic rise from mantle depths without appreciable crustal differentiation.

Refolded F2 folds, Clarke Bluff

ITINERARY

DAY 1 - HAWEA TO HAAST

The control structure at the outlet of Lake Hawea, adjacent to the Lake Hawea turn-off, is used to control the level of the lake for hydroelectric purposes. Water from Lake Hawea flows into the Clutha River and feeds the hydrostation at Roxburgh. Lake Hawea, like most of the major South Island lakes, is glacial in origin and is very deep, in places its bottom reaching below sea level. The road follows the western shore of the lake. Views to the north are of the ranges on either side of the Hunter Valley.

NOTE; The lake level is controlled for hydroelectric purposes. The excellence of the lakeshore exposures is dependent on the lake level being low. Unfortunately the tour leaders have no control over this factor!

STOP 1: Hawea Foreshore

Exposure of textural zone IIB psammites, pelites and metatuff. Psammites are cleaved but generally lack the segregation lamellae present in the pelites, although a coarse lamination is locally developed parallel to cleavage by pressure solution. This results in dark mica-rich seams dividing the rock into thin lenses or microlithons parallel to cleavage. Microscopically, they retain traces of the original clastic texture in a thoroughly recrystallised matrix. Occasional colourless pumpellyite without prehnite indicates the rocks belong to the pumpellyite-actinolite facies. Graded bedding is occasionally preserved in the interbedded psammite/pelite units.

Bedding (S_o) is the form surface of tight to isoclinal folds (wavelength ca 1 metre) with sporadic quartz lodes developed parallel to the axial surfaces (S_1). The lodes contain additional albite and calcite and typically have a chlorite selvedge adjacent to the enclosing schist. The folds (F_1) generally show sinistral vergence and occasional graded bedding indicates that they face southwest. This suggests that the rocks are part of the eastern limb of a southwest facing F_1 syncline.

Thin early quartz veins are occasionally found folded and transposed by F_1. More commonly however, folded quartz veins are discordant to F_1 folds, suggesting emplacement after the initiation of F_1 folds and folding during a later stage of deformation during which tightening up of the F_1 structures took place.

Bedding and S_1 are occasionally folded into tight chevron or kink style folds with steep axial surfaces and steeply plunging hinges. Locally they develop an axial plane crenulation cleavage. Regionally folds of this style and orientation are common in north striking belts paralleled to faults. They are post-metamorphic in age and represent the third phase of deformation recognised in the Lake Hawea area. 2-3 cm quartz gashes, often in *en echelon* arrays are associated with shallow dipping kinkbands that represent the fourth generation of structures (F_4). Folds of this generation are widespread throughout the Hawea section. A third post-metamorphic generation of structures consists of northeast trending faults with associated locally developed folds. The fault planes are impregnated with ankeritic carbonate and commonly have well indurated breccias developed on them. These faults may be related to the Otago block fault system.

STOP 2: West arm of Lake Hawea - east end

The section comprises units of pelitic and interbedded pelitic and psammitic schist, together with units of conglomerate and rare, very thin greenschist horizons (metatuff?). The section is just upgrade from the zone IIIA isotect and from the greenschist facies isograd, so that clinozoisite has largely replaced pumpellyite. The greenschists are rich in actinolite. Thick irregular quartz lodes parallel to S_1 are common, and lamination is developed in all psammites although it is very variable in intensity; some thin units of intensely laminated schist may be seen. The conglomerates range from granule to cobble conglomerates, although the clasts are so strongly deformed that generally only the larger ones are recognisable. A prominent band of cobble conglomerate (see section) is folded into an F_1 fold. Well over 60% of clasts are of intrabasinal psammite and pelite, while the exotic clasts include tonalite, adamellite and epidosite. K-feldspar in these clasts is largely replaced by chessboard albite+stilpnomelane and biotite by chlorite, but much of the original igneous texture is preserved. Prominent pressure shadow tails of quartz and albite are developed on the clast margin parallel to the foliation. Measurements of clasts suggest a strain ellipsoid shape of 4:1:0.25 (75% flattening perpendicular to foliation), with the long axis parallel to the F_1 fold axis (Norris and Bishop 1990). This estimate of flattening undoubtedly represents a minimum value, due to the difficulty of measuring the most deformed clasts.

F_1 folds in bedding are easily recognised at the east end of the section - they are very appressed and transposition along their axial surfaces is locally strongly developed. F_2 folds, with moderately steeply southward plunging axes, occur sporadically, particularly in the D_1 quartz lodes. A crenulation cleavage is developed locally around the folded lodes. F_2 folds and S_2 cleavage increase in intensity towards the west end of the section. F_4 kink folds and associated quartz gashes and veins are abundant - they usually dip shallowly westward, with some *en echelon* gashes dipping more steeply. The road outcrop opposite the passing bay show intense development of F_4 kink bands to the extent that a crude crenulation cleavage is developed.

Many generations of veins containing quartz and other silicates may be seen – these apparently formed during all stages of the metamorphic and structural history. Their presence attests to the ease of transfer of material in solution – plentiful fluid inclusions in the vein material indicate the former presence of a fluid phase

STOP 3: West Arm, Lake Hawea

The party will work its way down to the first exposures on the lakeshore about 100 m to the east (provided the lake level is not too high - otherwise we will examine the road cuttings). For the next 200-300 m eastward there are extensive exposures of interbanded psammites and pelites showing intensive folding by the D_2 generation of structures. The rocks are in textural zone IIIB, greenschist facies, chlorite zone. Note the folding of S_1 segregation laminae and the development of an S_2 crenulation cleavage. The folds in general have formed by a buckling process and psammites and pelites form class 1C and 3 styles respectively (as defined by Ramsay 1967). The folds show thickened hinges and thinned limbs, sometimes to the extreme; the process is helped by pressure solution along the axial surface cleavage which locally leads to a differentiated crenulation cleavage.

The D_1 quartz lodes represent heterogeneities in the rocks during D_2 folding - folds in psammite bands often show intense distortion in the neighbourhood of a buckled quartz lode. The D_2 deformation appears to have been strongly non-co-axial at least locally, as F_2 folds with S_1 as form surface have been refolded by identical folds of ostensibly the same generation. In the more pelitic lithologies, the quartz lodes largely controlled the development of minor structures. Boudinage and the development of quartz rodding may also be seen. Refolded F_1 folds are occasionally recognisable within this section. As along most of the West Arm section, the F_2 folds show sinistral vergence.

STOP 4: West Arm of Lake Hawea - west end

Textural zone IV, greenschist facies. F_2 and L_2 are here northward plunging, whereas to the east along the lower grade part of the section they plunge south. A zone of F_3 folding and associated faulting crosses the section immediately east of these outcrops and the change in plunge takes place across this zone. Minor kinks and fractures of the F_3 generation may be seen in these outcrops.

Note the highly attenuated F_2 folds and the very flattened quartz lodes that were so prominent at lower grades. The F_2 folds here show sinistral vergence, which coupled with the northward plunge, indicates that they lie on the west limb of a macroscopic F_2 synform, whereas the rocks to the east lie within the east limb of the synform.

The road climbs over the narrow neck separating Lakes Hawea and Wanaka. A spectacular view of Lake Wanaka is obtained from a vantage point on the west side of the neck. The road follows the eastern shore of Lake Wanaka to the head of the lake at Makarora. Here the Makarora River flows south from the Main Divide into the head of the lake, forming an extensive delta. A short distance past Makarora the road enters the Mount Aspiring National Park and begins its climb to the Haast Pass. Beech forest forms an extensive cover on the lower slopes of the mountains, while snowy peaks of the Main Divide including Mt Brewster (2423 m - 7950 ft) are visible, if the weather permits. From the pass summit the road winds down the valley of the Haast River through the narrow gorge known as the Gates of Haast, and on to Pleasant Flat where panoramic views of the Southern Alps are obtained, looking up the valleys of the Landsborough and Clark Rivers to Mt Hooker (2652 m - 8700 ft). The lushness of the vegetation reflects the dramatic increase in rainfall that takes place across the Main Divide (e.g. 305 mm - 12 inches/year) at Alexandra and in excess of (6350 mm 250 inches/year) at Haast River.

All the way from Lake Hawea the road has been heading in a fairly constant northerly direction, parallel to the isograds and isotects in the schist. Hence, although a long way from the last stop, the rock type and metamorphic grade are essentially the same.

STOP 5: Gates of Haast

The schists exposed in the extensive road cuttings are pelitic schists of TZIII, chlorite zone. Several outcrops expose a spectacularly deformed conglomerate, with prominent light green, probably tuffaceous, clasts. Strain analysis indicates a constant volume strain ellipsoid of 3.6:1.3:0.21 (i.e. almost 80% shortening normal to the foliation (Norris & Bishop 1990)).

STOP 6: Clarke Bluff

Roadside exposures at the confluence of Haast and Landsborough Rivers are of textural zone IV quartzofeldspathic schist and greenschist. Thick, laterally persistent, segregation laminae (S_1) are tightly folded into isoclinal folds, often with sheared out limbs; the resulting axial surface foliation (S_2) defines the form surface of intense F_3 folds and is intersected at a high angle by steep eastward dipping 1 cm thick quartz-albite segregations developed parallel to S_3. The mesoscopic F_3 folds plunge steeply south and have a symmetrical vergence, which taken with the high angle between S_2 and S_3, suggests proximity of a macroscopic F_3 hinge zone. Since F_3 vergence is westerly, the macroscopic fold at Clarke Bluff must be synformal. The schist assemblages at this outcrop contain occasional biotite and are situated virtually on the biotite isograd. A few hundred metres to the east biotite is absent, and the rocks belong to the chlorite zone, greenschist facies. Since the F_2 folds deform a segregated foliation, they must be at least equivalent to the F_2 folds at L. Hawea. Thus there seems to be an extra phase of syn-metamorphic folding here. In general, there are more phases of ductile folding in higher grade schists than at lower grades. We think that these fold phases are in part a continuum formed during a non-coaxial deformation history.

