

# Geological Society of New Zealand Inc 2003 Annual Conference



1 - 4 December  
University of Otago  
Dunedin

## Field Trip Guides

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**GEOLOGICAL SOCIETY OF NEW ZEALAND  
ANNUAL CONFERENCE 2003  
POST-CONFERENCE FIELD TRIP FT6**

**SOUTHERN ALPS TECTONICS AND  
QUATERNARY GEOLOGY**

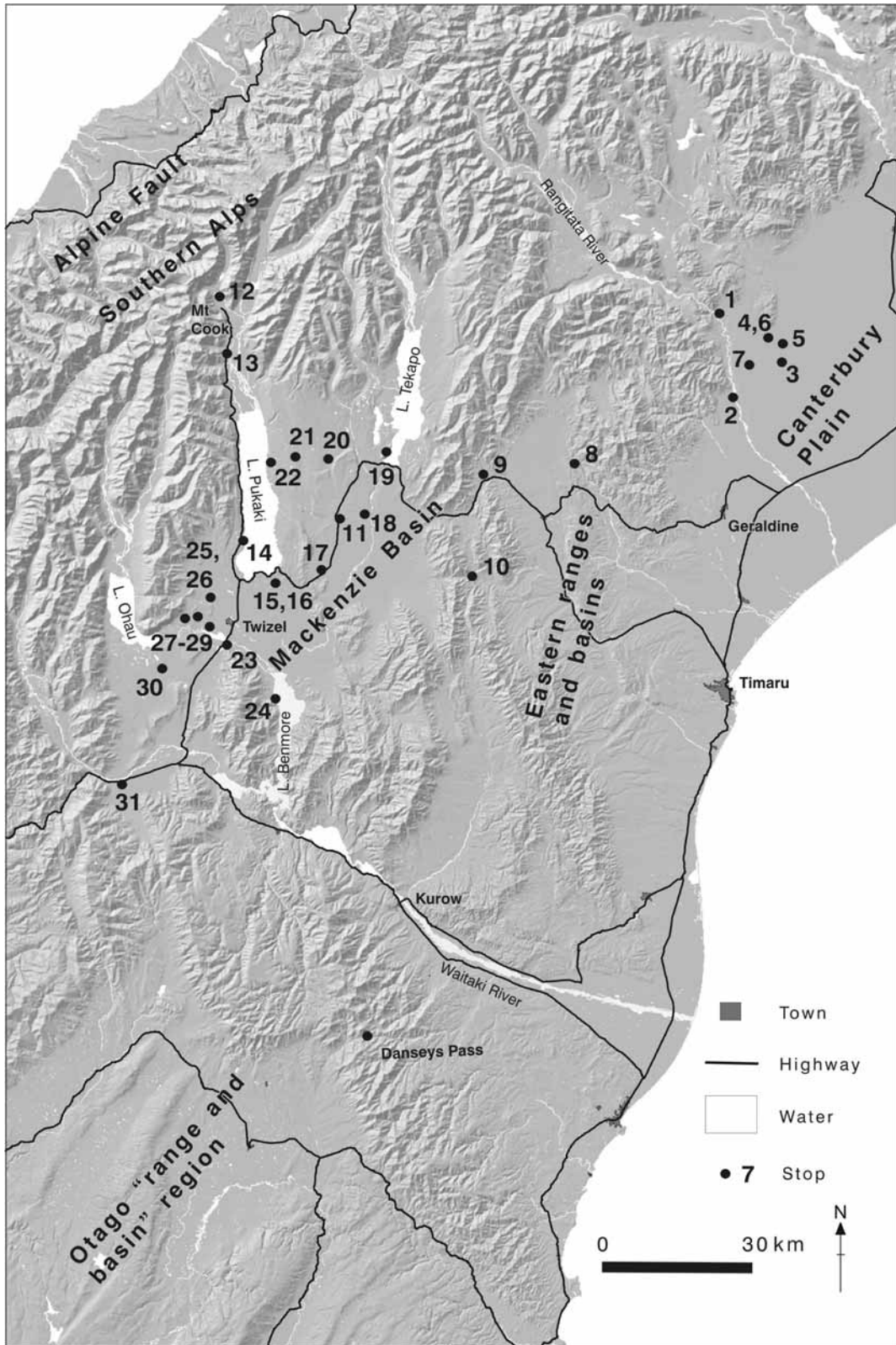
**David Barrell and Simon Cox**

**INTRODUCTION**

The Southern Alps are the product of distributed deformation east of the Alpine Fault. This fieldtrip involves a transect across the eastern side of the plate boundary deformation zone, examining the effects of this deformation from the Canterbury Plains through the eastern foothills ranges and basins to Aoraki/Mt Cook, returning to Dunedin via the Otago Basin and Range province. Highlights include the Canterbury range-front active faults; active faults within the eastern foothills; glacial and post-glacial geology and geomorphology of the Mackenzie Basin and Torlesse Terrane structure and faults.

**ITINERARY**

The field trip leaves St. Margaret's College, Dunedin, at 5.30 pm on Thursday 4 December, travelling north to Geraldine for an overnight stop (Fig. 1). Day 1 commences with aspects of geomorphology and active tectonics near the Rangitata River, at the boundary between the Southern Alps range-front and the Canterbury Plains. The trip proceeds west to Twizel, stopping to view selected tectonic and landform features. Day 2 heads north to Mount Cook village, where there will be a short walk to the Mueller and Hooker glacier termini to view Holocene moraines, the effects of present-day glacial retreat, and aspects of Torlesse rocks that are visible in the surrounding mountain slopes. The trip returns to the Mackenzie Basin and on to Lake Tekapo, where (weather permitting) Late Pleistocene glacial geomorphology will be viewed from Mt John. The return to Twizel includes stops at Irishman Creek Fault and the mid to Late Pleistocene lateral moraines surrounding Lake Pukaki. Day 3 traverses the southwestern Mackenzie Basin, stopping to examine Late Pleistocene – Holocene displacements of the Ostler Fault, and aspects of Quaternary geology/geomorphology. The trip then proceeds down the Waitaki valley to Duntroon, and west via Danseys Pass into the Otago Range and Basin province. Travelling via Middlemarch and Dunedin airport, the trip finishes in Dunedin at 4 pm on Sunday 7 December.

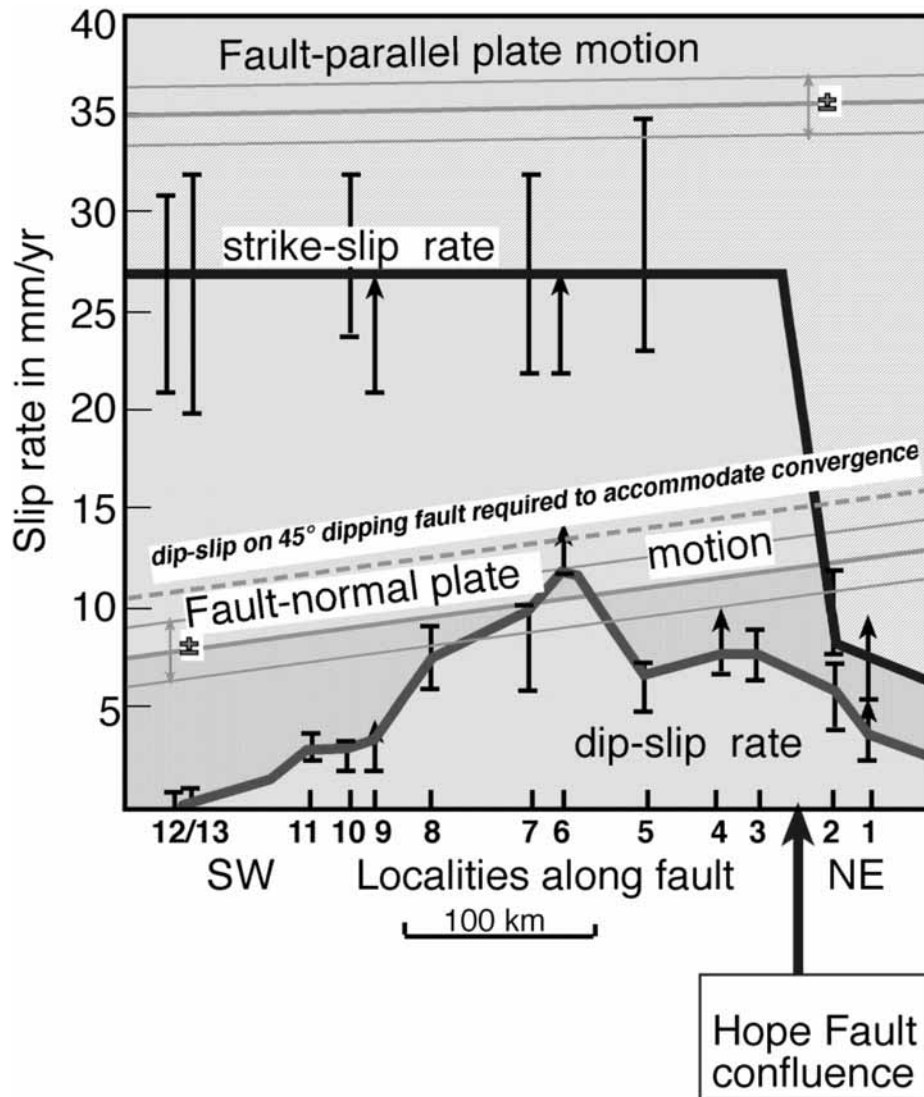


**Fig. 1:** Locality map

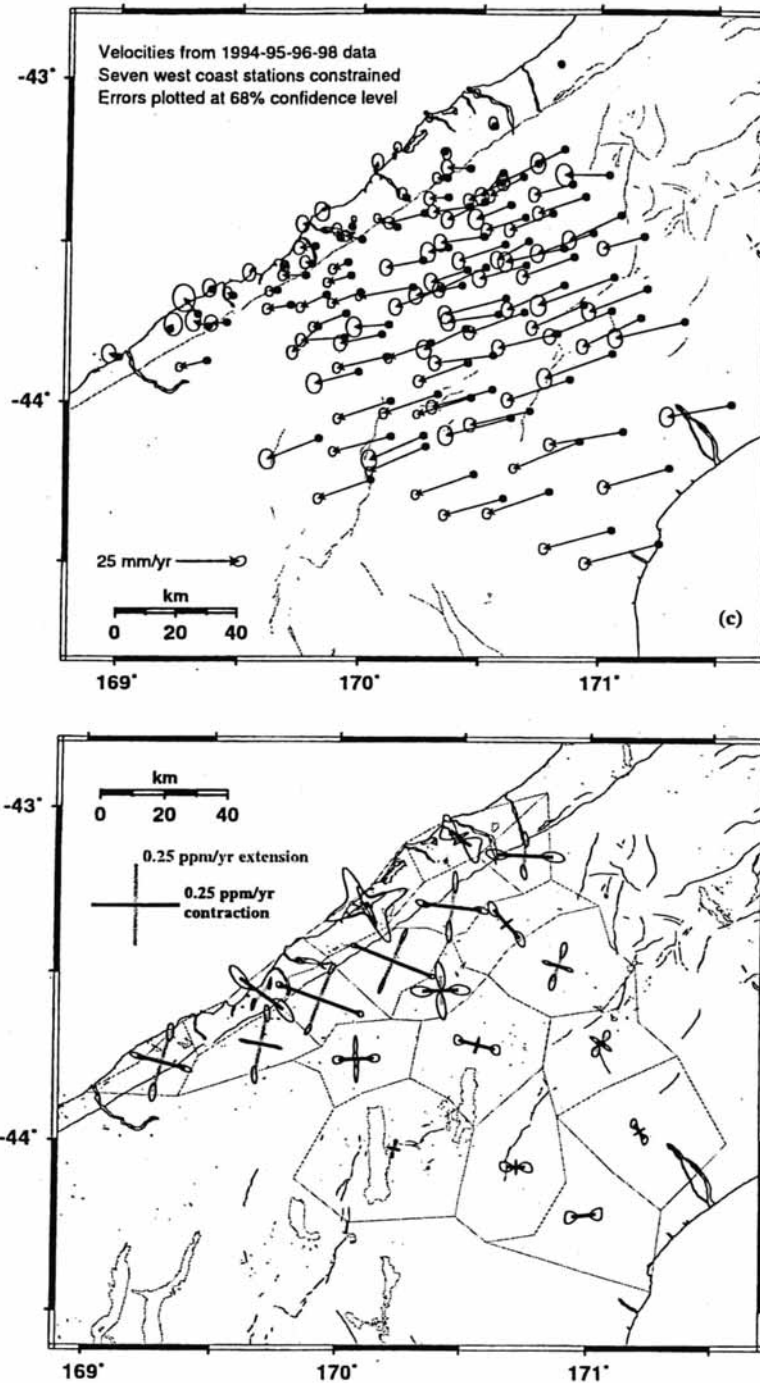
## OVERVIEW OF TECTONICS & QUATERNARY DEFORMATION

Terranes in the South Island of New Zealand have been both offset and bent by the Pacific-Australia plate boundary (Norris 1979; Spörli 1979; Sutherland 1995, 1996, 1999; Molnar *et al.* 1999; Mortimer *et al.* 1999). Plate reconstruction constrained by satellite altimetry suggests the 440-470 km offset on the Alpine Fault accounts for c. 55% of the late Eocene-Recent plate displacement, with c. 45% accommodated by distributed dextral shear (Sutherland 1999). Late Quaternary strike-slip displacement rates along the Alpine Fault ( $27 \pm 5$  mm/yr) make up 70-75% of the fault-parallel inter-plate motion (Fig. 2), and are relatively constant compared with dip-slip rates (0 to >10 mm/yr) which are greatest adjacent to the highest mountains (Norris & Cooper 2001). Geodetic surveys show that rocks in the immediate vicinity of the Alpine Fault are currently storing elastic strain energy that corresponds to 50-70% of the plate motion rate (Pearson 1994; Pearson *et al.* 1995; Beavan *et al.* 1999; Fig. 3). Importantly, a significant component of both long term and contemporary deformation is “missing”.

