GEOSCIENCES 09

Annual Conference
Oamaru, NZ

FIELD TRIP 2

FAULTS, FRACTURES AND FLUID FLOW IN BASEMENT ASSEMBLAGES

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Leaders: Virginia Toy, Rick Sibson, Nick Mortimer

Geology Dept, University of Otago and GNS Science

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Introduction

The purpose of this trip is to examine primary sedimentary structures plus brittle and ductile deformation, together with evidence of faulting and fluid flow in the variably metamorphosed Torlesse Terrane Mesozoic accretionary wedge. We will drive up the Waitaki River from Oamaru and mainly look at rocks in two places, Benmore Dam and Maraewhenua River. In the morning at Benmore Dam we will examine folded sandstones and mudstones with excellent primary sedimentary structures, brittle faults, fault-fracture meshes, and fractures with zeolite and quartz - prehnite - epidote - pumpellyite vein assemblages. In the afternoon at Maraewhenua River we will visit spectacular exposures of polyphase deformed and quartz veined low-grade Haast Schist developed from protoliths similar to those seen in the morning.

Overview and Geological Background

Torlesse Terrane and the Otago Schist

The Eastern Province basement of New Zealand's South Island is composed of metasedimentary units accreted to the Gondwana margin from the Permian to early Cretaceous. In the Waitaki valley, inland from Oamaru (Fig. 1), the basement is the sandstone-dominated, mainly marine turbiditic, Permian-Triassic Torlesse Terrane of prehnite-pumpellyite metamorphic facies (Forsyth, 2001). To the south, metamorphic grade increases to pumpellyite-actinolite facies and the sedimentary rocks become foliated. In New Zealand, the progressive development of foliation and segregation is mapped in five textural zones (Turnbull et al., 2001). TZIIA and higher rocks are mapped as Otago Schist (of Jurassic-Early Cretaceous age). In the Waitaki valley, bedding and foliation are generally steep and the transition from "greywacke" to schist occurs across a number of NW-SE striking fault blocks, inliers and outliers (Fig. 2). Probably, these are structures inherited from the Mesozoic accretionary wedge in which the Torlesse Terrane was deformed and metamorphosed.

Waitaki Valley and the Waitaki Fault system

The Waitaki River originates in the MacKenzie Basin, and flows SE along the Waitaki Valley towards the Pacific Ocean just north of Oamaru. The valley is the geomorphic expression of the Waitaki Fault system, which comprises a series of strands, some active, and displays NE-side down net slip. Arguably, the total throw across the Waitaki Fault system is small (perhaps <1 km).