Lamprophyre, tinguaite and trachyte dykes cross-cut the schists at Clarke Bluff. A rather weathered lamprophyre dyke about a metre in width cuts the schists at Stop 6, and a second, very thin, dyke shows development of a metasomatic alteration aureole. These intrusives are members of a post-metamorphic dyke-swarm that has been traced northwards to the Alpine Fault (fig. 4).

STOP 7: Pivot Creek

This tributary of Haast River drains predominantly biotite zone schists and good examples of varied quartzofeldspathic, greenschist and metachert lithologies can be sampled in float. Talc-carbonate-chlorite-quartz rocks, representing metamorphosed ultramafites, outcrop upstream in the hinge zone of a macroscopic antiformal F_3 fold. Pivot Creek also contains abundant float of ocellar lamprophyres (occasionally containing cognate hornblende gabbro xenoliths), sodalite- and cancrinite-bearing tinguaites, and trachytes. Dyke contacts with country rock schist show varying degrees of fenitization (Na-metasomatism) with the development of aegirine- and riebeckite-bearing assemblages. Carbonate impregnated and veined float boulders are derived from the vicinity of a norsethite-bearing carbonatite dyke outcropping upstream.

STOP 8: 18 Mile Bluff

Oligoclase zone quartzofeldspathic schists and gneisses with sub-horizontal schistosity are exposed in the core of the post-metamorphic (F_4) Haast Antiform. Views to the southwest up the valley of Gap Creek look practically along the axis of the structure, while schistosity traces on the ridge to the west pick out the complementary Thomas Synform. These large folds fold the isograds but predate the lamprophyre dykes; to the north, near Moeraki River, the folds intersect obliquely the trace of the Alpine Fault.

To the south, folds of the Haast Antiform-Thomas Synform generation have been mapped through the Matukituki River area (Craw 1985), where they are associated with the Moonlight Fault. At Bobs Cove, Lake Wakatipu, Turnbull et al. (1975) describe Oligocene limestones (preserved along the trace of the Moonlight Fault) which are folded by structures having an identical style and orientation to Haast Antiform-type folds further north. The post metamorphic folds at Haast

River are interpreted to be post Oligocene, but are cut by lamprophyre intrusions of late Oligocene-early Miocene age. The structural and geometric relationships and chronological development of the Haast folds and associated faults and fractures in south Westland-northwest Otago has been compared to the structures generated during laboratory clay-model simulation of right lateral wrench regimes (Cooper et al. 1987). They interpreted the folds, Riedel shears, tension fractures and dykes of western Otago as forming during the initial stages of dextral wrenching that was to result in the propagation of the Alpine Fault plate boundary through western South Island. The age of the lamprophyre dyke swarm constrains the age of formation of the Haast Antiform-type folds, which in turn constrains the inception of the Alpine Fault to early Miocene times. Intrusion of highly alkaline and carbonatitic magmas at this time argues strongly for an early transtensional character to the Alpine Fault.

STOP 9: Big Bluff (not visited in 2009)

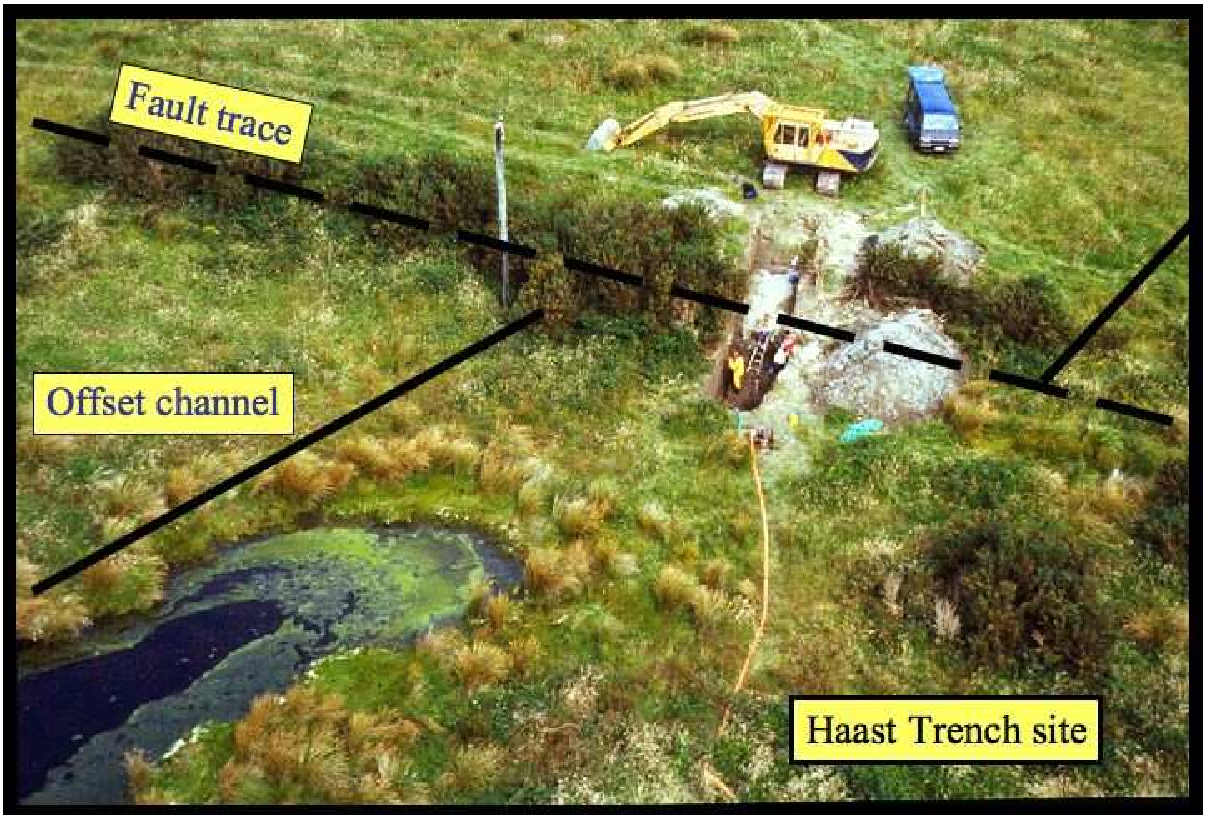
A section of oligoclase zone quartzofeldspathic schists and gneisses with interlaminated garnet amphibolite and rarer metachert. The dominant $S_{2\text{-}3}$ foliation dips steeply eastwards. L_3 lineations now plunge northward (rather than southward as at Clarke Bluff) since the Big Bluff and Thomas Bluff area lies on the west limb of the post-metamorphic fold belt. Mineralogically the quartzofeldspathic schists contain the assemblage quartz-oligoclase- microcline-muscovite-biotite-sphene±garnet lacking the albite characteristic of the peristerite-bearing garnet zone schists further east. The amphibolites, which represent metamorphosed basic tuffs or flows, are composed of hornblende- oligoclase-garnet-sphene-rutile±biotite. Assemblages are diagnostic of the amphibolite facies.

From Big Bluff to Haast, the road crosses the line of the Alpine Fault, and the mountains suddenly give way to the low lying coastal plain. The rounded bush-clad knob to the right of the road is Mosquito Hill, composed of rocks belonging to the Paleozoic Tuhua orogenic belt.

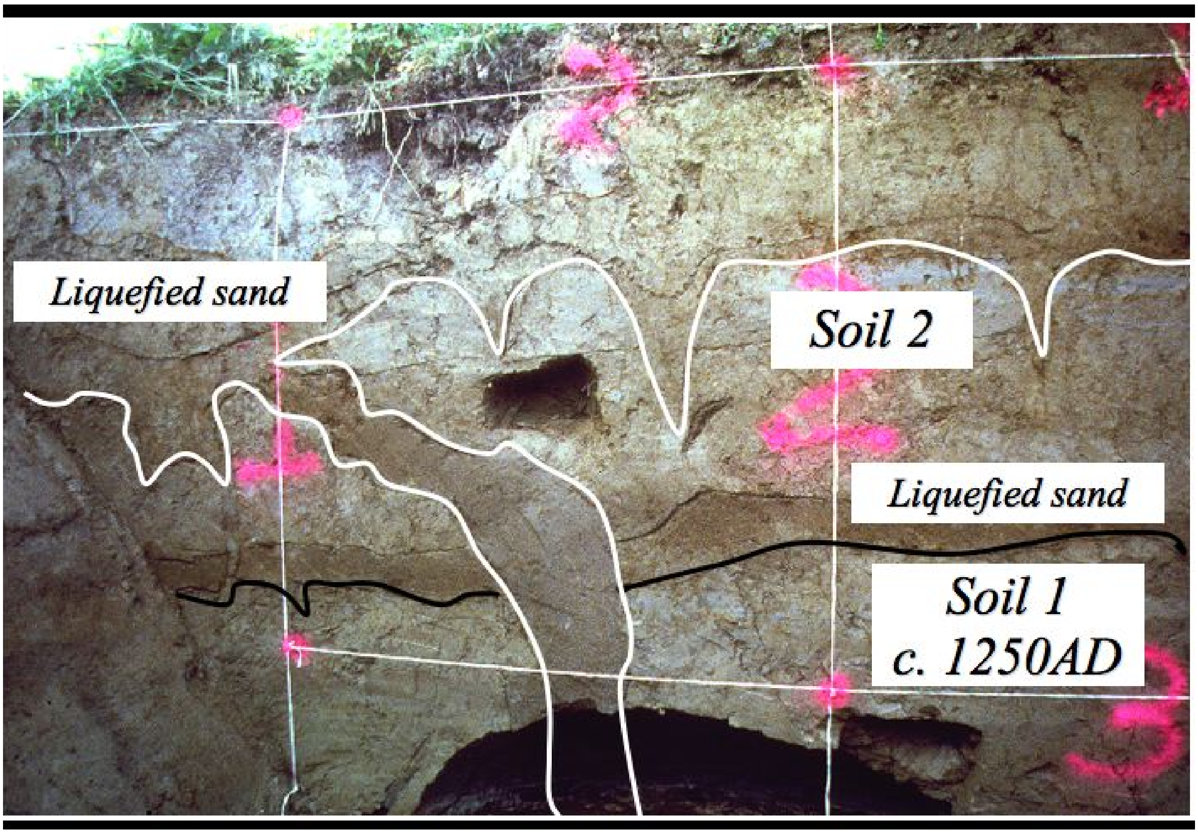
STOP 10: Alpine Fault Trace

A Recent trace of the Alpine Fault is visible crossing the paddock next to the road (SH6). Vertical displacement of a terrace and lateral displacement of the terrace riser may be seen (fig. 5). The terrace is displaced vertically by 1.5 m, south side up, and its riser by 16m of right slip (authors' unpublished data). It is thought likely that the displacement of the terrace may represent the last two events on the Alpine Fault within the last 800 yr. On the north bank of the Haast River, the Alpine Fault trace is marked by a 5 to 10 m high scarp, displacing a terrace composed of fluvial sediments radiocarbon dated at between 7300 and 4000 y B.P. A creek channel, deeply incised into the terrace is offset dextrally by 94 m at the fault scarp. Horizontal and vertical offsets of the terrace have occurred at minimum rates of 23.5 mm/y and 2.25 mm/y respectively, for the past 4000 years (Cooper and Norris 1995).