Estimated uplift and exhumation rates vary across the Southern Alps, from c. 1 mm/yr in the southeast near Lake Pukaki, to c. 6-10 mm/yr immediately adjacent to the Alpine Fault where the rainfall and erosion rates are much higher (e.g., Wellman 1979; Adams 1980a,b; Simpson *et al.* 1994). Quaternary slip is clearly demonstrated on structures within the Mackenzie Basin and along the southeastern margin of the Southern Alps (e.g., Ostler and Irishman Creek Faults, Canterbury Range Front and Fox Peak Faults). Uplift rates calculated from faulted and folded glacial and post-glacial landforms correspond closely with those measured by geodetic survey (0.4-1 mm/yr) (e.g., Blick *et al.* 1989; Van Dissen *et al.* 1993), but these are a relatively insignificant component of the total plate motion (Lensen 1975; Walcott 1998). A major backthrust near the drainage divide crest of the alps, the Main Divide Fault Zone, juxtaposes rocks with different thermochronological ages indicating significant late Cenozoic vertical displacement (<5 Ma) (Tippett & Kamp 1993ab; Cox & Findlay 1995). However, definitive evidence for active fault slip and slip-rates within the central Southern Alps is lacking - probably due to high erosion rates, resulting in extreme youth of landforms and a consequent lack of preserved tectonic features. The presence of elevated topography and earthquakes provides indirect, yet strong, evidence that at least some of the observed contemporary deformation must be permanent in this region (Pearson 1993; Leitner *et al.* 2001). However, the extent to which “missing deformation” occurs within the central Southern Alps, occurs locally along known active faults as distributed deformation (e.g. as fault-folds), or occurs offshore is quite unclear.



**Fig. 2:** Diagram showing the variation of strike-slip and dip-slip rates along the Alpine Fault. The estimated values at each locality are shown with vertical bars. Minimum values are shown with an arrow at the upper end. A “best-fit” line representation along the fault is shown in heavy black. The fault-parallel and fault-normal components of the interplate slip vector are also shown using Nuvel-1 pole (DeMets *et al.* 1994), together with uncertainties, which are shown as thin lines either side of the mean value line (from Norris & Cooper 2001).



**Fig. 3:** The 1994-1998 average strain rates within 19 regions of approximately uniform strain rate, calculated from a GPS dataset after removing obvious outliers. The strains are plotted as magnitude and direction of axes of the principal strain rates, together with 68% confidence regions on those rates. The black lines represent contraction, the grey ones extension. The scale bar shows an engineering strain rate of 0.5ppm/yr, made up of 0.25 ppm/yr E-W contraction and 0.25 ppm/yr N-S extension (from Beavan *et al.* 1999).

## **DAY 1: ACTIVE FAULTS OF THE EASTERN FOOTHILLS**

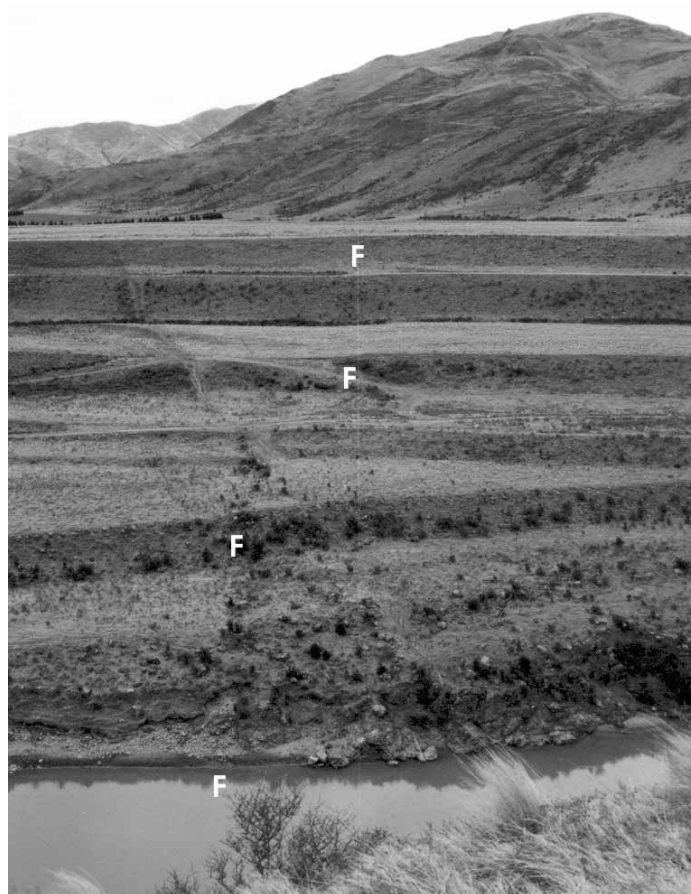
### **THE CANTERBURY RANGE-FRONT**

The range-front at the western margin of the Canterbury Plains marks the clearly visible eastern margin of the Southern Alps plate boundary deformation zone. Active faulting along the range-front has only recently been reported, in part by Oliver and Keene (1989) and in more detail by Barrell *et al.* (1996a, b), although near Mt Somers, Speight (1938) discussed the probable existence of Late Quaternary faulting. The relatively late recognition of Late Quaternary tectonic features along the Canterbury range-front is probably due to their expression as broad warps or flexures of the ground surface, rather than as “classic” sharp, well-defined fault scarps. The first stop is the mouth of the Rangitata Gorge where a sharp fault scarp on the lowest river terraces changes into a broad flexure on higher river terraces, probably reflecting the effect of increased gravel thickness on the surface expression of deformation. Subsequent stops will inspect broad steps on the Late Pleistocene outwash surfaces of the Canterbury Plain in the Peel Forest to Montalto area. Some of these steps were mapped in some detail by previous workers (e.g. Speight 1941, Gair 1967) and interpreted as being of stratigraphic origin. We will consider the merits of an alternative interpretation that they were formed by Late Quaternary faulting.

Significant Late Quaternary fault activity is seen along the range-front from Mt Hutt in the north, to Orari River in the south. Between the Orari and Hae Hae Te Moana rivers, there is good evidence for Mid-Late Quaternary faulting, but the amounts and rates of slip appear to be markedly less than to the north. From Hae Hae Te Moana River to Timaru, no Mid-Late Quaternary tectonic activity has been recognised along the “range-front” (western margin of the Canterbury Plain) which here appears to be a dip slope descending from the “eastern ranges and basins”, which lie to the west.

#### **Stop 1: Klondyke fault scarp/flexure (NZMS260 map reference J36: 677144)**

A NE-SW trending fault scarp crosses a flight of river terraces at the mouth of the Rangitata gorge. The scarp is sharply preserved, upthrown about 2 m to the NW, on the lowest terrace, some 8 metres above flood level (Fig. 4a). This terrace surface has a rudimentary AC soil profile, suggesting that it is no more than a few hundred years old. The fault is exposed in the riverbank, with greywacke displaced up to the NW against very compact, grey aggradation gravel. Rising up the flight of terraces to the SW, the fault scarp becomes progressively broader and ill-defined, and on the highest terrace, about 60 m above the river level, is barely discernable as a subtle, 30 to 40 m wide, flexure of the terrace surface (Fig. 4b). This highest terrace is considered to be a Late Otira Glaciation (Marine Oxygen Isotope (MIS) Stage 2) outwash surface.



**Fig 4:** (Above) view NW of Klondyke fault scarp (c. 2 m high) crossing left-right on low terraces. (Below) view SW of fault/flexure extending up the terrace flight (F = approximate toe of scarp/flexure)



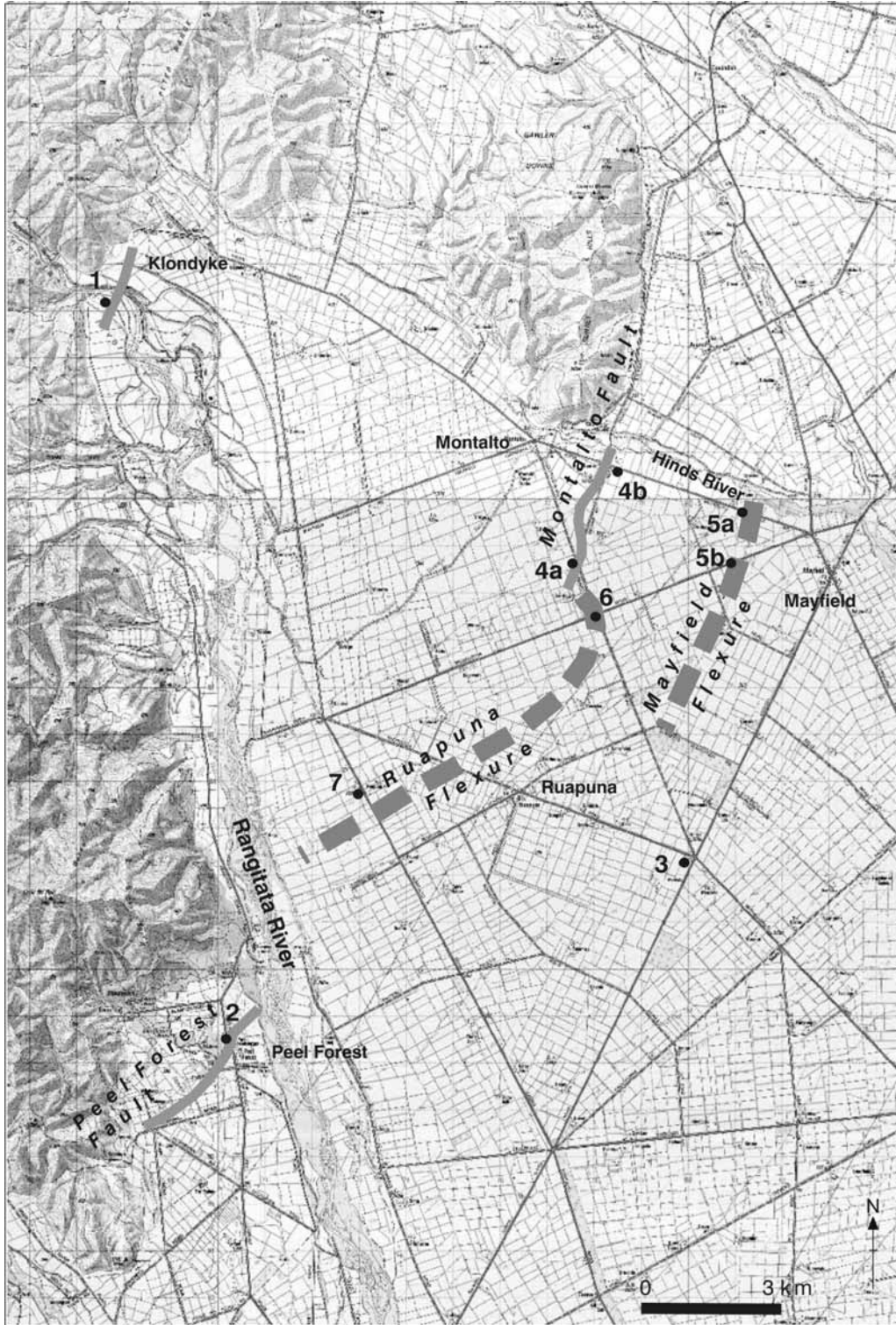
As far as can be ascertained, on account of its breadth and poor definition, the tectonic flexure has about the same throw on the high terrace as the sharp fault scarp on the lowest terrace. This suggests that the fault has had only one surface rupture in the past c. 14,000 years and the rupture occurred only a few hundred years ago. The other feature of note here is the second-highest river terrace, which is capped by 6 m of unsorted angular greywacke debris that is thought to be part of the run-out from a large rock avalanche deposit in the middle part of the Rangitata gorge (Barrell *et al.* 1996).