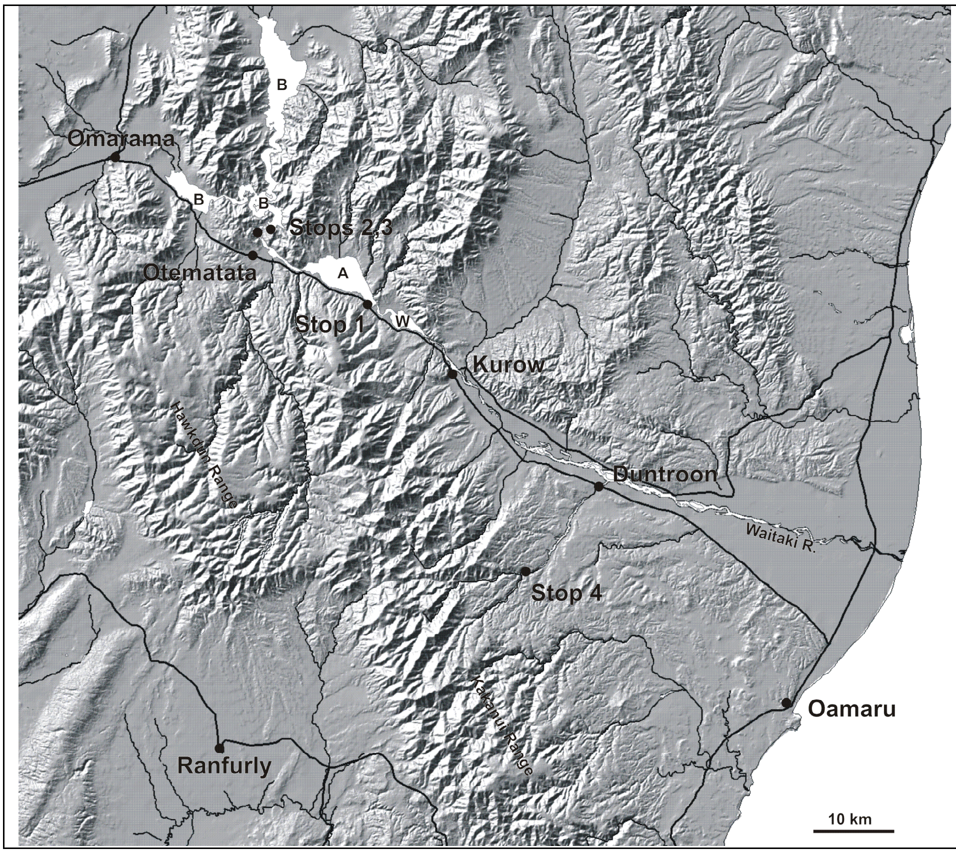


Figure 1.
Digital terrain model of the fieldtrip area showing stops 1-4.

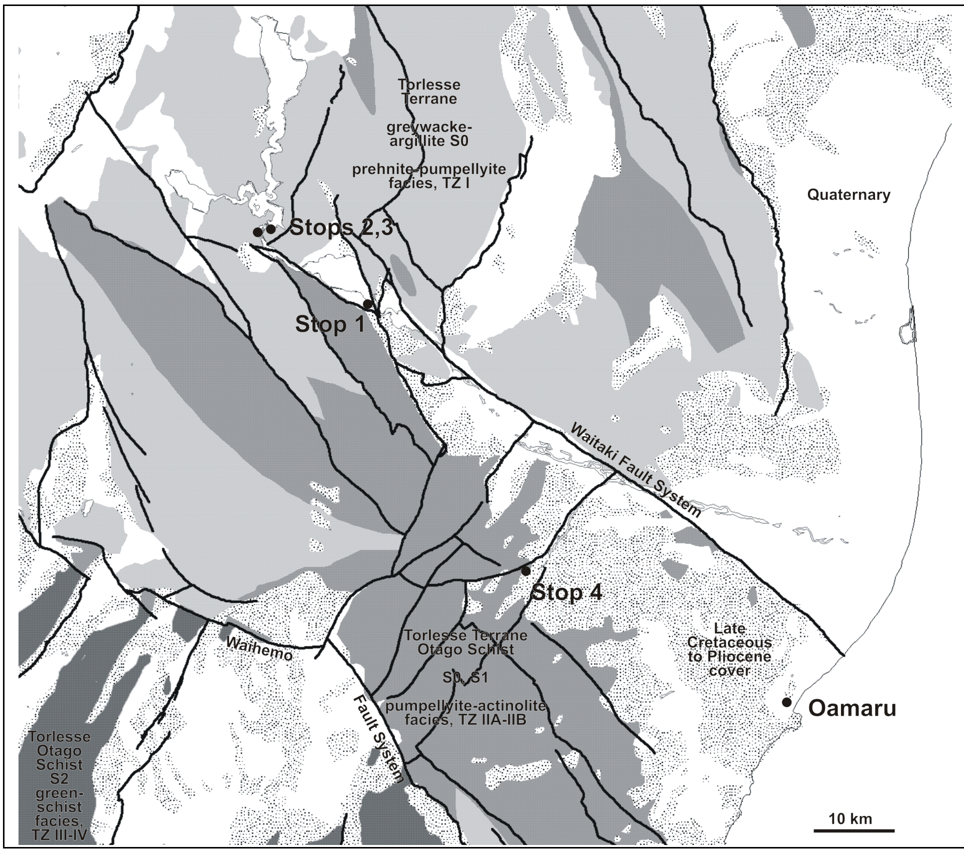


Figure 2.