During late summer 1998, a joint IGNS-OU Geology Department team excavated four trenches across the Alpine Fault in south Westland. Two trenches were dug at the Haast River site, and two at Okuru River, to the south. The examination and detailed logging of the trench walls show that there have been three recent earthquake events on the fault trace, each resulting in a lateral offset of approximately 8 m. ^{14}C dating of seeds in fossil soils gave somewhat ambiguous results, due to sedimentary reworking, but the three events have been tentatively identified at immediately prior to 850 ± 50 yr B.P. (equivalent to an age in calendric years of 1100-1200 AD), later than 400 ± 120 yr B.P. (equivalent to 1420-1630 AD). and later than 262 ± 56 yr B.P. (equivalent to 1640-1670 AD).



(a) Alpine Fault trace at Haast and site of one of the trenches



(b) Trench wall showing liquefied sand injections and buried soils from last two earthquake ruptures

DAY 2 - HAAST to FRANZ JOSEF

STOP 11: Haast River Bridge

From the Haast River bridge there are excellent views of the Alpine Fault scarp. The Alpine Fault is the major structure of the South Island and represents the boundary between the Pacific and Australian plates. In Westland the fault separates Haast Schist to the east from Tasman Metamorphic Belt rocks to the west.

At the present day the Alpine Fault is active and has an oblique-slip character - recent terraces and their associated channels, rivers and streams attest to both lateral and vertical movement. The total dextral slip on the fault is constrained by the 460-480 km lateral displacement of the Dun Mountain Ophiolite Belt (Wellman 1955), while the restricted outcrop of high-grade kyanite-bearing, amphibolite facies schists adjacent to the fault requires appreciable vertical uplift, which may be as high as 25 km (Cooper 1980).

Although the extent of these displacements is reasonably well established, the timing of the dextral shear was for a long time the subject of controversial debate. Wellman (1964) proposed that the plate boundary and the Alpine Fault are entirely of Neogene age, a view supported by sea-floor spreading results (e.g. Molnar et al. 1975) and by the sedimentary history of southern New Zealand (Carter and Norris 1976). Suggate (1963) however, proposed that part of the transcurrent movement took place during the Rangitata Orogeny (Jurassic-Cretaceous) and part in the Kaikoura Orogeny (Miocene-Recent). Other plate tectonic reconstructions (e.g. Weissel et al. 1972) also require a plate boundary through New Zealand from the inception of sea-floor spreading in the late Cretaceous. A critical line of evidence by Suggate is the apparent lateral offset by only ca 130 km of presumed coeval Cretaceous lamprophyre dyke swarms. However, work has shown these dyke swarms to be non-coeval and in fact the southern swarm to be of Neogene age (see discussion for Haast section and Cooper et al. (1987)).

The average rate of plate displacement at Franz Josef is 37.5 mm/y (DeMets et al. 1990, 1994), with a plate vector of 071°. The motion is obliquely convergent on the plate boundary, with components normal to the fault of 10 mm/y, and parallel to the fault of 36 mm/y. Due to a lack of suitable dated marker horizons at the Alpine Fault, the rate of transcurrent movement as determined from geological field evidence is not tightly constrained, but is between 60 and 75% of that predicted. Resurveys of 100 yr old geodetic networks suggest that accumulating elastic strain is distributed over a zone up to 100 km wide east of the Alpine Fault (Walcott 1978), with the total integrated shear strain consistent with the plate tectonic rate. Shear strain rates in the range 0.5 to 0.6 ppm/y with a principal axis of relative contraction at about 110° were reported for networks in the central and northern parts of the Alpine Fault (Walcott 1984, fig. 6). These determinations have been supplemented by results from small aperture networks, centered on the fault, such as the one extending across the fault at Haast River (Wood and Blick 1986, fig. 6). Strain rates at the fault range fom 0.4 to 1.4 ppm/y, but with essentially the same azimuth of relative contraction.

Over the last 15 years, high precision GPS measurements have been made across the South Island (e.g. Beavan et al., 2000) that provide a detailed map of strain accumulation. Shear strain reduces exponentially east of the Alpine Fault and is best fitted as representative of elastic strain around an east-dipping fault that is fully locked to depths of 5-10 km (Beavan et al. 1999; Pearson et al.

2000) and creeping aseismically at c. 25 mm/yr below this depth, although some degree of interseismic coupling may persist to as deep as c. 18km (Wallace et al. 2007).

Uplift and strike-slip rates at the Alpine Fault itself have been determined on the basis of displacement of marine and fluvial sedimentary sequences, and offset landforms:

- at Paringa River, 45 km northeast of Haast, localised rates of 10.7 mm/y (Suggate 1968), revised to 13.7 mm/y (Simpson et al. 1994) and a more regional rate of 7 to 8 mm/y (Simpson et al. 1994) have been calculated for the last 16 ka

- at Haast River minimum vertical and horizontal rates of 23.5 mm/y and 2.25 mm/y have been calculated for the last 4 ka (Cooper and Norris 1995).

- at Okuru River, 5 km south of Haast, a vertical rate of 4 mm/y has been determined for the last c. 10 ka (Cooper and Bishop 1979; Norris & Cooper 2001).

- at Hokuri Creek, Lake McKerrow, Hull and Berryman (1986) document uplift rates of 2.2 mm/y and 1.6 mm/yr for marine shells northwest and southeast respectively of the Alpine Fault. Sutherland and Norris (1995) document an uplift rate of 1.4 mm/y at a locality 1 km northwest of the fault in the same region, based on displacement of marine shells.

- Sutherland et al. (2006) have calculated a horizontal rate based on offset moraines and other glacial features of 23.5 ± 2 mm/y determined over a time span of 75 ka

- Barnes (2009) examined the bathymetric expression of glacial geomorphic features formed in the last 20 ka, offshore Fiordland, to determine strike slip rates of 27.2 (-3.0/+1.8) mm/yr between Milford and Caswell Sounds, increasing southward to 31.4 (-3.5/+2.1) mm/yr between Caswell and Doubtful Sounds.

In contrast to the measured uplift rates, the rate of uplift at Haast at the present day, predicted from plate motions (DeMets et al. 1994), should be as high as 9 mm/y. The discrepancy between rates of vertical motion observed at the Alpine Fault south of Haast and those predicted can probably be explained by distributed movement within the Haast Schist east of the fault and offshore shortening by underthrusting of the Tasman Sea.

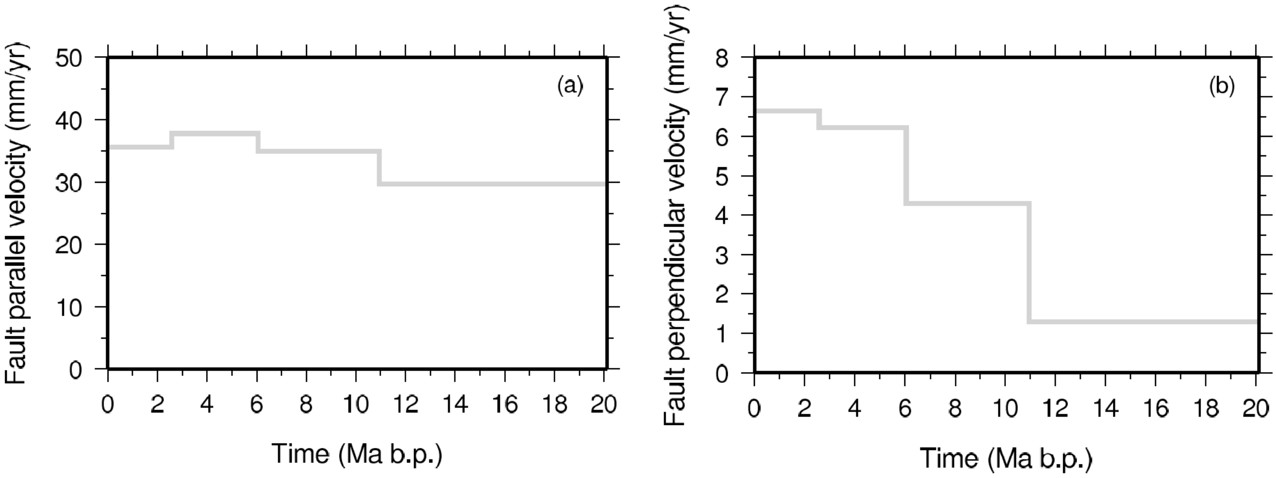


Fig. 7: Components of velocity of the Pacific with respect to the Australian Plate (a) parallel to, and (b) perpendicular to the Alpine Fault in its central section, calculated from the plate motion model presented by Cande & Stock (2004)

The most recent plate motion models for the region, from new fits of magnetic anomaly and oceanic fracture zone intersections (fig. 7), indicate that the component of oblique plate motions that results in convergence across the plate boundary has increased relatively steadily over the last 20 million years (Cande & Stock 2004). However, it is likely uplift rates accelerated markedly around 5 Ma, when data from the Waiho-1 petroleum borehole indicate there was a dramatic increase in the sedimentation rate offshore (Sutherland 1996). Accelerating uplift since the Pliocene is also compatible with the sedimentological evidence from West Coast stratigraphic sequences where Alpine Schist detritus is first encountered in gravels only 2 m.y. old (Wellman 1979). The c. 5 Ma age is commonly accepted as the age of initiation of the Alpine Fault as a distinct structure (e.g. Toy et al. 2008).