**Stop 2: Peel Forest fault scarp (K37: 702986)**

In Peel Forest township, about 100 m NW of the Department of Conservation field centre, a 5 to 7 m high, broad step running NE-SW across a high-level Rangitata alluvial surface, correlated with the Late Otira Glaciation, is interpreted to be a fault scarp / flexure (Fig. 5). Assuming a >14,000 year BP age for the offset surface, a vertical slip rate of < 0.4 mm/year is implied. Note the gradient anomaly extending for about 500 m NW of the upper side of this step, interpreted to be a backtilt. Also note the fluvial riser west of the road that is much steeper and well-defined than the fault scarp / flexure, and is absent on the downthrown side of the fault. Travelling west down Horsfall Road, at the southeast end of the township, at Kowhai Stream (J37: 693968), the fault scarp is absent on the youngest alluvial surfaces 300 m NW of the road, but is evident, with increasing height, on older alluvial surfaces SW of the stream. From the intersection of Horsfall, Blair and Scotsburn roads, 200 m up the NNW extension of Blair Road (J37: 685967), a c. 2 m high, relatively broad, fault scarp crosses a terrace surface of Scotsburn Stream. Collectively, these sites suggest multiple movements of this fault, post c. 14,000 years, with a cumulative throw of 5 to 7 m within this period.

**Stop 3: Gravel pit – corner SH72 & Shepherds Bush Road (K37: 801024)**

Exposures in this gravel pit illustrate the nature of deposits underlying the principal fluvioglacial outwash surface of the Canterbury Plain. Note the texture and sorting of the sandy gravels, and the “Lismore-type” soil profile developed on the deposits (Kear *et al.* 1967). Lismore soils are typical of the soils found on Late Otiran outwash surfaces in sub-humid areas of the Canterbury Plains. Deposits and soils of similar nature and age are thought to be present, although not exposed, at stops 4 to 7.



**Fig 5:** Location map of the Rangitata area

**Stop 4: Montalto fault scarp (K37: 776087)**

A 3 m fault scarp crosses Coskeries Road, lying within a 500 m wide channel cut c. 3 m into the Canterbury Plain outwash surface on the upthrown side of the fault. The channel is absent on the downthrown side of the fault. Travelling NE along Lower Downs Road, the fault scarp is crossed twice, and then is crossed again on Mayfield – Klondyke Road just east of the Lower Downs Rd intersection. Here the fault scarp across the “main” Canterbury Plain surface is about 6 m high, and on the upthrown side of the fault an isolated alluvial terrace remnant stands several metres above the main plain surface. These relationships suggest at least one fault surface rupture that elevated the isolated high terrace remnant before or during formation of the Canterbury Plain “main” aggradation surface, at least one more rupture during formation of the Canterbury Plain outwash surface, which led to the incision of the Coskeries Rd channel, followed by at least one subsequent surface fault rupture.

**Stop 5: Mayfield flexure (K37: 814097)**

A c. 300 m wide, c. 2 m high NE-SW trending step on Mayfield – Klondyke Road is interpreted as a tectonic flexure because it lies transverse to the slope and relict braid-channel patterns of the Canterbury Plain surface. It coincides with a SE decrease in the incision of the Hinds River. The water race sits at about the crest of the flexure. Along strike on Moorhouse Road (K37: 813087), the flexure has a similar breadth and height, with the water race still following its crest. The water race appears to have been positioned to take advantage of the subtle topographic step produced by the flexure.

**Stop 6: Montalto Fault/Ruapuna flexure (K37: 780075)**

Here at Moorhouse Rd/Coskeries Rd intersection, the 3 m-high Montalto fault scarp of Stop 1 is visible 1 km N along Coskeries Road, but loses its surface expression a few hundred metres south of that location (Fig. 5). The road intersection lies in the middle of a very broad NE-SW trending, up-to-the-NW topographic rise. This subtle topographic feature is most evident looking W along Moorhouse Rd, where the ground surface bends away out of view about 200 m away (i.e. the horizon disappears) across the crest of the rise. Less dramatic is a flattening of the outwash surface gradient about 400 m E along Moorhouse Rd, at the assumed toe of the rise. This rise is interpreted as a tectonic monoclinical warp (Ruapuna flexure) that represents the southwest continuation of deformation associated with the Montalto Fault.

**Stop 7: Ruapuna flexure (K37: 731038)**

The topographic expression of the Ruapuna flexure is easily seen on Ealing – Montalto Road, which crosses the crest of the flexure at K37:731038. Looking southeast along the road from a position 200 m northwest of the crest, on the slightly backtilted upthrown side, the road disappears from sight as it descends the flexure. Similarly,

looking northwest along the road from the toe of the flexure, which is very poorly defined but lies between 0.4 and 1.0 km SE of the crest, the gradient anomaly is shown by the road disappearing over the crest. To allay any suspicions that these are optical illusions, look southwest of the road, and see a river terrace riser that is up to 10 m high adjacent to the crest of the rise, but decreases progressively in height across the flexure, dying out at the toe of the flexure. The throw at this location is estimated to be  $10 \pm 5$  m, the uncertainty reflecting the uncertain position of the toe of the flexure (Barrell *et al.* 1996). A point to note is the value of having a long unobstructed view (e.g. straight road) for identifying broad zones of surface deformation.

## **EASTERN RANGES AND BASINS**

The ranges and basins of South Canterbury are formed by a series of NE to NNW trending Late Cenozoic faults and folds. Basins occupy the synclines, in which Tertiary sediments are preserved, along with extensive Quaternary alluvial terrace and fan gravels. The ranges are either homoclinal fault blocks or anticlinal ridges with at least some degree of faulting on one or both margins. Mesozoic basement rock of the Torlesse Terrane, predominantly textural zone (TZ) 1 greywacke/argillite, with minor TZ2 semischist is exposed in the ranges, locally with remnants Tertiary sedimentary cover. Within the Tertiary sediments, “orogenic” (lithic) sediments begin to appear in the middle Miocene (c. 13 Ma) in Central Otago (Youngson *et al.* 1998), but in parts of southern Canterbury, the youngest of the “pre-orogenic” quartzose sediments may be as young as latest Miocene (Kapitean: Field and Browne 1986). The quartzose sediments are overlain, generally concordantly although not necessarily conformably, by poorly lithic (generally greywacke) conglomerates that in the relatively few locations where they have been dated, contain Wanganui-series fossils (i.e. Pliocene-Pleistocene; < 5 Ma). These lithic conglomerates indicate the onset of uplift and exposure of Torlesse basement within the region, and they may indicate onset of development of the range-basin topography.

Significant Late Quaternary fault activity is recognised on the Fox Peak Fault, and to lesser degrees on the Dalgety Fault, Albury Fault and Hunters Fault.

### **Stop 8: Opuha Dam (J37: 408878)**

Constructed in the late 1990s, Opuha Dam is a multi-purpose structure that provides water storage for summer irrigation, power generation, and a recreational lake. During construction, the partially-built dam was overtopped during a period of heavy rain, causing breach and erosion of the earth fill, and extensive flooding downstream, though damage was largely confined to paddocks, fences and flood protection works. The dam site lies on a Torlesse greywacke escarpment forming part of a dip slope descending into the eastern margin of the synclinal Fairlie Basin. The site takes advantage of the

topographic relief and solid foundation conditions provided by a narrow gorge cut in greywacke basement, with the broad basin upstream providing an extensive, relatively large-volume reservoir. We will inspect exposures of Torlesse greywacke and fault zones in the vicinity of the dam.

**Stop 9: Fox Peak Fault – Mt Dobson Road (I37: 257850)**

The NE-SW trending Fox Peak Fault is a major reverse fault that has upthrown the Two Thumb Range relative to the Fairlie Basin. At Mt Dobson skifield access road, the fault is marked by several sub-parallel scarps within a 2 km wide zone, displacing alluvial terraces of Firewood Stream (Beanland 1987, Cutten 1990) (Fig 6). Conditions permitting, we will examine the fault scarps and exposures in Firewood Stream. At several sites along the fault, vertical offsets of assumed Late Otiran alluvial surfaces imply a vertical slip rate of the order of 1 mm/year.

**Stop 10: Dalgety Fault – Mackenzie Pass Road (I38: 223660)**

The N-S trending Dalgety Fault lies along the eastern foot of the Dalgety and Rollesby ranges. At Mackenzie Pass Road, a fault scarp, upthrown to the west by several metres, crosses an alluvial terrace of Hayter Stream. Conditions permitting, we will inspect crushed and sheared greywacke of the fault zone, exposed in the north bank of Hayter Stream. Between Mackenzie Pass and Burkes Pass, on Rollesby Valley Road, at I38: 223716, an E-facing escarpment on alluvial fans, approximately 300 m west of the road, is interpreted to be the northern continuation of the fault scarp seen at Hayter Stream. Tentative age estimates of offset alluvial surfaces suggest a vertical slip rate of less than 0.5 mm/year.

**Stop 11: The Wolds fault scarps/flexures – SH8, Irishman Creek (I38: 985785)**

Viewed west from the SH8 - Tekapo canal intersection, a series of NE-trending faults and flexures cross a high terrace mapped as Wolds moraine and outwash (Fig xx). The faults are upthrown to the SE and anticlinal flexures occur the upthrown side. There are inconclusive indications that these tectonic features continue across Balmoral-age outwash terraces as very subtle, low-amplitudes warps, but they do not appear to affect Mt John, Tekapo or post-glacial alluvial surfaces (see Fig. 7).