If the weather is clear, the view southwards from the Haast bridge shows flat-topped steps up to 1.3 km long developed at **ca** 1450 m a.s.l. on schist ridges east of the Alpine Fault. Lower, less widespread, steps are also present, the most conspicuous being at 960 m a.s.l. Rounded quartz granules, with surface textures indicative of a high energy subaqueous environment, closely similar to textures on present day Haast beach pebbles, have been collected from both high altitude terraces (Cooper and Bishop, 1979). The horizontal steps are interpreted as remnants of uplifted marine platforms which developed on an open-ocean coast as the Southern Alps were rising. Unfortunately the age of these high altitude surfaces is not known and the chances of a direct determination appear slight.

A detailed analysis of contoured topographic maps of the Alpine Front suggest that correlatives of the Okuru platforms occur over the length of the Southern Alps. Furthermore a flight or sequence of terraces, comprising 16 discrete surfaces, can be recognised from the Haast area northeastwards to Hokitika. Field work has established that rounded quartz pebbles occur on most of these surfaces. A similar number of terraces have been recognised worldwide (e.g. Chappell's work on Huon Peninsula, New Guinea), and are interpreted as having formed during interglacial high level stands, preserved by uplift on tectonically active coastlines. Using the New Guinea stratigraphy of terrace ages (determined from radiometric dates on coral), plots have been constructed of altitude of Westland terraces against inferred age (fig. 8). A straight line relationship implies (a) that a correct correlation has been made with the New Guinea sequence, and (b) that the uplift rate has been constant over the time period during which the terrace flight developed. The slope of the straight line gives the rate of uplift. For the past 140 000 years the uplift rate appears to have been constant at approximately 5.8 mm/y at Haast rising to 7.8 mm/y at Franz Josef (Bull and Cooper, 1986).

Although based on tenuous correlations, the Haast uplift rate based on high altitude terraces is compatible with that determined at nearby Okuru River by Cooper and Bishop (1979). The increase in uplift rate to the northeast predicted by terrace uplift is also compatible with the increased summit elevations that occur northeastwards towards Mt Cook, with the uplift map proposed by Wellman (1979), and with measured dip-slip rates on the Alpine Fault (Norris & Cooper 2001).

The Haast River area appears to mark a change in the character of the fault; to the northeast the trace is segmented, broken into more northerly trending thrusts (with development of thick cataclasites) and more easterly trending strike slip sections, while to the southwest the present day uplift component, southeast of the fault, decreases and the fault is predominantly strike slip in character, but with the trace having a 'normal' (055-058°) trend (Berryman et al. 1992, Cooper and Norris 1995).

From Haast, the road follows the coastal plain as far as Ship Creek, crossing a series of prominent shore-parallel dune ridges and alternating interdune hollows clothed in unmodified lowland rainforest. These coastal progradation plains extend up to 3 km inland and have developed close to the mouths of all the major south Westland rivers (Haast, Okuru, Waiatoto, Arawhata and Awarua). Wells and Goff (2007) mapped the dune sequences at five river mouth sites and dated the time of progradation and dune building using the ages of colonizing conifer trees. On the basis of 960 tree ages, they showed that dune formation has taken place in distinct and synchronous episodes, separated by long periods without lasting progradation. Six regional episodes are evident since A.D. 1200. The oldest trees on each dune set indicates dune deposition was complete as early as the decades of A.D. 1830, 1720, 1620, 1500, 1430 and 1280, each episode differing by no more than 20-53 years regionally, and therefore inferred to represent the regional response to the same causal mechanism. Wells and Goff (2007) interpret each dune system as reflecting rapid fluvial transport of large post-seismic sediment pulses from mountain catchments to the coast. The formation of each dune therefore relates to major Alpine Fault earthquakes. Four of the six regional dune-building episodes can be correlated to previously identified earthquakes on the Alpine Fault at A.D. 1826, 1717 and ca 1615. Another earthquake at ca A.D. 1460 has been resolved into two possibly separate events at A.D. 1500 and 1430, while the timing of the A.D. 1220 earthquake has been bracketed between A.D. 1280 and 1230.

From Ship Creek, the road climbs over two well-developed Quaternary terraces, the Sardine terraces of Nathan (1975); the lower terrace (Sardine 1) is underlain by river gravels resting on lake silts whereas the Sardine 2 terrace is underlain by marine sediments deposited during an interglacial highstand of sea-level. Both terraces are older than 40,000 y. B.P. The road winds through spectacular cuttings within highly deformed late Cretaceous-Cenozoic strata and Paleozoic Greenland group.

STOP 12: Pegmatite Quarry

The quarry in bush behind the Paringa Post Office exposes granitoid rocks of the Paringa Suite (Tulloch et al., 2009) intruded by pegmatite(s) and lamprophyric dikes. The granite is a magnetite-epidote-hornblende variety with I-type characteristics, and a subduction-related, multi-element signature. It has been dated at 369.4±1.4 Ma (Tulloch et al., 2009). The granite is intruded by granite pegmatite(s) rich in muscovite and containing rare hexagonal prisms of beryl, granular garnet and prismatic tourmaline. Lamprophyric dikes are of unknown affinity, but are unrelated to lamprophyres of the Alpine Dike Swarm seen at Lake Hawea and in the Haast River Valley.

STOP 13: Paringa River (overview from the road only in 2009)

At Paringa River, recent mapping of the Alpine Fault trace has revealed the existence of an extensive Haast Schist-derived thrust nappe resting on West Coast basement (Greenland Group greywackes, variably hornfelsed; Tuhua granitoids and moraine). Erosion of the nappe by the Paringa River and its tributaries has resulted in the abandonment of the nappe (on Ward Hill, fig 9A) and re-establishment of the active fault zone farther east as a series of southeast-dipping thrust faults, linked by swarms of steeply-dipping, east-striking strike slip faults (fig. 9A, Simpson et al. 1994). In the Paringa River, 700 m upstream of the main road, the mylonite-schist basement, exposed at river-level, is overlain unconformably by a series of fossiliferous marine silts, sands, and fluviatile cross-bedded gravels interbedded with lacustrine silts and buried forest horizons (fig. 9B). Collectively these sediments comprise the Paringa Formation (fig. 9C), a sequence ranging in age from 13,400 (Suggate, 1968) to 3570 years B.P. (Simpson et al., 1994) that was deposited when ice of the last (Kumara-3) glacial advance retreated back up the valley. Sea-level was about 70 m lower than now, marine faunas in the silts near the base of the formation indicate water depths of about 40 m, and the fossil locality is now about 36 m above sea-level. This requires 146 m of uplift in 13 400 years, a rate of almost 11 mm/year. The Paringa Formation silts occupy the flanks of an asymmetric anticlinal structure (Suggate 1968; Adams 1979), draped over a schist-cored basement ridge upthrust along an active strand of the Alpine Fault (Simpson et al., 1994). Unconformities in the sequence attest to the progressive thrusting and growth of the anticline, which trends at an angle of about 30° more northerly than the average Alpine Fault strike (fig. 9A). While the 11mm/yr uplift rate of Suggate (1968) is mathematically correct, it applies to a very restricted locality on the axis of the anticline or upthrust ridge. Over a distance of 350-400m southeast of this active segment of the Alpine Fault, the attitude of the Paringa Formation changes from moderately southeast dipping (values close to 40°) to effectively horizontal (fig. 9B). Removing the effect of tilting due to localised uplift, Simpson et al. have calculated a regional uplift rate of 7 to 8 mm/yr, appropriate to the Paringa River area for the past 16 ka (Fig. 10).

The schists here are curly schists (protomylonites) and become increasingly mylonitised westward towards the Alpine Fault. Occasional examples of deformed garnet-mica pegmatites may be seen. These occur widely in highest grade schists between Haast and Moeraki Rivers and were mined for mica during World War II. Conventional U-Pb dating of monazite and SHRIMP dating of zircon from a Mataketake Range pegmatite yielded concordant dates of 68 m.y. (Chamberlain et al., 1995), interpreted as representing a late Cretaceous thermal event associated with regional extension.

STOP 14: Doughboy Creek

In its lower reaches, near the road, Doughboy Creek flows through thick gravel terraces, and the hard rock sequence is not exposed. However, approximately 1.5 km upstream, a large slip exposes quartzofeldspathic mylonite containing abundant deformed pegmatite veins. The undeformed protolith of these veins 8occurs on the crest of the Mataketake Range, some 10 km to the SE of this location. The pegamtites were deformed within the fault zone, developing extensively recrystallied quartz, feldspar, and muscovite fish that are visible in many hand specimens, such as the blocks that have washed down Doughboy Creek. The decrease in mean thickness of pegmatites between the schists of the Mataketake Range and the protomylonites at Doughboy Creek indicate shear strains of between 10 and 15 (Norris & Cooper 2003). This analysis is further discussed in description of Stop 15.

N.B. The prominent granite and pegmatite boulders forming the stop banks at the Paringa River, and the sea wall at nearby Bruce Bay are from the Tuhua Group of late Paleozoic age and are quarried at a site behind the Paringa Post Office.

STOP 15: Hare Mare Creek and the Waikukupa Thrust Complex

In the area around the Waikukupa River, mapped by Norris and Cooper (1997) (fig. 11), schist-derived mylonites and cataclasites are thrust over fluvio-glacial gravels of the Okarito Formation, generally considered to belong to an early advance of the last glaciation (Otiran).

Mapping in the thick bush has located the basal thrust zone, the Waikukupa thrust, in several localities - it generally dips at an angle of around 30° to the east or southeast, although variation in strike is apparent. Erosion has cut into the thrust sheet, in places leaving klippen on the tops of ridges. Slickenside lineations on the fault plane (fig. 12) tend to trend east-west rather than directly down dip, suggesting the thrusting is oblique (cf. Gaunt Creek locality). Internal structures of the thrust sheet indicate thrusting to the northwest and updip shortening of the thrust sheet (fig. 13).

Providing the Waikukupa River is negotiable, we intend to examine the Waikukupa Thrust sheet in a large open slip on the true left bank of the river, due west of Hare Mare Creek. At the head of this slip, recent downcutting by the stream has exposed the sole of the Waikukupa thrust, resting on fluvio-glacial gravels. Immediately above the basal thrust plane, with its associated thin clay-rich gouge zones, is a variable thickness of extensively veined and altered minty green cataclasite, commonly from 0.5-4m thick elsewhere, but sometimes much thicker, as observed here. Above this is schist-derived mylonite, cut by innumerable zones of cataclasis and fault gouge. The mylonites are derived from both quartzofeldspathic schist and amphibolite and have been imbricated along steep thrusts, forming duplex structures with associated large kink folds (fig. 14).

Notable are extremely attenuated quartz-feldspar-mica pegmatites. While the quartz and feldspar have been highly deformed and recrystallised, the large books of mica are commonly still preserved. The thickest pegmatite we have seen in these **mylonites** is 5 cm thick, although continuous along strike over at least 100m. In contrast, the maximum thickness of the pegmatites in the **schists** in the Mataketake Range, 100 km to the south, is around 48 m. Immediately north of the Mataketake Range, the pegmatite zone strikes obliquely into the Alpine Fault mylonites and pegmatites have been smeared out by oblique shear northwards to Waikukupa River (Norris and Cooper 1996). The decrease in mean thickness of pegmatites between the schists of the Mataketake Range and the mylonites and ultramylonites of Waikukupa River indicate shear strains of between 200 and 300.

The underlying Okarito Formation consists of mainly schist-derived, coarse, poorly-sorted gravels containing well-rounded pebbles and boulders of metagreywacke. Horizons of cross-bedded silts and fine sands are common. A dip of as much as 45° to the west has been observed beneath the thrust sheet. Locally, thrust faults cut the Okarito Formation below the main thrust.

Hare Mare Creek locality:

In a large slip on the true left bank of Hare Mare Creek, a fault plane is exposed that thrusts mylonites and cataclasites over steeply tilted gravels and slivers of mylonite (fig. 15). The thrust plane strikes about 015° and dips 25°-30° E. Slickenside lineations trend 065°. Above the thrust plane is a similar sequence of pale-green cataclasites and schist-derived mylonites as observed further west above the Waikukupa thrust. However, the geometry indicates that the Hare Mare thrust plane overlies the Waikukupa thrust (fig. 11B), and indeed, exposure in a neighbouring creek (and sometimes in the bed of Hare Mare Creek) shows the former overthrusting both gravels and schist mylonites. Other zones of green cataclasites from mylonites within the area suggests considerable imbrication of the thrust complex.

The Hare Mare Creek locality is very similar to the Gaunt Creek outcrop in its major features, except that the underlying gravels are more deformed and there are no talus deposits indicative of the thrust reaching the surface. West-dipping normal faults occur within the overlying mylonite wedge, as do imbricate duplex structures rotating the mylonitic foliation to high angles of dip. These structures decrease in intensity upwards/ eastwards. Minor thrusts occur within the gravels below the Hare Mare thrust, and a weak crenulation cleavage structure is locally developed in mica-rich silt horizons. A prominent set of steeply dipping fractures, commonly with fault gouge, strikes NW-SE throughout the whole area. Hydrothermal alteration and carbonate/sulphide deposition is widespread on fractures within the mylonites and cataclasites. A hot spring, with associated orange-coloured discharge, was intermittently active some 20 years ago further up Hare Mare creek.

Recent work has shown that the most recent thrusting is along the Hare Mare thrust as far as the Waikukupa River, but is then transferred via a swarm of steeply dipping, east-west striking, strike-slip faults across onto the Waikukupa thrust which continues down to Fox Glacier. Combining estimated displacements on both Hare Mare and Waikukupa thrusts suggests a minimum slip rate of 22 to 30 mm/y, similar to displacement rates determined elsewhere in Westland.

Norris and Cooper (1997) interpreted this structure as follows:

1. Following the Okarito glacial advance (c. 65 ka), oblique thrusting along the buried Alpine fault emplaced mylonites over the glacial deposits and formed an oblique thrust complex extending out to the west.
2. Erosion of this thrust complex by the Waikukupa river, particularly during the later Moana advance (22-18 ka), caused the thrust sheet to become subcritical.
3. An "out-of-sequence" imbricate, the Hare Mare thrust, became the major locus of deformation along the fault.

4. South of the river, little erosion took place so the Waikukupa Thrust remained the active structure.
5. An east-west striking dextral strike-slip fault developed to link the two active parts of the Alpine Fault, probably following one of the many faults with this orientation already present in the hangingwall.

The Alpine fault at Waikukupa River is broken into thrust segments, trending somewhat more north-south, and strike-slip segments trending more east-west (i.e. parallel to the relative plate movement). This pattern may be repeated along the whole length of the fault (fig. 16)(Norris and Cooper 1995). The Paringa structure seen yesterday (fig. 9A) is probably a similar feature. North of the Cook Saddle (just before the small roadside quarry in the cataclasite), the Waikukupa thrust is cut off from the main front of the Alps by erosion along the Waikukupa River. This erosion probably triggered the backward imbrication that formed the Hare Mare thrust and its linking strike-slip faults.

STOP 16: Road cutting South of Docherty's Creek.

Fresh road cuttings (2009) offer a superb, and uncommonly accessible exposure of the footwall sequence to the Alpine Fault. A series of amphibolites and amphibole- and biotite-bearing granitoids are cross-cut by numerous small-scale faults and clay gouge zones, which impart a steep 070-striking fabric. A particularly prominent ultracataclasite principal slip surface near the uphill end of the outcrop contains 1cm laminae with slight colour variations. The granitoids are also cut by numerous potassium feldspar-bearing pegmatites, and by quartz, carbonate, and chlorite-bearing veins. En-echelon arrays of near vertical extensional veins striking NE-SW suggest the brittle fabric in the granitoids formed during dextral shearing.

The granitoids are probably either Late Devonian to Early Carboniferous or Cretaceous in age (Muir et al. 1994). The deformation may be pre-Alpine Fault, such as occurred within the Fraser Complex (Rattenbury, 1987), or related to Alpine Fault deformation, which would be consistent with the observation of dextral strike slip. Similarly, the abundant veins attest to movement of large quantitites of fluid through the rock, may be coeval with the modern tectonic regime, or much older.

STOP 17: Alpine Fault Overthrust at Gaunt Creek

In historic time, the Waitangitaona River (fig. 17) has aggraded more than any other similar sized West Coast river. In the 1950s, concern at the aggradation prompted investigation when it was found that most of the material was being supplied from Gaunt Creek, a tributary that cuts across the Alpine Fault. Gaunt Creek was then, and still is, eroding the base of a large face more than a 100 m high that exposes shattered and brecciated schist mylonites thrust over schist gravels. The continued aggradation of the Waitangitaona River led in 1967 to the anticipated shift from its original course, across the lower Whataroa flats, to its present one through Lake Wahapo.

On the north bank of the River, immediately after descending from the stop bank, there is an exposure of foliated granite cut by shear zones and by mafic dykes. The rock is part of the West Coast basement and is probably best included in the Fraser Complex (Rattenbury, 1987). The dykes cut the foliation in the granitoids but are themselves deformed by cataclastic shear zones. The age of similar dykes further north is equivocal but probably late Cretaceous (Adams & Nathan, 1977; Rattenbury, 1988). A short distance further up river, exposures of probable glacial lake silts with turbidites and drop-stones may be seen underlying the major terraces of fluvioglacial outwash.

The large slip at Gaunt Creek is illustrated in fig 18 (Cooper & Norris 1994), which is a **map of the face** projected onto a vertical plane trending 140° and scaled by radial-line plotting from a set of overlapping photographs (N.B. It is **not** a true cross-section), and in fig 19.

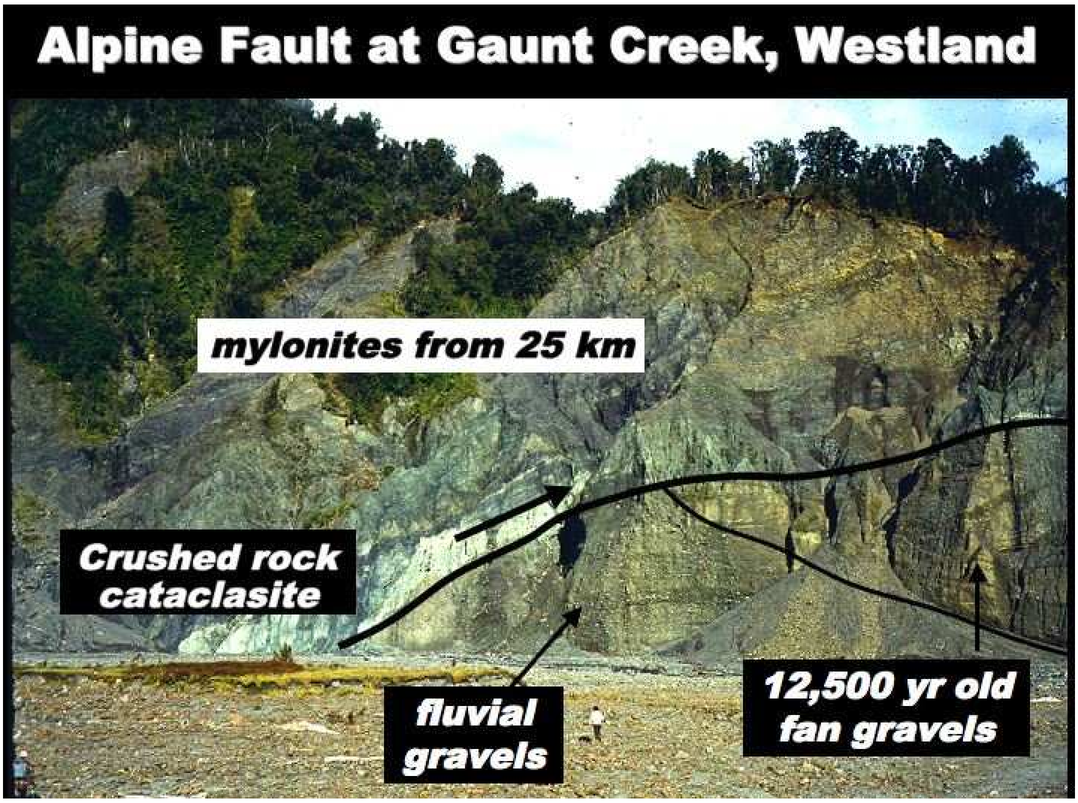


Figure 19

The main feature of the exposure is the overthrust of cataclastic mylonites over gravels. At the base of the overthrust is a zone up to 30 m thick of **pale-green cataclasites** overlying a 10-40 cm thick **grey gouge** (the fault principal slip zone, p.s.z.) above gravels. The base of the cataclasite has a mean strike of 059° and dip of 38°SE, although it is cut by higher-angle shears, and contains a steep east-dipping internal fabric. Slickensides on the grey gouge are variable in orientation - the mean of the dominant set trends almost due east, although at the level of Gaunt Creek a prominent lineation plunges gently to the SW. All these are quite oblique to the dip direction of the thrust plane (fig. 18).