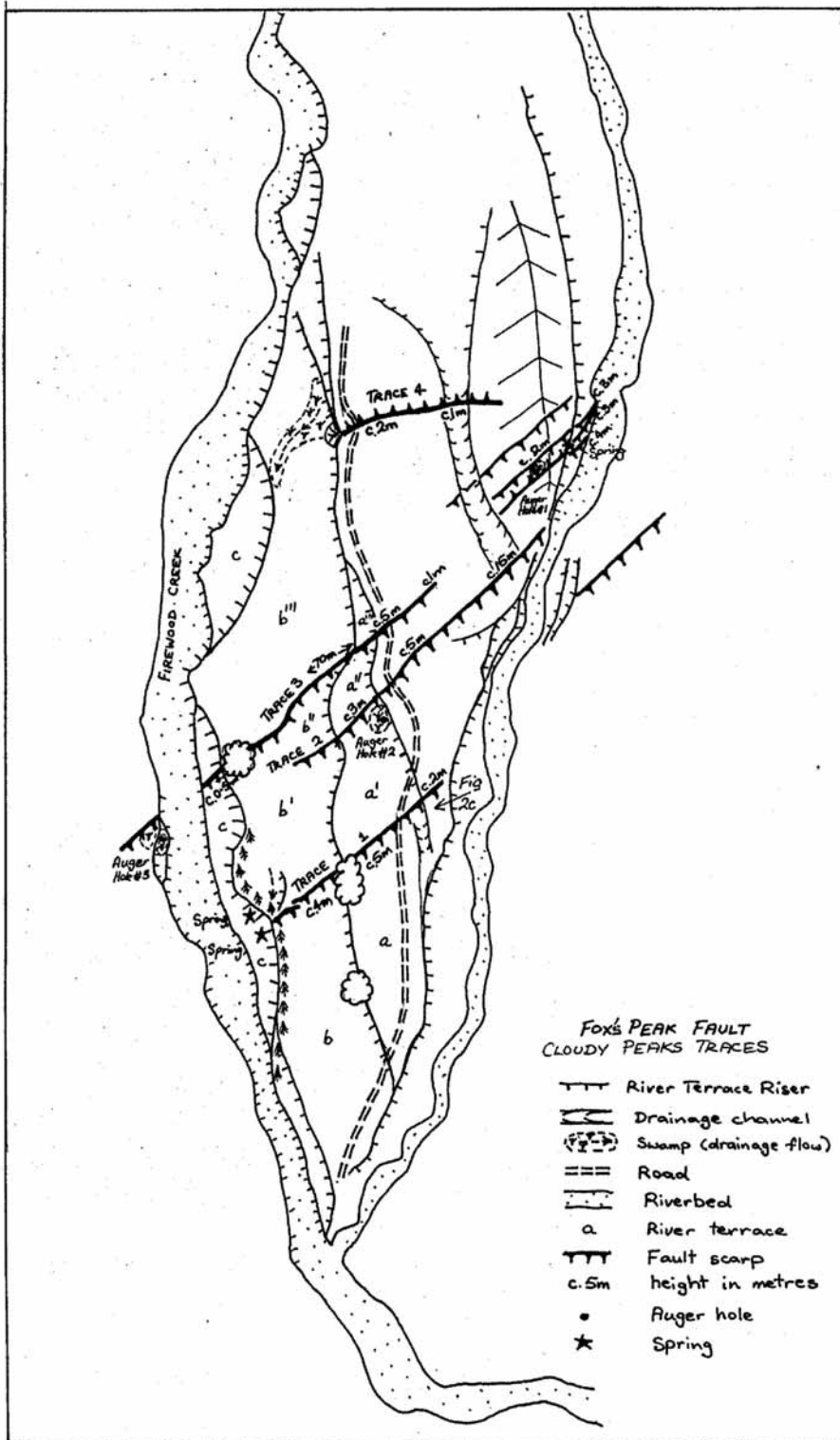


Fig. 6: Map of Fox Peak Fault scarps at Mt Dobson Road (from Cutten 1990)

## DAY 2: LANDFORMS AND TECTONICS OF MT COOK–MACKENZIE BASIN

### MACKENZIE BASIN

The Mackenzie Basin is a large tectonic depression, bounded to the east by the eastern ranges and basins, and to the west by the Southern Alps. Late Cenozoic sediments are preserved beneath parts of the Mackenzie Basin, and are exposed where uplifted along Quaternary faults. Lakes Ohau, Pukaki and Tekapo occupy glacial troughs last occupied by ice during the last glacial maximum (LGM). Moraines surround the lakes and extensive outwash plains extend out across from which alluvial fans have encroached onto the outwash surfaces (Fig 7). Drainage from the lakes exits the basin through the Benmore gorge, which marks the start of the Waitaki valley.

Glacial Deposit	Assigned Climatic Event	Assigned Oxygen Isotope (MIS) Stage and (Age)	Comments
Holocene till/outwash	"Neoglacial"	1 (0 – 5 ka)	Supported by 14C dates
Birch Hill Formation	Late Glacial	1 – 2 (10 – 12 ka)	Supported by 10Be dates
Tekapo Formation	Late Otira Glacial	2 (16 – 18 ka)	Supported by 14C/10Be dates
Mt John Formation		2 (18 – 24 ka)	Supported by 10Be dates
Balmoral 2 Formation	? Early Otira Glacial	4 (59 – 71 ka)	Correlation with MIS 4 uncertain
	Kaihinu Interglacial	5	None recognised
Balmoral 1 Formation	? Waimea Glacial	6 (128 – 186 ka)	Correlation with MIS 6 uncertain
	Karoro Interglacial	7	None recognised
Wolds Formation	? Waimaunga Glacial	8 (245 – 303 ka)	Correlation with MIS 8 uncertain. May include deposits from more than one glacial event

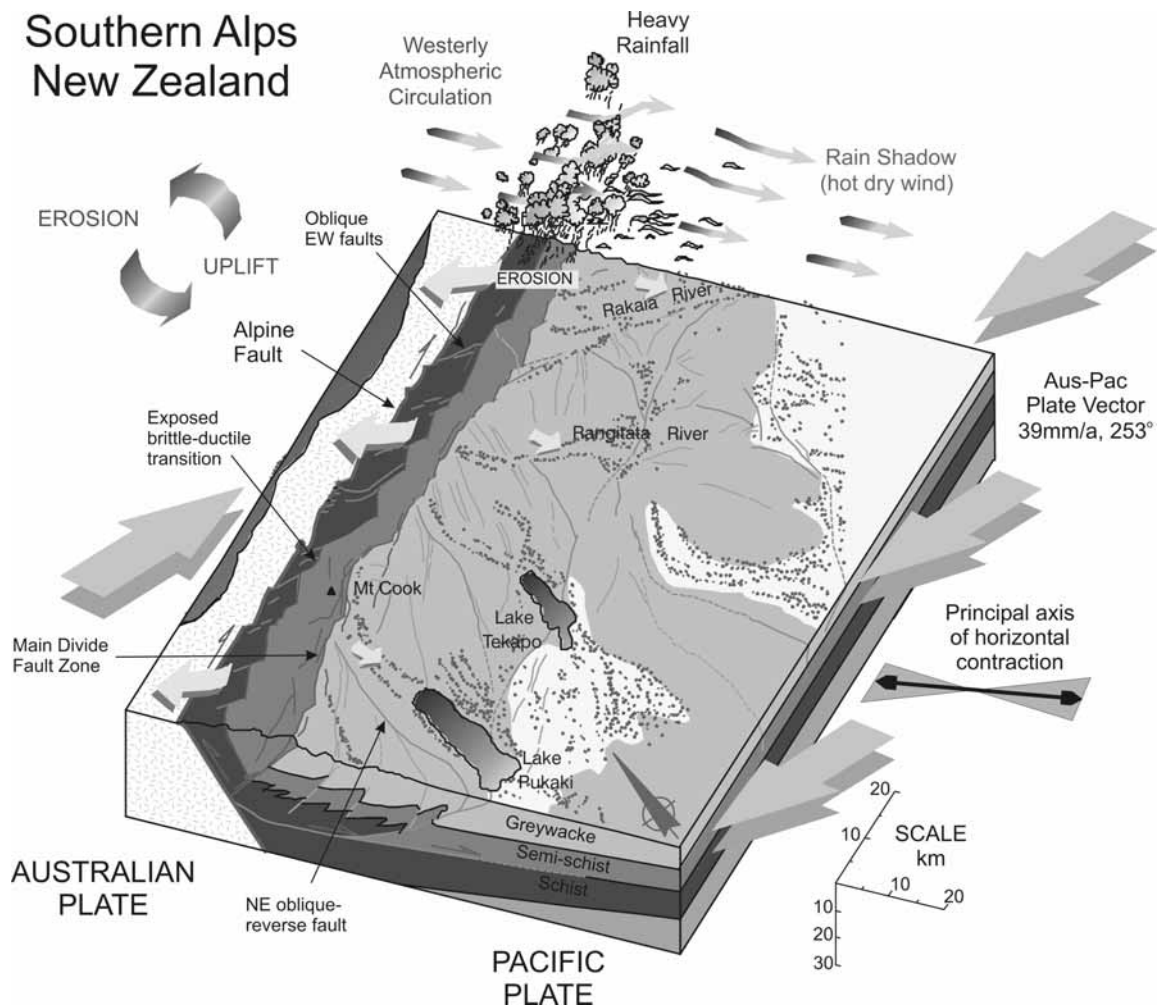
**Fig. 7:** Glacial stratigraphy of Mackenzie Basin – Mt Cook area. “Interglacial” phases are shaded. MIS 8 may be a minimum age for some or all of Wolds Formation.

### SOUTHERN ALPS

#### *Distributed deformation and the nature of the brittle Cenozoic overprint*

Geological mapping of the central Southern Alps of New Zealand (QMAP Aoraki - Cox & Barrell in prep) is revealing the effects of distributed dextral transpression east of the

Alpine Fault plate boundary. Differential uplift and exhumation in the central Southern Alps during the past c. 5-6 Ma has exposed a near-continuous mid-upper crustal section that has been delaminated from the rest of the Pacific Plate and deformed in the hangingwall of the Alpine Fault (Grapes 1995, Grapes & Watanabe 1992, see Fig. 8). Mid-crustal mylonites and amphibolite facies schists adjacent to the fault suffered ductile deformation that constructively reinforced and reoriented the pre-existing metamorphic fabrics (Little *et al.* 2002a). An exhumed, fossil, brittle-ductile transition zone separates western schists from relatively unmetamorphosed eastern greywackes and semischists that were metamorphosed during the Mesozoic, but suffered brittle effects of late Cenozoic transpression (Little *et al.* 2002b). Belts of cleaved greywacke and semischist c. 2 km thick also crop out on the eastern side of Mackenzie Basin (near Burke Pss in the Rollesby and Two Thumbs Ranges), where they are unconformably overlain by Paleocene to Miocene sediments indicating that these semischists were uplifted before the Tertiary, presumably in association with Mesozoic tectonics.



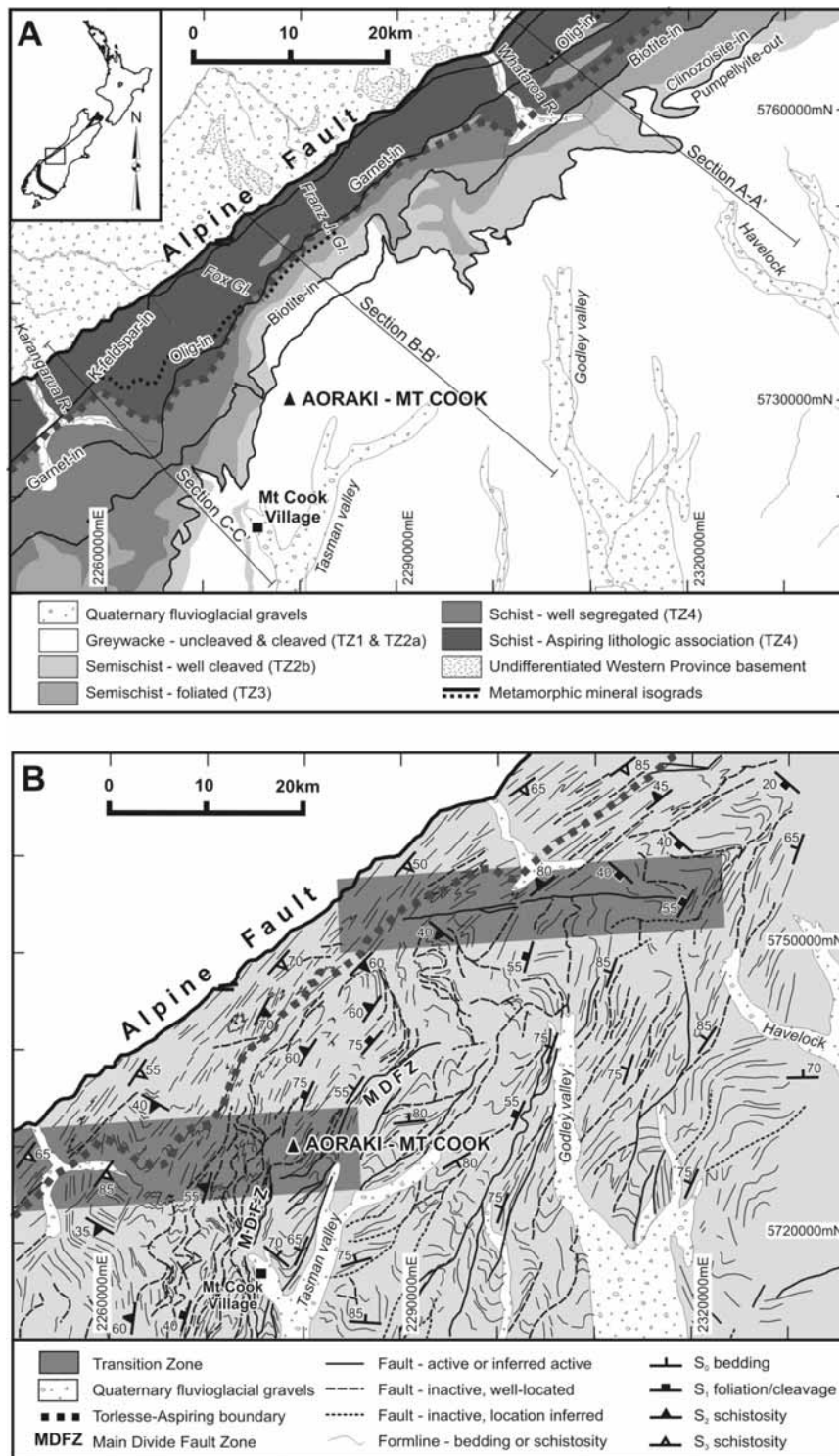
**Fig. 8:** Block diagram summarising the tectonics of the Southern Alps.