In detail, the p.s.z. is composed of sub-planar layers of slightly different colour and particle size range, ranging from 5-60 mm in thickness. The thickest layer is sometimes injected as flame-like structures into the overlying cataclasite. Individual layers contain C-like shears of much finer-grained material, and calcite laminae. The latter indicate fluids passed through the gouge after its formation. Particle sizes within the gouge have been measured using a laser particle size analyzer (Boulton and Toy 2008). The resulting particle size distributions are not fractal, indicating either that the gouge was not formed by constrained comminution during cataclasis, or that finer particles in the C-shears were not sufficiently represented in the analyses.

The overlying pale-green cataclasites contain abundant pseudotachylyte, within which the glassy matrix has mostly been devitrified or altered to a mixture of clay minerals and sericite (Toy 2008). In outcrop the pseudotachylytes now appear a blue-grey, pale grey, or brown. Some of the more voluminous pseudotachylyte bodies contain quartz and carbonate-filled amygdules, and late calcitic cements are common. Formation of these pseudotachylytes within the cataclasite mass indicates that co-seismic slip was well-localised (i.e. the mass probably did not deform by distributed cataclastic flow), and that fluids were only locally present during seismic events.

Stable isotope data have been obtained from carbonate cements in the p.s.z. and both carbonate cements and cross-cutting calcite veins in the immediately overlying gouge both here and at the Hare Mare Creek locality. In both cases, the carbon-oxygen isotopic ratios are consistent with an increasingly rock-exchanged fluid source with the transition from cross-cutting veins to cataclasite to p.s.z. cement. This may indicate that the p.s.z. offers the highest permeability pathway for fluid transport from depth within the fault rocks.

The basal cataclasite thins and is cut out upwards, but then reappears at the base of the overthrust further out to the west. The dip of the basal contact here is quite different, being about 30°S on a strike of 120°. This change is almost certainly due to the thrust reaching the surface and rotating under gravity to parallel the ground. It coincides with a change in the overthrust material from sub-horizontally bedded **schist-derived fluvial gravels** to **mylonite- and cataclasite-derived fan gravels** on a depositional slope of approximately 30°W. The latter contain large **slump masses** of mylonite and cataclasite derived by gravitational collapse of the thrust front - they have been subsequently overthrust themselves by the mylonites. The slumped masses preserve the mylonitic foliation, with some back-tilting and imbricate slide zones. The base of the slump packets in places overlie a weathered silt horizon with fine-scale cross-beds - presumably the surface of the shingle fan at that time. The upper surfaces of the slump packets are eroded and overlain by angular mylonitic fan debris. The occurrence of pale green cataclasite amongst the slump masses indicates that the basal thrust zone was exposed at the surface. In contrast, the fluvial gravels below the fan sequence are dominantly schist-derived, suggesting that the thrust zone was not locally exposed at the time of their formation. The thrust cuts through these gravels at a moderate angle of dip.

A thick sequence of younger fluvial gravels overly the dipping fan sequence. The basal thrust can be traced into these with the gravels above the trace being disturbed by continued movement. Several pieces of wood have been obtained from the fan gravel sequence and have been dated by ^{14}C methods as 12,650 ± 90 whereas wood from the younger fluvial sequence has been dated as 10,300 ± 130 y BP. Approximately 180 and 110m respectively of displacement has occurred since the deposition of these gravels, indicating a minimum displacement rate along plate vector-parallel slickenside trends of between 18 and 24mm/yr.

Above the pale green cataclasite zone is a zone of black and olive green **cataclased ultramylonites**. These materials contain abundant seams of **pseudotachylyte,** commonly generated by slip along shears juxtaposing olive green and black materials, and oblique to the ultramylonite foliation. Injection structures up to 10 cm long attest to the fact these melts were highly mobile / low viscosity. Fresh pseudotachylyte glass has been obtained from this zone (see Norris and Cooper 2007) but the matrix of most pseudotachylytes is now composed of an alteration or devitrification assemblage (commonly felted masses of sericite) as in the underlying pale green cataclasites. The ultramylonite has a pervasively-developed greenschist-facies mineral assemblage, in which sericitised feldspar porphyroclasts are embedded in a generally fine-grained matrix of chlorite+quartz+muscovite with minor titanite+opaques+clay minerals. Banding of these minerals defines a disjunctive cleavage suggesting pressure solution processes were involved in this deformation. Allanite, with clinozoisite rims, is relatively common suggesting some of these rocks are derived from a footwall, granitoid protolith. The rock is full of anastomosing minor shears, generally filled with incohesive gouge, which are both steeper and shallower than the main thrust.

Further upstream, the cataclasites pass into **schist-derived mylonites,** also containing large numbers of anastomosing gouge zones. The general attitude of the mylonitic foliation is parallel to the basal thrust. In many places, however, it has been imbricated on shears to form steep dipping packets, i.e. a series of duplex structures developed between major thrust zones parallel to the basal thrust. Occasional pseudotachylyte veins have been observed in this zone too. Further upstream, where Gaunt Creek enters its gorge, the foliation is more regular at 40° to 50° SE, with fewer shears and duplex development. A 40° to 50° dip is similar to that recorded from most creek sections in the area (Sibson et al., 1979) and is considered to represent the approximate dip of the main Alpine Fault plane. Mylonites derived from both amphibolites and quartzofeldspathic schists may be observed. Analysis of the imbricated shears and rotated mylonitic foliation suggests a thrust direction to the NW (fig. 18).

Quartz-rich layers in the mylonites contain strong quartz crystallographic preferred orientations (CPOs) as shown in fig. 20. The CPOs have a consistent asymmetry indicating a high ratio of simple to pure shear strain, with a shear sense of dextral-up to the NW that is consistent with the mesoscopic shear sense indicators and with the slip on the active fault. The strong CPOs, which would have developed during dislocation creep attest to intense localisation of shear strain along the fault zone within the lower crust (Toy et al. 2008).

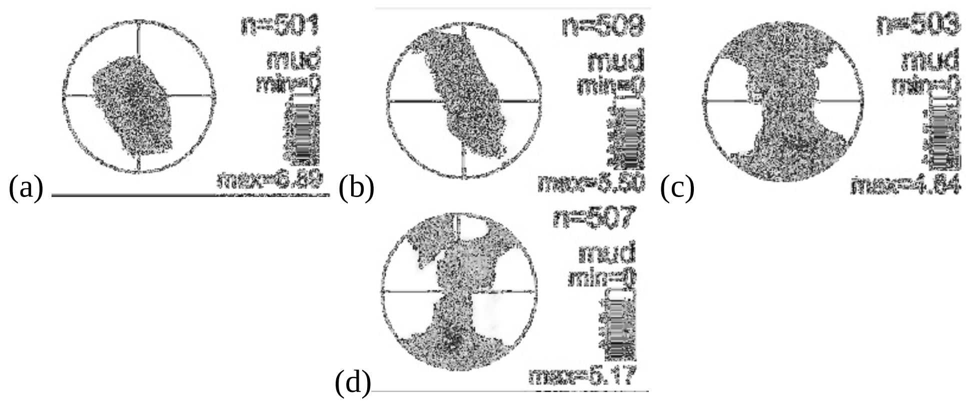


Fig. 20: Cartoon illustrating the types of quartz c-axis CPOs from the Alpine Fault mylonites at Gaunt Creek (Toy et al. 2008). (a) to (d) were collected progressively further from the Alpine Fault. (a) Y-maximum pattern, indicative of deformation at amphibolite facies conditions. (b) Transitional Y-maximum - single girdle. (c) Asymmetric single girdle, typical of deformation at greenschist facies conditions. (d) Symmetric crossed girdle, indicating less simple shear strain was experienced near the margins of the mylonite zone.

Numerous steep, cross-cutting faults and gouge zones may be observed in the outcrop. A prominent series of normal faults dipping to the west can be seen cutting the mylonite sheet above the gravel face - these were presumably developed during the rotation of the thrust sheet as it thrust out onto the surface. Many of the fault gouges and shears contain carbonate deposits and sulphide minerals, attesting to the percolation of warm fluids through the fractures. Zones of **hydrothermal alteration** can be seen around many fractures. In the mylonites, quartz veins cross-cut the mylonitic foliation, indicating fracturing and fluid flow above the brittle-ductile transition.

Our interpretation of the history of Alpine Fault deformation recorded at Gaunt Creek is:

1) The main fault plane dips southeast at about 40°-50°.

2) During a period of aggradation, the basal fault plane together with its associated mylonites and cataclasites was buried by schist-derived fluvial gravels. While the fault may have continued to cut up through the gravels during this period, the cataclasites would not be exposed at the surface provided aggradation kept pace with fault movement.

3) Aggradation ceased and erosional downcutting began. The fault zone became exposed at the surface. Mylonitic and cataclastic debris formed talus fans in front of the advancing thrust front. Blocks of mylonite and cataclasite slumped off the scarp down the fan surface. The thrust wedge continued to advance across the fan gravels, its attitude rotating to conform with the ground surface.

4) The slope of the aggrading fan lessened, and gravels again covered the thrust plane. More recently, extensive downcutting by Gaunt Creek has exposed the fault zone in the present slip.

Kinematic history of the mylonite zone

Asymmetric shear sense indicators, shear band and S-C fabrics, quartz CPO 'X'-axes and various types of lineations that occur within the exhumed mylonites have triclinic symmetry (i.e. the finite stretching direction is not perpendicular to the vorticity vector). In particular, macroscopic object lineations are not usually parallel to the simple shear direction, despite high total simple shear strains ($\gamma \geq 150$). The various fabric elements record different proportions of the total strain experienced by the mylonites and reflect different aspects of the kinematics of the deforming zone, but collectively record a progressive evolution of strain. During uplift and exhumation the simple shear strain component became more dominant and progressively more localized into shear bands cross-cutting the mylonitic foliation.

Many object lineations preserved in the mylonites are inherited from the pre-mylonitic fabrics and this has affected the distribution of their orientations. In particular, SW-plunging quartz rodding lineations are commonly preserved in the distal mylonite zone. In places these lineations have been only partially rotated into parallelism with the mylonitic stretching direction during shear focused within mylonitic shear bands (fig. 21).

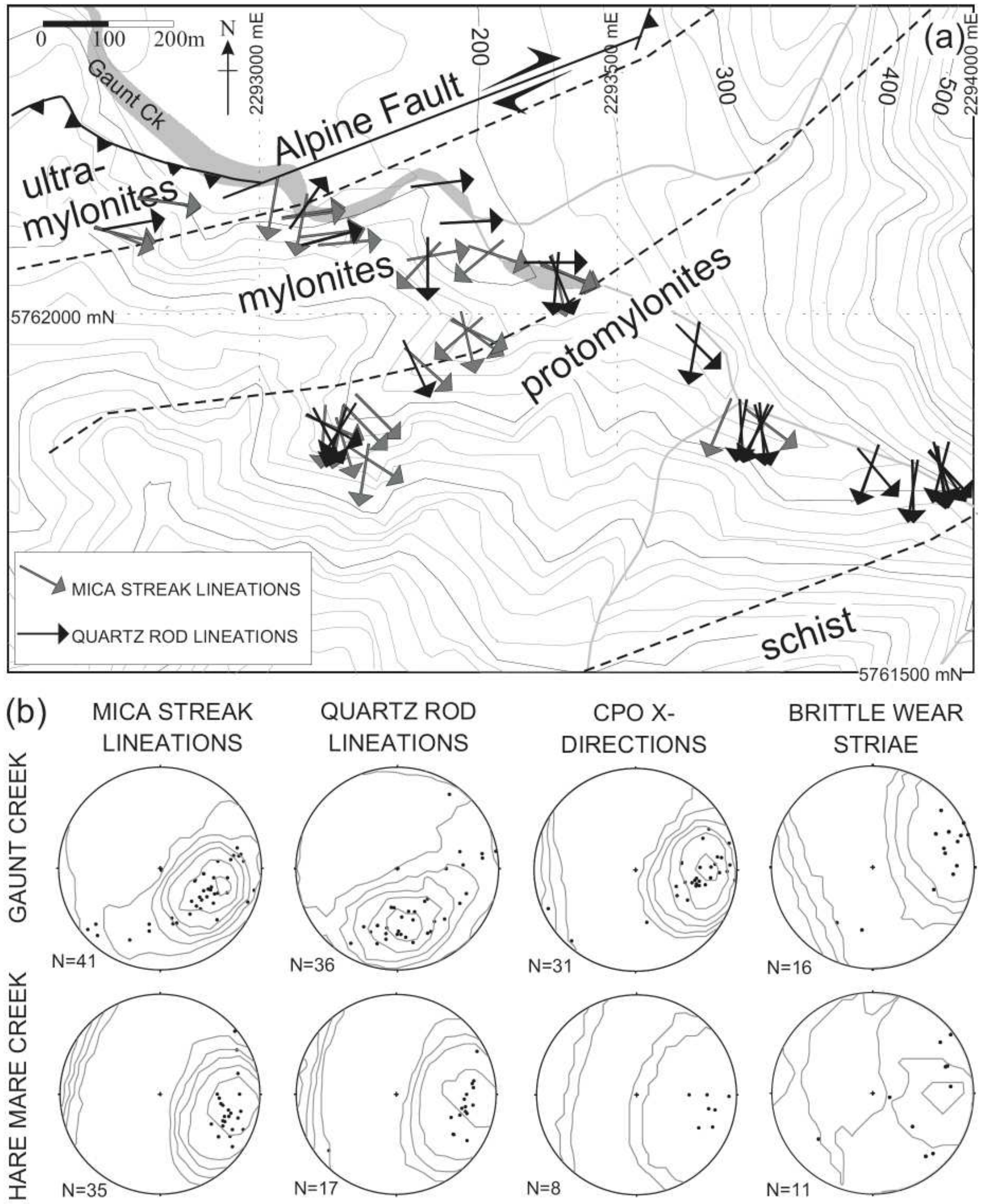


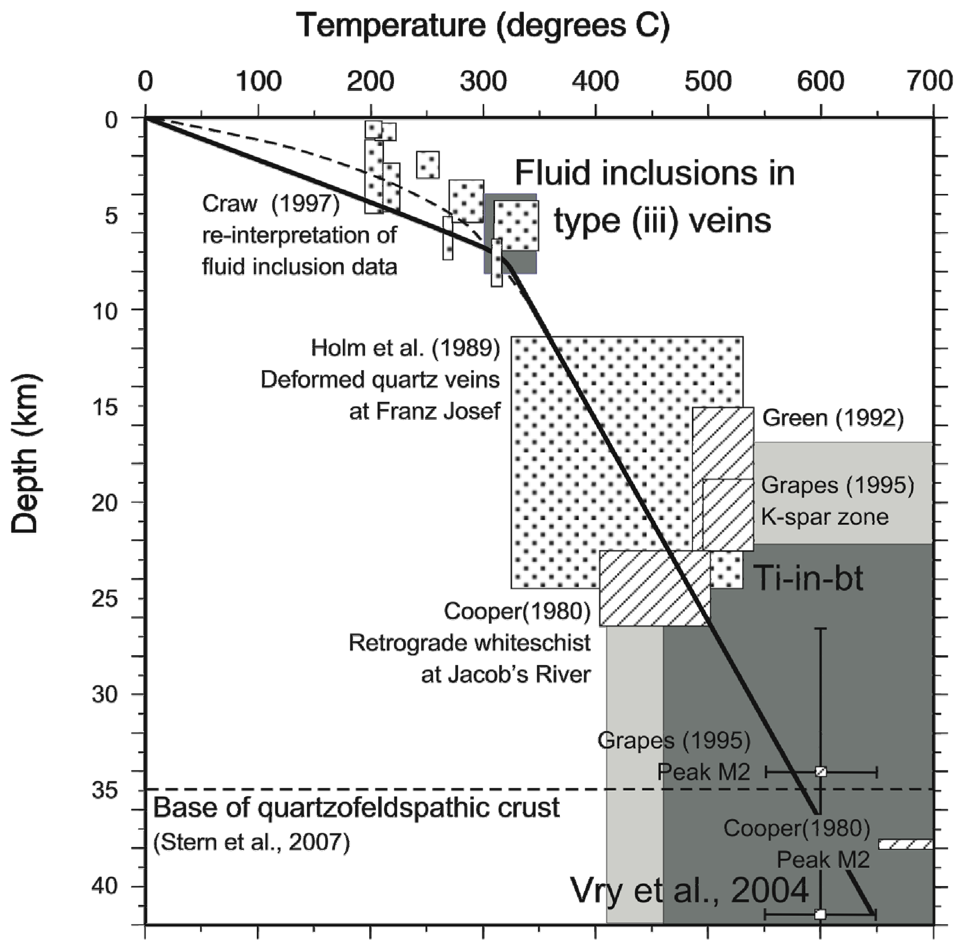
Fig. 21: Summary of mica streak, quartz rod and brittle lineations, and CPO fabric data from Gaunt Creek and Hare Mare Creek. (a) Map shows variation in distribution and orientation of quartz rod and mica streak lineations in the Gaunt Creek section. (b) Plots of lineation data are equal area lower hemisphere Schmidt projections. Kamb contour intervals are 2.0 in all plots.

Clues about the thermal structure of the Alpine Fault at depth from studies of the exhumed sequence at Gaunt Creek

Quartz veins within the fault rocks were formed and deformed at temperatures ranging from >500ºC to immediately above that of the brittle-viscous transition (~325ºC), illustrating that fluids are present throughout the fault zone. Mixed CO_2-H_2O fluid inclusions are hosted in quartz veins in foliation boudinage structures in the mylonites here. The structures represent transitional ductile-brittle behaviour. These inclusions were trapped from immiscible fluids so P and T at the time of trapping can be estimated from them via microthermometric studies. These results indicate trapping conditions of ~325±15ºC and ~0.35 kbar. Vein microstructures indicate fluid temperatures were equal to rock temperatures. Assuming hydrostatic fluid pressure, the veins were trapped at depths of <8 km for an average density of mixed H_2O-CO_2 fluids in the shallower crust of >500 kg m^{-3}.

Considering this result in the context of pre-existing thermobarometric estimates in the fault rocks and the immediate hangingwall allows definition of a most likely uplift path P-T profile within the fault zone (Figure 22). In this model, the uplift path P-T gradient of fault zone rocks above the brittle-viscous transition is of the order of 40ºC km^{-1}. Below the brittle-viscous transition, the uplift path P-T gradient is 8-14ºC km^{-1}. The P-T profile within the fault rocks is comparable to that in the immediate hanging wall Alpine Schist (see fig. 22).

Fig. 22: Summary of existing constraints on thermal structure of the Alpine Fault zone and a proposed 'best-fit' thermal profile (Toy et al. in prep)



STOP 18: Alpine Fault trace through Franz Josef Township

The trace of the fault is clearly visible as a scarp, now modified by construction operations, extending from the end of the Tartare track to the Westland Park Headquarters. It causes a noticeable rise in the highway between the township and the Park HQ, and is best preserved just below the road in the Park HQ grounds. It is thought to have originated in the last major displacement on the fault around 550 y ago (J. Adams, pers. comm.).