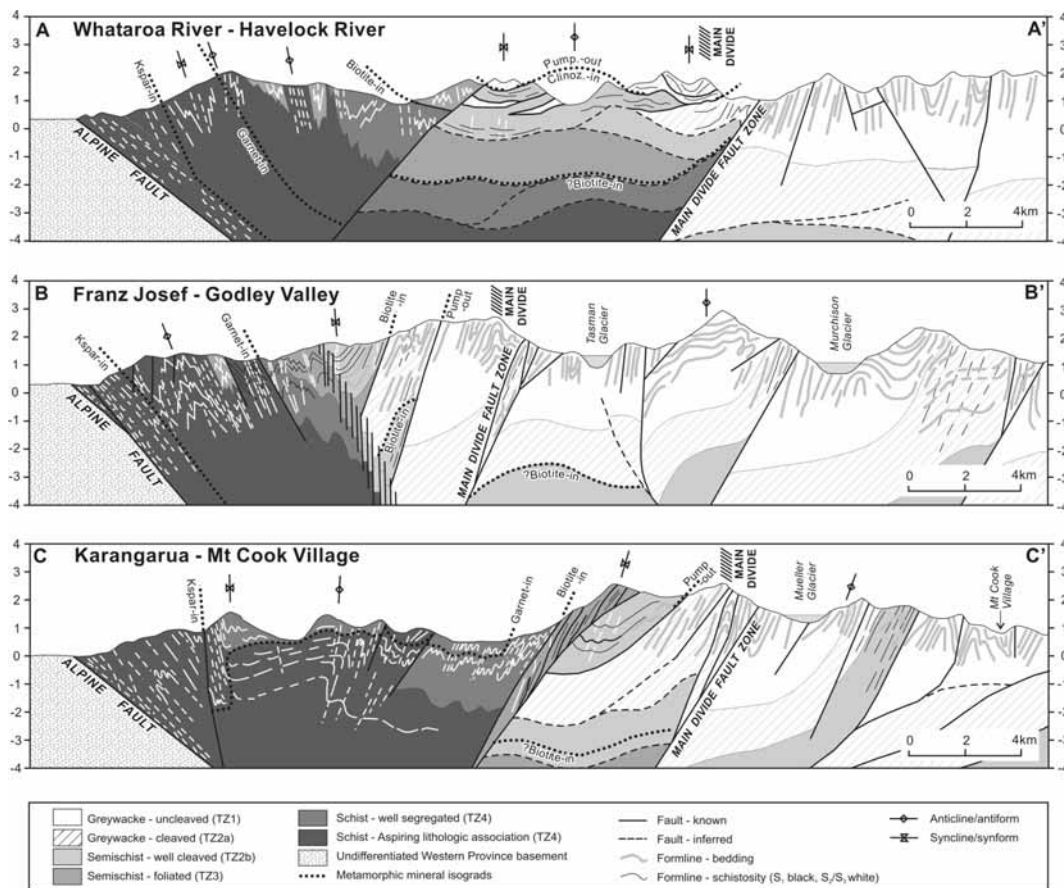
The greywackes are a compositionally monotonous sequence of sandstone-mudstone, with steeply dipping bedding and steeply plunging folds that were imbricated, tilted and folded during the Mesozoic. Sequences predominantly face west or southwest, but locally eastward-facing sections up to 10 km thick have been overturned and provide regional-scale structural marker units (Cox 2002). A clockwise regional swing in bedding (from 320° to 030° strike) occurs from around 60 km SE of the Alpine Fault (c. Mackenzie basin), matching the Cenozoic oroclinal bending of Mesozoic terranes in the southern South Island. The hinges of steeply plunging folds are similarly deformed, with folds becoming tighter and with shorter wavelengths in proximity to the Alpine Fault.

The central Southern Alps region is dominated by an en-echelon array of northeast (025° or 055°) striking, oblique-slip (reverse dextral) backthrusts dipping 40-60° west. Steeply plunging folds are transected, overthrust and rotated by late Cenozoic fault displacement. In the region of highest mountains (30 km southeast of the Alpine Fault) seismic reflection data suggests the faults have deformed the top 10 km of the crust into a large, 15 km wavelength antiform. Locally, strong partitioning has occurred between the 080-150° directed fault plane slip and deformation of adjacent wall rocks. Observed oblique-reverse fault slip directions are consistent with contemporary geodetic shortening and historic earthquake focal mechanisms (up to M6.2), but definitive evidence for active Holocene displacement and displacement rates is lacking for these faults due to extreme erosion rates and consequent lack of preserved tectonic features.

Geophysical and geological data have recently been assembled by Little *et al.* (2002c, in review) to explore along-strike variations in convergence rate, geomorphology, exhumation state, structure, and ramp behaviour of uplifted rocks (Figs. 9, 10). A central segment of the Southern Alps has a higher uplift rate, more relief, and a narrower orogenic width than surrounding regions. There, the east-tilted crust of the Pacific Plate exposes a narrower crustal section in plan view, and exhumes rocks that yield late Cenozoic (“Alpine-age”) thermochronometric ages that are younger than those in surrounding regions. New hornblende  $^{40}\text{Ar}/^{39}\text{Ar}$  dating indicates that lower crustal rocks exhumed from temperatures of >500-550°C in the late Cenozoic are confined to an elongate, 20 x 5 km-wide region in the central Southern Alps. This culmination of deeply exhumed rocks is the only part of the present-day range that may have achieved exhumational steady-state. To the north and south, the hanging wall of the Alpine fault retains mid Cenozoic and older (“inherited”) Ar/Ar and K-Ar ages for micas and hornblende. Subhorizontally layered, remnant plugs of the original crustal hanging wall ramp are apparently still preserved further north and further south in the Southern Alps (the Alpine fault must have <70 km of dip-slip there). They infer the presence of lateral ramps striking parallel to the plate motion, with tearing of the delaminated Pacific Plate above the lateral ramps.



**Fig. 9:** Geological map from Little *et al.* (in review), showing variation in metamorphism and structure along the Southern Alps.

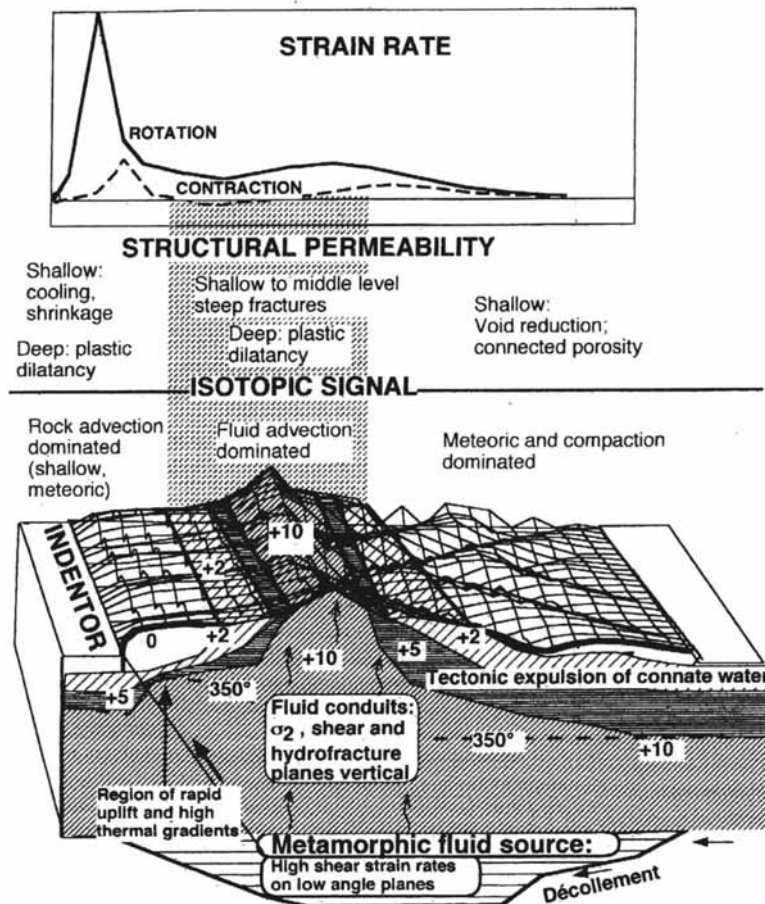


**Fig. 10:** Geological cross-sections from Little *et al.* (in review), showing variation in metamorphism and structure along the Southern Alps. Refer to Fig. 9 for location.

### Fluid Flow

The Southern Alps hosts an active fluid flow regime (e.g., Koons & Craw, 1991ab; Jenkin *et al.* 1994; Koons *et al.* 1998; see Fig. 11), as demonstrated by numerous hot and cold springs, extensive late-stage mineralisation, ubiquitous veining and in the results of isotopic and fluid inclusion studies (e.g., Barnes *et al.* 1978; Cox *et al.* 1997, Craw *et al.* 1994; Jenkin *et al.* 1994; Upton *et al.* 1995, Koons *et al.* 1998). Indicated fluid sources within the Southern Alps include metamorphic dehydration reactions, basinal brines and meteoric water. No evidence has been found for any magmatic source for fluids in the Southern Alps. The liberation of metamorphic fluid during uplift has been the favoured mechanism for the formation of post-metamorphic veins in the schist (Craw 1988). However, there is increasing evidence to suggest that meteoric fluid makes up a large proportion of the fluid in the upper, brittle crust and that it may contribute significantly to fluid flow beneath the brittle-ductile transition (Jenkin *et al.* 1994; Upton *et al.* 1995). Basinal brines appear to percolate to considerable depths in

fault zones east of the Main Divide and mix with metamorphic fluids (Templeton *et al.* 1998, Upton *et al.* 2003, Horton *et al.* 2003).



**Fig. 11:** Summary of mechanical and isotopic correlations across an oblique collision orogen such as the Southern Alps. Rotation and contraction sections are from mechanical numerical models. The isotopic values presented are the permil difference between measured  $\delta^{18}\text{O}$  values and those expected from a topographically dependent meteoric water curve. The  $350^\circ\text{C}$  isotherm and topographic shapes (Koons & Craw 1991a,b) provide thermal and mechanical reference parameters for the orogen. In rock-advection dominated regions adjacent to the plate boundary, deep assemblages are overprinted by strong meteoric signatures as rapidly cooling rocks are flushed with topographically driven fluids. In fluid-advection dominated regions of the Main Divide, relatively shallow assemblages have anomalously deep signatures, implying communication with deeper fluid production sources along near-vertical fractures associated with minor dilatancy. Isotopic signatures in outboard regions arise from interaction of expelled basinal brines with meteoric, topographically driven fluids.

A magnetotelluric experiment measured the transmission of naturally-occurring electromagnetic waves over a 150 km transect across the Southern Alps (Wannamaker *et al.* 2002). It found a U-shaped middle to lower crustal conductive zone extending to about 30-km depth, interpreted to represent the release of metamorphic fluids into fractures in the deep crustal root. Fluid interconnection and electrical conduction are thought to be promoted by deformation. The shallow brittle part of the Alpine fault, however, was thought to be a poor electromagnetic conductor because the surrounding rock (Alpine Schist) has already lost much of its fluids.