STOP 19: Waiho Valley and Franz Josef Glacier

The Franz Josef glacier descends through the mountains to an altitude of around 400m a.s.l. where it forms the Waiho River. The glacier has generally been retreating since the 18th century when it extended well beyond the present car-park (see sign by side of road). The retreat has been punctuated by short-lived advances, for instance in 1946-50 and again in 1965-67, since when it retreated steadily until the mid 1990s when a further rapid advance began and is still in progress. The bed of the Waiho River is constantly shifting due to the rapid erosion and material transport taking place. An idea of the erosion potential in this part of the Alps may be gained from the events of December 1965 when, following 300mm of overnight torrential rain, a great glacier burst occurred sending a torrent of sediment and ice-laden water down valley. The access road was washed away while the floodplain was raised by as much as 18m over a distance of 2 km. An estimated 10^6 m^3 of ice and at least as much of sediment was carried down valley in one night (Sara 1970).

Many ice-scoured outcrops of Alpine Schist are to be seen within the valley. We will drive up the car-park and then walk up to the glacier. There are no specific stops - the following notes are intended as a guide only. We will stop at suitable outcrops to examine the features described.

Deformation in the Alpine Schists of the Waiho Valley

Schists exposed within the Waiho Valley, Westland, 1-5 km east of the Alpine Fault trace, have been uplifted during the late Cenozoic formation of the Southern Alps. A sequence of mesoscopic structures is recognised extending backwards in time from the most recent **brittle displacements of glacially scoured surfaces** through structures exhibiting brittle-ductile transitional behaviour to uniformly ductile deformational features (fig. 23) (Holm et al., 1989).

Kinematic analysis of the various groups of structures suggests a progressive rotation of the subhorizontal principal shortening direction in an anticlockwise sense, with the most recent structures giving a shortening direction consistent with geodetic and microearthquake data. The rotation is compatible with oblique-slip right-lateral shear. Brittle structures include both **subhorizontal and subvertical extension fractures,** suggesting an alternation between intermediate and least principal stress orientations, and arrays of right and left lateral faults. The more ductile structures also show extension in both horizontal and vertical directions. Brittle-ductile transitional structures comprise **arrays of ductile extensional shear zones, extension veins and internal boudinage features,** which overprint **ductile buckling and boudinage of arrays of quartz veins cross-cutting the dominant foliation**. Analysis of the vein deformation suggests a shortening strain of around 50% perpendicular to the foliation.

The deformed veins cross-cut **upright mesoscopic and macroscopic folds** which commonly develop **high-strain zones on their limbs,** parallel to the dominant foliation. Within these high-strain zones, a strong **stretching lineation** is developed plunging gently SW, approximately perpendicular to the stretching lineation in the mylonites along the Alpine Fault. This suggests that the folds and their associated high-strain zones are not related to uplift on the Alpine Fault, although they may have originated at depth during an earlier phase of dominantly strike-slip motion.

Fluid inclusions have been examined from quartz crystals in sub-horizontal extension fractures formed during the late brittle phase, in extension fractures related to internal boudinage structures formed during the brittle-ductile phase, and from the deformed veins. Pressure- temperature estimates of around 700 bars at 280°C for the brittle phase and 1.5 kbars at 350°C for the brittle-ductile transition were obtained. The deformed veins show evidence of extensive fluid infiltration during the later phases - probable primary inclusions give an isochore from which an estimate of around 5 kbars and 450°C is suggested for their deformation. Well-developed biotite selvedges attest to deformation taking place within the biotite stability field.

The Pressure-Temperature-time path indicated by the data (fig. 24) represents very rapid uplift from depths of 15-20 km. The results are consistent with recent numerical modelling of thermal and mechanical behaviour of the crust during rapid uplift and with the present high heat flow in the area. A cooling mechanism involving fluid flow through the brittle zone will develop feedback relationships with the brittle-ductile transition within the uplifting rock mass.

Occasionally, hot springs have emerged in the bed of the Waiho River. The springs represent forced circulation of groundwater through fractured rock that is hot because rapid uplift has brought it from depth faster than it can cool.

On the route to Slippery Rock at the snout of the glacier, smooth rock surfaces expose typical Alpine schist of the Waiho Valley. The schist contains occasional bands of greenschist and also rare thin marble horizons. The metamorphic grade is garnet zone. Many of the brittle and brittle/ductile features described above may be seen deforming the dominant foliation. The schist between the car-park and Slippery Rock lies within a ductile high strain zone related to the "Alpine folding" (F_3 of Findlay (1987)) (fig. 25). Minor folds have been largely sheared out within their axial plane foliation. This foliation is crosscut by quartz veins (often with biotite selvedges and sometimes with carbonate centres) which have themselves been buckled and boudinaged during ductile deformation.

Quartz crystals growing in flat-lying extension fractures may be seen in some localities. The site of a drill-hole lies at the old roadcut (now largely infilled with gravel), from which heat-flow measurements indicate a near-surface thermal gradient of about 70°C/km (Allis, 1986). Just past here, a spectacular quartz-filled pull-apart within a boudinaged layer is prominent.

At Slippery Rock, (buried under ice in 2007), displacements on foliation planes were described by Adams (1979). Displacements have also occurred on a number of fractures cutting the surface. Analysis of displacements at five localities within the Franz Josef and Fox valleys indicate a principal horizontal shortening direction trending 126° ± 10°, an orientation compatible with geodetic and microearthquake studies (Norris & Cooper, 1986). The displacements are interpreted as forming by release of accumulated tectonic elastic strain following retreat of the glacier (figs 26, 27, 28).

"At Slippery Rock (S71/825663), just downstream of the present snout of the Franz Josef Glacier and 4.7km southeast of the Alpine Fault, an outcrop of schist was ice-rounded and smoothed by ice. However, the smoothed surface has since been displaced by movement on faults parallel with the schistosity plans and parallel with the strike of the Alpine Fault. The throw on individual faults was measured with a micrometer in April 1978, and each displacement was traced laterally to confirm that the offset was not a local ice-scour feature. Across a 106m traverse normal to the schistosity planes there are 21 faults with a total throw of 236mm (Fig. 6), the largest throw being 30mm. All the faults are upthrown on the southeastern (Alpine) side. The relatively small and closely-spaced displacements on the many schistosity plane faults suggest that the drag displacement has been progressive and aseismic.

Horizontal offset on the schistosity plane faults is difficult to measure because there are no good reference lines, but one schistosity plane fault that jumped from ne schistosity plane to another left a tensionsal gap 9mm wide. Displacement was 17mm upthrown to the southeast and 9mm dextral, a vertical/horizontal ratio of 2.0. An associated st of four fractures at about 45 degrees to the schistosity crossed by the traverse shows dominant dextral movement (V/H = 0.2).

There has been general retreat of the Franz Josef Glacier during the last 100 or so years. Slippery Rock was just covered by ice 14 years ago and covered by more than 70m of ice 100 years ago when the glacier extended 2km farther downstream. If the smoothing is 14 years old, the differential uplift rate across the outcrop is 17mm/year; if 100 years old, 2.4mm/year". (Adams, 1979).

STRUCTURES FORMED DURING UPLIFT IN ALPINE SCHISTS, WAIHO VALLEY

(a) Early deformed cross-cutting veins

(b) Early buckled vein cutting foliation

(c) Internal boudinage (brittle/ductile)

(d) typical Alpine Schist

(e) late-stage subhorizontal open fracture

(f) euhedral qz and calcite crystals in fracture

DAY 3 - FRANZ JOSEF TO DUNEDIN

STOP 20: Moeraki River Mouth or Murphy Beach

EITHER

We will leave the vans at the end of the Munro Track, just by the Moeraki Motels, and walk out to the coast (20 minutes). Towards the coast, the track crosses outcrops of the Cretaceous Otumotu Formation. fig. 29 is a detailed map of the coastal section based on mapping by Andrew Willsman (3rd year report, 1989). Letter symbols for the different formations are given in the stratigraphic columns in fig. 30 and the regional setting is shown in fig. 31 (from Nathan, 1977).

We will walk northwards along the beach, depending on time and tide, as far as the Buttress Conglomerate. We will then return along the beach examining the rocks on the way. Pay attention to attitude of bedding, younging directions, provenance and probable sedimentary environment of the various formations. The Arnott volcanics are well-exposed on the beach - see if you can find evidence for mode of formation (flow, sill, tuff, etc) and attitude.

If there is time on the way back along the track, we will examine an outcrop of the Greenland Group basement a short distance up a side creek.

OR

In roadside outcrops southwest of Murphy Creek are exposed the late Cretaceous Tauperikaka Coal Measures showing much internal faulting and deformation. From a bush track down Murphy Creek we can access Murphy Beach, on the north side of which are exposed highly bioturbated sandstones of the Whakapohai Sandstone (see Nathan (1977)) (figs. 30, 31). On the south side of the bay are tuffaceous sediments, breccias and columnar basalts of the Arnott Basalt. Recent dating of the base of the Tokakoriri Formation, immediately overlying the Arnott Basalt, has yielded a U-Pb age of 61.4 ± 0.8 Ma (Phillips et al. (2005).

STOP 21: Knights Point

At Knights Point, latest Cretaceous to Paleocene Arnott Volcanics are overlain by the marine Knights Point terrace, studied in detail by Cooper & Kostro (2006). Terrace sediments form a horizontal, 11 m thick sequence, with a basal boulder bed resting on steeply dipping Cretaceous bedrock. Heavy minerals within the sands and gravels include pyroxenes and spinel derived from the Dun Mountain Ophiolite Belt, transported 85 km by fluvio-glacial and longshore drift processes, metamorphic and igneous detritus from the Haast River, 22 km to the southwest, and more proximal detritus from the local West Coast basement and overlying Tertiary sequence. An optical luminescence age of 123 ± 7 ka for sands dates to the last interglacial and requires uplift of the Australian plate since then of 0.86 mm/yr.

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