### *Recent Geophysical Experiments*

A series of large-scale geophysical experiments was carried out across the South Island of New Zealand from 1995-1998 (see Stern *et al.* 1997). The experiments were multi-disciplinary, multi-national projects aimed at obtaining a better understanding of continent-continent collisional processes across the Australian-Pacific plate boundary. Teams included scientists from: Geological and Nuclear Sciences, Victoria University, Otago University, Michigan Institute of Technology, Oxford University, San Deigo State University, University of California Los Angeles, University of Southern California, University of Utah, University of Wyoming, and University of Wisconsin. Their experiments collected some very large sets of data, which have now been processed and results have started to come out in a variety of ways. Over 50 scientific papers and posters have been presented at conferences and nearly 30 papers have been published more formally in scientific journals. The improved knowledge of how the South Island deforms will be used in local hazard models and mitigation, and internationally by scientists seeking to understand how the earth works. Seismic anisotropy and p-wave delay studies, for example, imply widespread deformation in the mantle beneath the Southern Alps, rather than slip on a narrow fault zone. They imply that rocks from the lower crust and mantle deform more or less uniformly by relatively viscous thickening, rather than under-thrusting of one slab of mantle lithosphere beneath another (Molnar *et al.* 1999).

A detailed seismic reflection survey was carried out during 1998 (called SIGHT98) in the Lake Pukaki region complementing earlier, cross-South Island, seismic transects done in 1995 and 1996 (Davey *et al.* 1995, 1998; Smith *et al.* 1995; Kleffman *et al.* 1998). The principal objective of SIGHT98 was to image the Moho and crustal root. Survey parameters were chosen to obtain the best possible information on features expected to occur at depths around 40 km and greater. The first 5 s (two-way time (TWT)) of SIGHT 98 data were processed separately to image features in the upper 12-15 km of the crust (Long *et al.* 2003). No major, continuous regional-scale features >10 km long were evident in the data, but there were numerous 2-3 km scale reflections and discontinuities, which are consistent with the known geology of monotonous greywacke

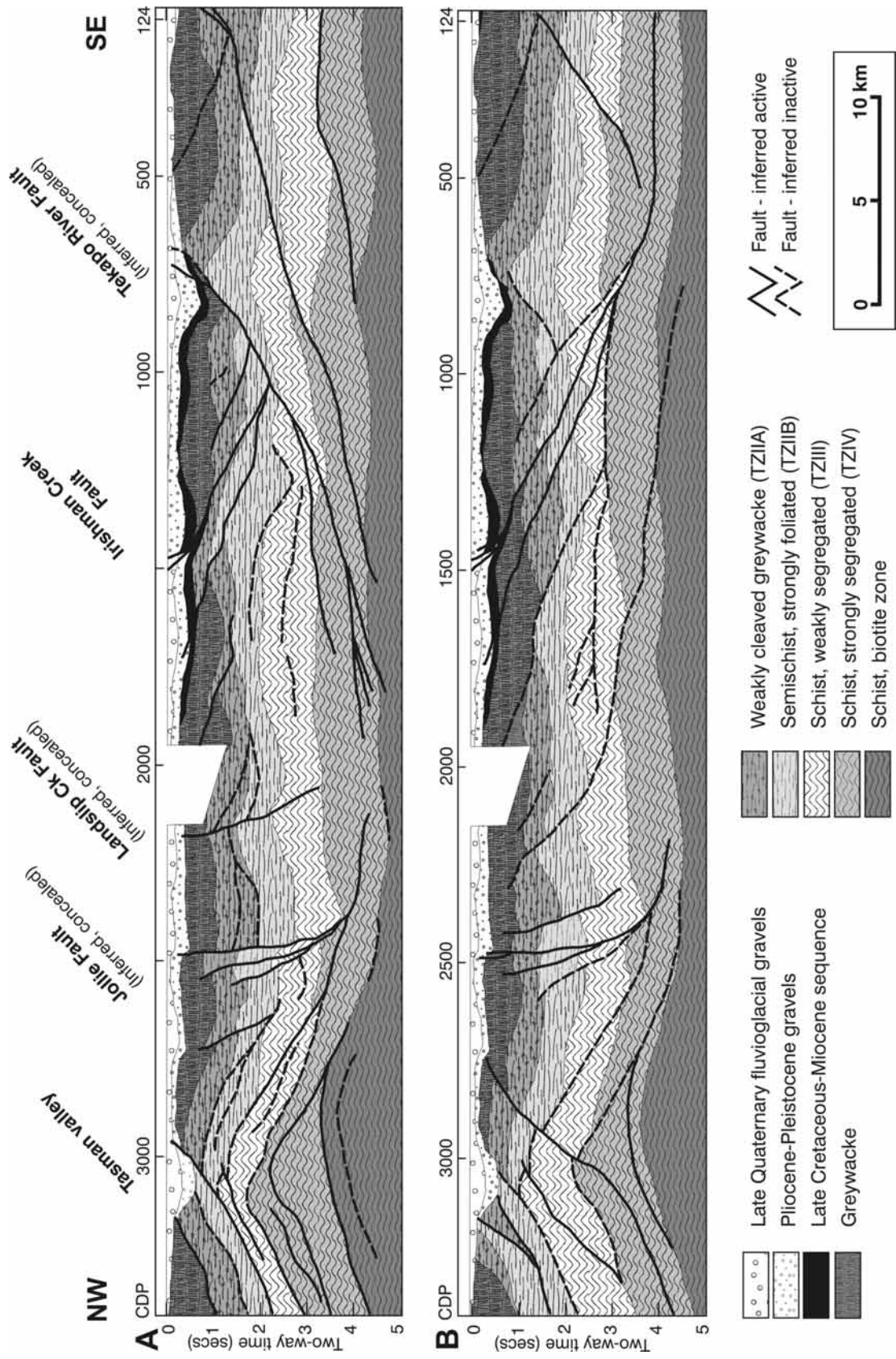
sequences overlying schist. Strong, well-defined reflections indicate that the active Irishman Creek Fault is a southeasterly dipping reverse fault with c. 1300-1700 m of Tertiary-Quaternary sediments preserved in the footwall and an uplifted greywacke basement “high” in the hanging wall. Some evidence exists for active faults beneath latest Quaternary gravels at the Jollie valley and Tekapo River. Oppositely dipping reflections and discontinuities define a large, c. 15 km wavelength antiform within bedrock beneath Tasman valley/ Mount Cook that is imaged to  $10 \pm 2$  km depths (3.5 s TWT).

Long *et al.* (2003) presented two “end-member” interpretations that were consistent with the seismic data observations, velocity models, and constraining features of exposed geology, and extend existing geological cross-sections to 10-15 km depth (Fig. 12). One interpretation assumes imaged structures are primarily backthrusts developed in response to distributed Cenozoic deformation southeast of the Alpine Fault plate boundary, incorporating features observed in contemporary geodetic strain and numerical plate boundary models. The second interpretation assumes structures are mostly Mesozoic, either reactivated or preserved by late Cenozoic deformation. The main difference between the interpretative cross-sections is the degree to which active structures link into basal detachment and high-strain zones at depth.

### *Numerical Modelling*

A number of 2D and 3D models have recently been published that claim to approximate continental collision across the Southern Alps. Some consist of finite-element solutions using complex but realistic rheologies (Beaumont *et al.* 1996; Braun & Beaumont 1995; Batt & Braun 1997, 1999; Koons *et al.* 1998), while others use analytical and numerical applications of critical-wedge theory (Koons 1990, 1994; Enlow & Koons 1998), and others are experimental sand-box analogues (Koons & Henderson 1995). The models are able to reproduce the mean topographic shape of the Southern Alps and provide a context for the interpretation of many of the observed structural features using relatively simplistic boundary conditions. Importantly, modelling suggests that a close relationship exists between tectonics and first-order topography (>15 km wavelength), and that local structure and strain may be related to, and can be predicted by, the mechanics of deformation (Koons 1994, 1995).

Models extended into three dimensions predict that lateral and convergent components of shear strain should vary differently as a function of distance from the Alpine Fault (Koons 1994; Braun & Beaumont 1995; Koons & Henderson 1995; Enlow & Koons 1998; Koons *et al.* 1998). Such partitioning is now suggested to have occurred during



**Fig. 12 (previous page):** Long *et al.* (2003) interpreted the upper crustal structure of the Mackenzie Basin area based on seismic reflection observations, velocity modelling, and geological constraints. The various shades of schist and greywacke represent the varying degrees of metamorphism. The thick black lines represent inferred active faults; the dashed black lines represent inferred inactive faults. **A:** Structure derived solely by Cenozoic processes. The faults to the southeast are interpreted to be back thrust off a deeper detachment fault. The anticlinal feature on the northwestern end is inferred to be a regional scale fold in which the northwestern limb is comprised of active westerly dipping faults. **B:** Structures from the Mesozoic are preserved and reactivated during Cenozoic deformation. The explanation for the antiform is the same as described above, but the Mesozoic structures on the southeastern limb have been tilted by folding.

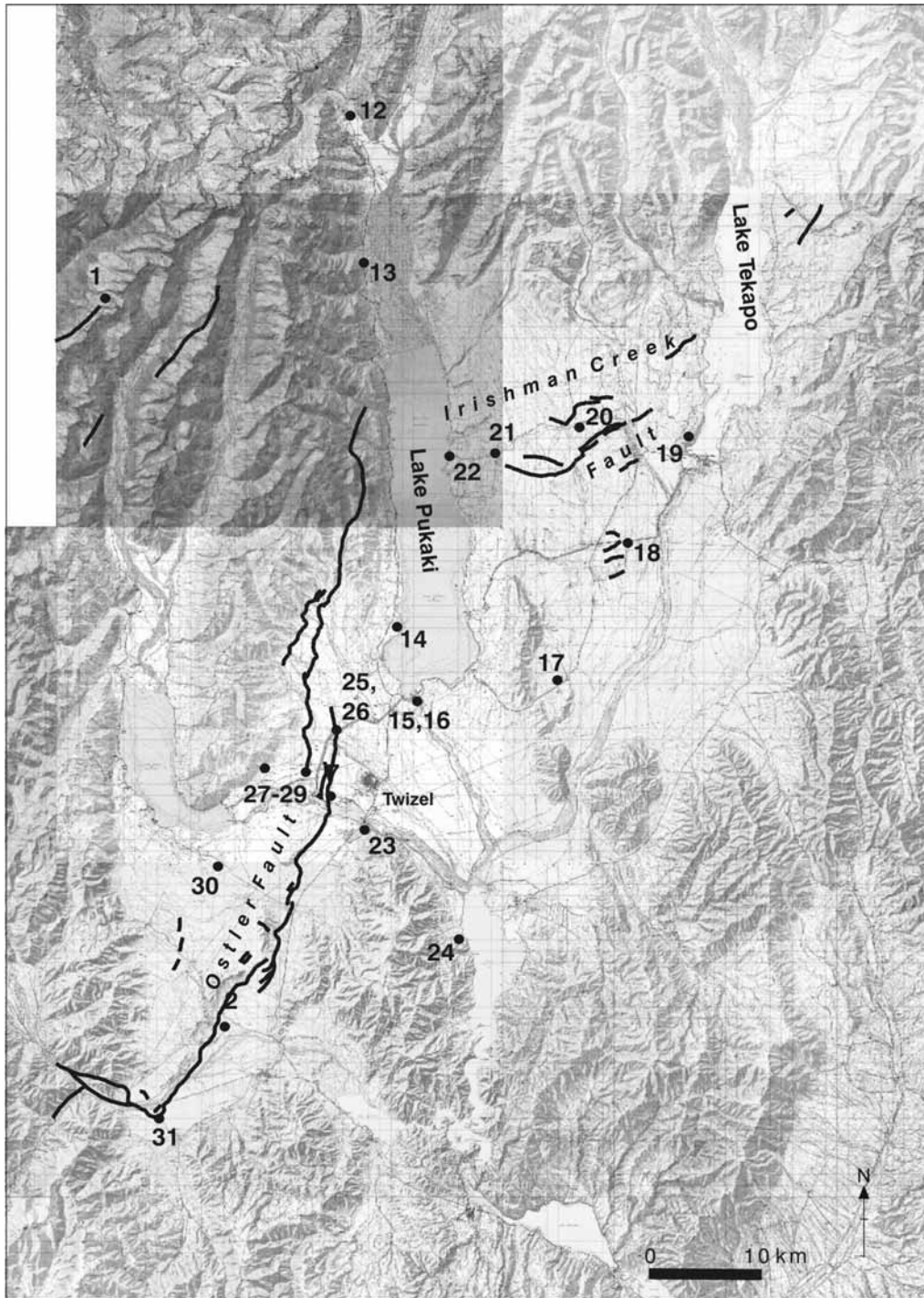
both observed late Quaternary strain and contemporary measured deformation (Norris & Cooper 2001; Beavan & Haines 2001). The modelling predicts different regions of characteristic deformation and corresponding tectonic style will occur within the collisional orogen (Koons 1990, 1994). These models have been used to place structural, thermochronological, geochemical, and geophysical observations into a contemporary dynamic context (e.g., Templeton *et al.* 1998; Koons *et al.* 1998; Batt & Braun 1999; Upton *et al.* 2000; Wannamaker *et al.* 2002). Critical wedge models of Koons (1990, 1994), for example, predict inboard (near Alpine Fault) and outboard (east of Main Divide) structural zones.

### **Stop 12: Mount Cook (H36: 762170)**

The Alpine Memorial on the Mueller Moraines provides a wonderful view of Mt Sefton, the Hooker Valley and Mt Cook (on a good day) (Fig 13). The Main Divide Fault Zone (Cox & Findlay 1995) is visible in the west wall of the Hooker Valley. We will use this location to introduce the basement rocks and structure of the Southern Alps. If the weather is fine it may be possible to see orange-staining of rocks in the fault zones on the Mueller Range, southwest of the lookout, and above Hooker Valley. This is siderite-limonite associated with fluid flow along the fault zones. We will also discuss the Southern Alps fluid hydrothermal system.

The Hooker and Mueller glaciers, like other glaciers in Mt Cook National Park, have been in rapid retreat since about 1980, although downwasting (reduction in height) of the glaciers had begun by early 20<sup>th</sup> Century following the c. 1890 peak of the last of the glacial advances of the “Little Ice Age” (Hochstein *et al.* 1995). Substantial Holocene moraine complexes rim the glacier terminal areas. The glacial withdrawal has partially exposed the stratigraphy in the inner margins of the lateral moraines, and in a few locations the glacial deposits within the moraines comprise successive layers of till,





**Fig 13:** Location map – Mackenzie Basin

with radiocarbon-datable wood and buried soils locally preserved on the inter-layer contacts (e.g. Gellatly *et al.* 1988; Burrows 1989). The stratigraphy and dating indicate that the moraine complexes were constructed by vertical accretion during a succession of glacial advances since approximately 5 ka, the so-called Neoglaciation (Porter 2000). Just outboard of the main Holocene moraine complex of the Mueller glacier, Foliage Hill (H36: 758167) has well-developed soils and weathering rinds on greywacke clasts, suggesting that the hill is the remnant of moraine formed in a glacial advance that ended at c. 7.2 ka (Birkeland 1982, Gellatly 1984), although Porter (2000) cautions that this age estimate is very ill-constrained.

Note the character and form of the Mueller glacier lake forming within the surrounding lateral and terminal moraines. At the next stop at Lake Pukaki, imagine the same scene scaled up many times, and moved back in time to 14 – 16 ka. The present-day rapid ice retreat and formation of lakes at the Mt Cook National Park glacier termini is an excellent small-scale analogue for the glacial withdrawal at the termination of the Late Otiran (MIS 2) glaciation.

The other feature to note is the concentric area of raised ground upon which Mt Cook Village and the Hermitage are constructed. It has been suggested that it is a moraine remnant, but it is more likely, given its position and form, to be the debris pile of a sizeable rock avalanche event, derived from the mountain-slope behind.

### **Stop 13: Freds Stream – SH80 (H37: 775060)**

The road runs through extensive hummocky ablation moraine of the Birch Hill glacial advance. A well-defined lateral moraine ridge marking the maximum height of the Birch Hill glacial ice can be seen on the opposite side of the Tasman valley about 150 m above the valley floor. The Birch Hill advance is attributed to a Late-Glacial interval of cool climate.

### **Stop 14: Lake Pukaki lookout – Peters Point – SH80 (H38: 800730)**

Lake Pukaki was formed during the rapid deglaciation at the end of the Last Glacial Maximum (Late Otiran) cold-climate phase. Note the similarity of shape and form with Mueller and Hooker glacier lakes currently forming under the modern rapid glacial retreat. The lookout is a good place to observe the location of a series of large-scale geophysical experiments that were carried out across the South Island of New Zealand from 1995-1998. The projects were multi-disciplinary, multi-national studies of the South Island, carried out with the purpose of obtaining a better understanding of continent-continent collisional processes across the Australian-Pacific plate boundary. We will discuss the experiments and their findings at the lookout, together with some aspects of numerical modelling and the regional tectonics of the Southern Alps.

**Stop 15: Lake Pukaki outlet – SH8 (H38: 819645)**

A track leading south from SH8 at H38:815646 down to the Pukaki River channel below the Pukaki Dam passes through Tekapo-advance moraine ridges, and crosses the outwash surface downstream of the frontal Tekapo moraine ridge. From the river channel, the nature of deposits under these landforms can be seen. Points to note are the thick rounded outwash gravel underneath the outwash plain which extends upstream beneath the till, the chaotic silt-dominated nature of the till, and the 20° lake-ward dipping contact of the till and outwash. The geological events here are: (i) aggradation of ?Mt John/?Tekapo outwash gravel in front of the Pukaki glacier; (ii) sufficient withdrawal of ice to allow silty lacustrine sedimentation in front of the glacier, and; (iii) Tekapo-age glacial re-advance that picked up and chaotically re-deposited the silty lake sediment as till (Hart 1996), out and over the earlier formed outwash deposits.

**Stop 16: Pukaki River (H38: 832629)**

Returning to SH8, and then down the track on the east margin of Pukaki River, brown weathered till is exposed in the riverbed at H38:832629. The brown weathered colour suggests that it is considerably older than the LGM Mt John and Tekapo glacial events; whether this till correlates with Balmoral or Wolds advances, or with some other unrecognised glacial event, is unknown.

Adjacent to the track, exposures show rounded, grey Mt John outwash gravel (MIS 2) extending close to the ground surface, capped by a few metres of chaotic till. The main landform in this area is Mt John moraine. The exposure illustrates that here, as in many other locations in the Mackenzie Basin, the extensive terminal moraine landforms are developed on a thin deposit of till that overlies thick, previously accumulated, outwash aggradation gravels. The relationships suggest that much of the up-building of the aggradation deposits occurred during the glacial advance, with the terminal moraines formed as a late-stage event when the glacier rode out over its outwash plain.

Note the colour and hardness of these Mt John gravel clasts, and the nature of the matrix, in order to compare these gravels with those that will be examined at Stop 17.

**Stop 17: Balmoral outwash gravels, Maryburn – SH8 (I38: 951660)**

A gravel pit on the north side of SH8 is excavated into outwash gravels of the Balmoral glacial advance of Lake Pukaki that formed a lobe into the eastern side of the Mary Range. Note the degree of weathering: the greywacke clasts are mostly slightly weathered; some discolouration throughout and are broken with moderate ease with a hammer. The matrix has a generally brownish colour. It is generally considered that the Balmoral deposits are older than the LGM: there is debate as to whether they relate

to (a) the Early Otiran glacial advances (MIS 4 – c. 65,000 years ago) or (b) the Waimean glacial advance (MIS 6 – c. 150,000 years ago). Is the degree of weathering commensurate with these gravels being (a) 3 times older than the Mt John gravels, or (b) 6 times older than Mt John gravels? Consider what factors might make it difficult to decide which answer, if either, is more likely.

Time permitting, the trip will travel north along SH8 to Tekapo canal, then west along the southern canal road to the penstocks down to Tekapo B Power Station, then back along the north side of the canal back to SH8. The main points to note are views south of the landforms of the Maryburn lobe of Pukaki Glacier (Balmoral outermost, Mt John innermost), the till-mantled greywacke knob of Mt McDonald north of the canal and, an engineering feature, the large fill embankment on which the canal crosses Mary Burn.

*After crossing SH8, the trip continues down the south side of Tekapo canal.*

**Stop 18: Tekapo canal – Wolds/Balmoral riser (I38: 013788)**

View the landforms – the Wolds moraine on which we are stopped versus the Balmoral outwash terrace below to the east

**Stop 19: Mt John (I37: 065883)**

This ice-eroded greywacke knob is the site of the University of Canterbury astronomical observatory, and affords excellent views of the glacial geomorphology in the vicinity of Lake Tekapo. Figure 14 points out some of the landforms to look for near Lake Alexandrina, including lateral moraines marking the maximum height of Late Otiran glacial ice, and deglacial ablation moraines, fan deltas and lake beaches in the general area of the lake. Southwest of the lake (left of Fig. 14 view), terminal moraines and outwash plains extend out into the Mackenzie Basin from the terminal moraines. Also note the terminal moraines on which Tekapo township is built.



**Fig. 14:** View NW from Mt John across Lake Alexandrina showing glacial, deglacial and post-glacial landforms.

*From here the field trip returns to SH8, turns right and then takes the next right onto Braemar Road, travelling up Fork Stream, before crossing the Irishman Creek Fault scarp, and then continuing along the downthrown side of the fault towards Lake Pukaki.*

#### **Stop 20: Irishman Creek (I37: 958888)**

From the bridge across Irishman Creek, there is a good view to the SE of the c. 200 m high fault-line scarp of the Irishman Creek Fault, with the crest of the scarp forming the Old Man Range. Note the antecedent gorge of Irishman Creek cut through the scarp. A prominent terrace in the gorge about 40 m above creek level can be traced downvalley to merge with Balmoral 2 outwash surfaces. The height of this terrace is probably indicates vertical throw on the fault. If the Balmoral 2 advance is MIS 4 (c. 65 ka), it implies a vertical fault slip rate of the order of 0.5 mm/year. This is compatible with a c. 5 - 7 m high scarp across a Mt John outwash surface 7 km farther northeast along the fault between Fork Stream and Lake Alexandrina. Note two large landslides on the fault-line scarp east (left) of the Irishman Creek gorge. Steeply SE-dipping Glentanner Beds are exposed adjacent to the fault in Irishman Creek and probably form the substrate within the fault-line scarp.

*From here, the field trip continues toward Lake Pukaki, crossing the lateral moraine complexes of the Pukaki Glacier, beginning with the Wolds moraines.*

**Stop 21: Pukaki lateral moraines (I37: 940892)**

This stop is on the highest part of the Wolds-age lateral moraine. Note the subdued, generally boulder-free landforms. The trip continues along Braemar Road, making a brief stop on the Balmoral lateral moraine at (I37: 920886) – would anyone like to pick a boundary between older (Balmoral 1) and younger (Balmoral 2) moraines? The trip then crosses a marginal outwash plain from the Mt John lateral moraine, before we stop briefly on the Mt John moraine crest at I37: 908870, and the Tekapo lateral moraine crest at H37: 895865. The field trip then descends down the deglacial moraines and meltwater terraces formed during the rapid glacier meltout and retreat at the end of the Late Otiran glaciation, about 16,000 calendar years ago (equivalent to about 14,000 conventional radiocarbon years BP).

**Stop 22: Lake Pukaki shoreline (H37: 852866)**

The shorelines and cliffines of Lake Pukaki are very young. The highest shoreline is 55 m above the original lake level. The original lake was raised about 15 m in 1951 to provide storage for hydro-electric power generation dams downstream in the Waitaki valley, and was raised by a further 40 m in 1979 (Read 1976, Irwin and Pickrill 1983). Most of the shoreline development visible represents about 25 years of shoreline processes under a widely fluctuating water level.

**Stop 23: Ruataniwha spillway (H38: 775538)**

The trip will stop in the carpark at the top, SW, side of the Ruataniwha dam/spillway, which was constructed at a location where the former Ohau River cut through a greywacke knob at the northern end of the Benmore Range. Torlesse greywacke is exposed in the southern margin of the carpark. Try and determine the way-up of bedding, and identify faults.

**Stop 24: Lake Benmore shoreline – Camp Creek (H38: 867432)**

In the shoreline cliff of Lake Benmore, the outwash gravels of the Mackenzie Basin approach lake level and are overlain by loess and alluvial fan sediments. The outwash is tentatively correlated with Mt John moraines at Lake Ohau. The loess has been dated by both thermoluminescence (TL) and optically stimulated luminescence (OSL) and both methods indicate an age of about 14 ka. This represents a minimum age for the underlying outwash gravel, and a maximum for the main post-glacial incision of the Ohau River at this location. This latter inference is based on the assumption that the alluvial fan deposits would not have formed at this location unless the side stream was gently graded to the main river. Presently, with the river (and now) lake deeply incised below the outwash surface, the side stream has cut a deeply incised slot down to the (former) river channel, and fan formation is no longer possible at this site.

## **DAY 3: GEOLOGY & TECTONICS OF SOUTHERN MACKENZIE BASIN**

### **Stop 25: Ostler Fault – Pukaki Canal (H38: 750615)**

The Ostler Fault passes under the Pukaki canal at this location (Fig. 14). The landscape on the south side of the canal was much modified during canal construction, by quarrying of steeply dipping Pliocene-Pleistocene Glentanner Beds (Kowai Formation) as a source of canal lining material. Prior to quarrying a low hill was present, known as Ram Paddock Hill (see Mildenhall 2001). The NNW-trending Ostler Fault scarp is easily seen on the north side of the canal. The throw on this strand (Ruataniwha Trace) of the Ostler Fault diminishes rapidly to the north and the scarp dies out 3 km NNW of the canal. Movement is taken up on two fault strands near the foot of the Ben Ohau Range to the NW; conditions permitting, these fault scarps can be seen running across alluvial fans 8 -10 km north of this stop.

### **Stop 26: Glentanner Beds – Fraser Stream (H38: 746606)**

At this location, Fraser Stream has eroded a cliff into a low hill on the upthrown side of the Ostler Fault, exposing moderately NW-dipping Glentanner Beds, with a NW-tilted cap of outwash gravel forming the surface of the hill. A good view is afforded from the road at H38:746610, adjacent to Loch Cameron, which is an artificial lake occupying the floor of the former canal-lining material quarry. Pollen samples were collected and examined from the Fraser Stream exposure, as well as from temporary exposures formed during canal construction in the former quarry, and in the canal foundation substrate (Mildenhall 2001).

Towards the base and left of the Fraser Stream exposure, silt and gravel dipping 36° NW contains late Pliocene (Waipipian – Hautawan) palynoflora that is indicative of cool temperate climate. This sequence is truncated by an angular unconformity, above which lie 26° NW-dipping gravels and silt, containing Mid-Quaternary palynomorphs indicative of cold climate (Mildenhall 2001). These are capped by a layer of outwash gravel that forms the surface of the hill, and is thought to be a backtilted Balmoral outwash surface.

*The trip crosses the Pukaki Canal and proceeds 3 km south to Glen Lyon Road.*

### **Stop 27: Haybarn scarp of the Ostler Fault – Glen Lyon Road (H38: 726581)**

This site is the start of one of the northern strands (Haybarn Trace) of the Ostler Fault that lies near the foot of the Ben Ohau Range (see Stop 25 notes). The c. 3 m high fault scarp displaces the oldest Mt John 1 outwash terrace beside the road, but does not appear to displace the lower, somewhat younger Mt John 2 outwash terrace. This indicates that the last movement on this southernmost part of the Haybarn Trace occurred during the earlier part of the Late Otiran glaciation, and contrasts the 10 – 20

m high fault scarp across similar-age surfaces 10 km farther north. Approximately 2 km west along Glen Lyon Road at H38:707577, a broad, 30 m-wide and c. 2m-high NE-SW trending rise, up to the NW, obliquely crosses both outwash terraces; this appears to be a tectonic flexure.

**Stop 28: Mt John moraines – Ohau Glacier - Glen Lyon Road (H38: 865574)**

In this area, 3 separate moraine ridges are recognisable within the Mt John moraine complex. An outermost, oldest ridge (Mt John 1) is preserved only west of the road, and the outwash surface emanating from this moraine is slightly higher than the Mt John 2 outwash surface on which the road sits. This outwash surface emanates from the more extensive moraine west and south of this location. As the trip proceeds across this moraine, a bench of hummocky ground halfway down the western side of this main moraine represents the Mt John 3 moraine ridge (H38:681571).

*The trip continues along Glen Lyon Road, onto the extensive Tekapo outwash surface and proceeds up to the Ohau Canal intake within the Tekapo moraine ridge enclosing Lake Ohau, then returns toward Twizel down the south side of the canal. The canal passes along the Tekapo outwash surface and then passes through a cutting up onto the Mt John 2 outwash surface.*

**Stop 29: Ostler Fault – Lake Ruataniwha, Max Smith Drive (H38: 750615)**

The road descends from the Pukaki Canal penstocks onto the Tekapo outwash surface 1 km west of the Ostler Fault scarp. The vehicles will pause briefly in a small v-shaped graben, known as the “Y” Fault. On approaching the main fault scarp, note the backtilt on the outwash surface. We will stop on the downthrown side to examine the c. 20 m high scarp on the Tekapo outwash surface. The scarp is approximately the same height on the Mt John 2 outwash surface forming the local skyline (Mansergh and Read 1973), indicating that there was no rupture of this part of the fault during the period between formation of the Mt John 2 outwash and Tekapo outwash.

Across the fault zone in this location, aseismic deformation has been documented by levelling profiles, indicating upward buckling or of the ground surface across the fault during the period 1966-1989 (Blick *et al.* 1989) (Fig. 15). This short-term rate of deformation is similar to the long-term average c. 1 mm/year slip rate indicated by height of Ostler fault scarps across Late Otiran outwash surfaces in this area (Blick *et al.* 1989, Van Dissen *et al.* 1993).

*The trip continues to SH8, along which the trip proceeds SW. Note the c. 150 m high Ostler fault-line scarp 2 km NW of the road, with some landslides on the scarp face. The flat surface at the scarp crest is Table Hill, and is probably a Balmoral 1, or possibly Wolds, outwash surface. Farther SW, the fault forms a 20 - 30 m high scarp*



*crossing a broad Mt John outwash channel extending from the Ohau Glacier. The trip proceeds west along Ohau Road, crossing this scarp. Note the presence of multiple small scarps in front of the main fault.*

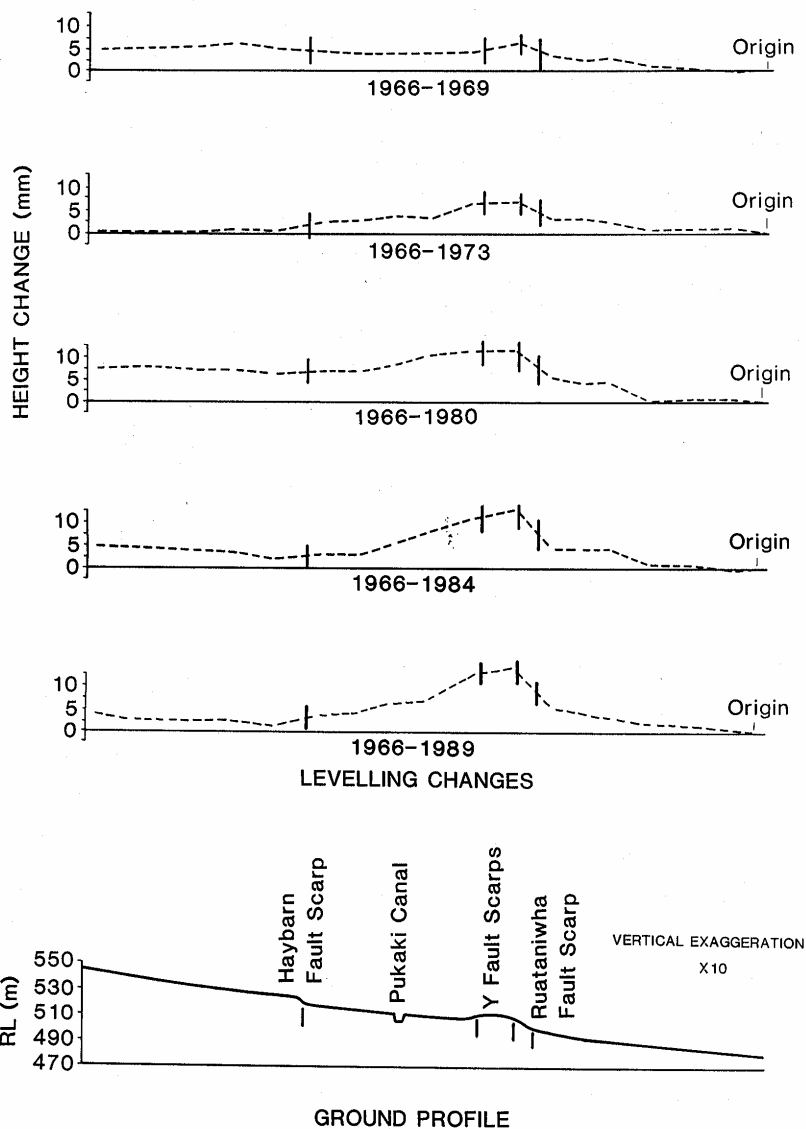
**Stop 30: Ohau moraine complex – landforms, deposits and soils (H38: 630507)**

The gravel pit exposes the deposits within the Mt John 2 moraine complex. The landscape comprises broad rises and depressions, and looks morainic, but the deposits in this exposure are rounded outwash gravel, with no indications of till. We will consider the possibility that this is an ice-overridden and scoured outwash plain, and the irregular topography is a drumlin landscape, rather than moraine in the strict sense. Note the degree of soil development, and thin loess, on the deposits.

Returning east on Ohau Road, note that the hummocky topography becomes sharper, and large rocks become abundant on the ground surface. At H39:658492, there is a well-defined moraine ridge, with sharp hummocky topography, east of which there is very subdued slightly hummocky topography. Some workers have interpreted the sharp moraine front as the limit of the Mt John advance, and assigned the very subdued hummocky topography lying east of the ridge to the Balmoral glacial event. At H39:666482, within the very subdued hummocky topography, we will examine a shallow gravel-pit exposure, and compare the weathering and soil profile on these deposits with that seen in the previous pit 5 km to the west. We will then consider whether a better interpretation is that the subdued hummocky topography is Mt John 1 moraine, and the sharp moraine ridge represents the Mt John 2 glacial advance.

*As the trip returns to SH8, note the backtilt of the Mt John outwash surface within 1.5 km of the fault scarp, and in the same area, “islands” of slightly higher outwash surfaces that were elevated by fault rupture events during the Late Otiran glaciation.*

*As the trip proceeds down SH8 towards Omarama, along the Mt John outwash surface, note the Ostler fault-line scarp to the west (right).*



**Fig. 15:** Levelling changes across the Ostler Fault at Glen Lyon Road, 1966 – 1989 (from Blick *et al.* 1989, Van Dissen *et al.* 1993)

**Stop 31: Ostler Fault scarp – “the Knot”, SH8 (H38: 630507)**

At this remarkable site, the NE-SW trending Ostler Fault does a right angle bend and heads off to the NW. It is one of the few locations where the transfer of slip onto a transverse structure is shown unequivocally by Late Quaternary fault scarps, and is an important caution for anyone trying to assess continuity of and relationships between older, inactive faults. Having diverted from SH8 at Omarama onto Berwen Road, we will cross the NE-SW trending scarp at H39:593272, the point at which it begins to swing NW, and stop at the NW-trending scarp where it crosses SH8 at H39:577277.

We return to Omarama via SH8, crossing the NE-SW trending scarp at H39:600285, where the fault begins crossing a flight of terraces descending to the Ahuriri River. Differing scarp heights on the different terraces demonstrates multiple fault ruptures within the Late Otiran and Holocene. From here, also note the badlands erosion within Glentanner Beds on the upthrown side of the fault at Claycliffs.

### **Return to Dunedin**

The trip returns to Dunedin via the Waitaki valley, stopping for lunch in Kurow, and then diverting southwest at Duntroon to travel over Danseys Pass into the Maniototo Basin and continuing along SH87 to Middlemarch in the Strath Taieri Basin, descending on to the Lower Taieri Plain and Dunedin airport. The trip finishes at St Margarets College, Dunedin at approximately 4 pm on Sunday.

The inland Otago “range and basin” region is quite different from the area in which we have been for the past few days. It has relatively gentle topography, whose dominant geomorphic feature consists of a peneplain surface, formed on the basement rock, that is warped or broken into a series of 15 to 20 km-wavelength parallel ridges and valleys by folds and reverse faults trending NE-SW. Basement rocks are schists with a relatively flat-lying foliation, exposed in the ridges/ranges, while top of the basement rock, and the peneplain, is commonly obscured by Tertiary and Quaternary sediments in the basins. The range-forming structures are active but collectively probably accommodate only a few mm/y. Jackson *et al.* (1996) used drainage patterns to demonstrate various processes in fold (and fault) growth and interaction, including how apparently continuous ridges were formed by the coalescing of quite separate propagating fold (and fault) segments. Where the basement rock is well-foliated schist, large-scale landsliding is typical along the range fronts.

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