Simplified geology of the fieldtrip area after Forsyth (2001).

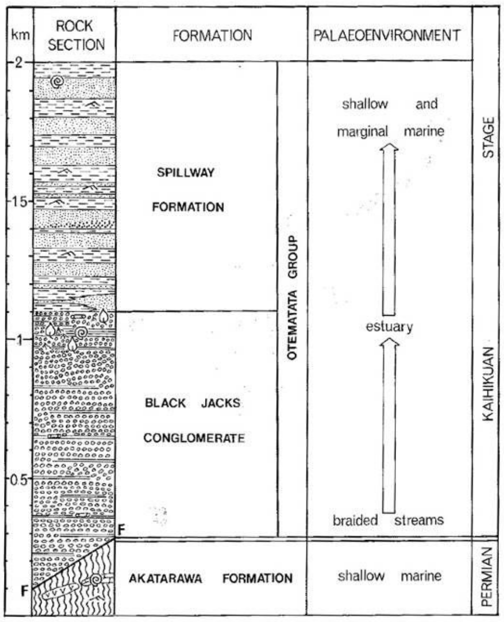
Non-schistose and schistose Torlesse basement shown in grey shades.; Late Cretaceous to Pliocene cover in dot pattern and Quaternary sediments white.

Itinerary
9:00 am
Depart from outside the Oamaru Opera House
Short toilet stop at Kurow

10:30 am
Stop 1: Aviemore Dam Lookout. E 2299608 N 56613376.

A 15 minute stop for an overview of the neotectonic and geomorphic expression of the Waitaki fault system, and the famous Waipounamu Erosion Surface (Forsyth, 2001; Landis et al., 2008). Low terraces to the SW are capped by Pliocene to Quaternary terrace gravels, over Early Miocene greensand. These units are juxtaposed against TZ IIB Otago Schist at the modern break in slope on an active strand of the Waitaki Fault system. The Kirkliston Range and Campbell Hills on the NE side of the Waitaki Valley, which rise much more steeply from the lake, have been uplifted in the Neogene along the main strand of the Waitaki Fault. However, the comparatively low metamorphic grade in the hills to the NE compared with the ranges to the SW suggests that the NE side was formerly downthrown, consistent with a history of tectonic inversion. The possibility of significant strike-slip displacement along the Waitaki Fault system may also need to be considered.

11:00 am
Stop 2a: Loch Laird Recreation Reserve, immediately downstream of the Benmore Dam, facing N into the dam spillway. E 2286796 N 5622630.
1.5 hours



Stratigraphy and relationships of formations of Otematata Group and adjacent Akatarawa Formation Lithological key as for Fig 1, other symbols after Fig 7

Figure 3: Stratigraphy of the Torlesse sandstones in the vicinity of Benmore Dam. From Retallack, 1983.

Exposures on the river banks provide excellent horizontal sections through subvertically dipping Torlesse sandstone and mudstone (at stop 3 the sections are vertical). Locally, the Torlesse Terrane has been mapped as Otematata Group with the Black Jacks Conglomerate (not seen on this trip) overlain by Spillway Formation which is what we are standing on (Fig. 3, Retallack, 1983). Sedimentary layers are cm to dm-thick, interbedded sandstone and mudstone with

excellent primary sedimentary structures, such as ripple marks and grading. Retallack (1983) interpreted a marginal marine depositional environment for Spillway Formation. This is unusual as most of the Torlesse Terrane comprises deep marine turbidites. On average, bedding strikes NE-SW and dips steeply to the NW. Facing/younging can be determined from graded bedding and truncated cm-scale cross-bedding and, in this small homoclinal section, faces/youngs east.
Microscopically the sandstones are poorly sorted subangular lithic feldsarenites with 10-20% clay matrix - classic greywackes (Fig. 4). The mudstones occasionally show a fissility but no throughgoing foliation or cleavage is evident. U-Pb dating of detrital zircons from samples near Kurow and Lake Aviemore show a cluster of (source area) ages between 250 and 270 Ma (Ireland 1992; Wandres et al., 2004).

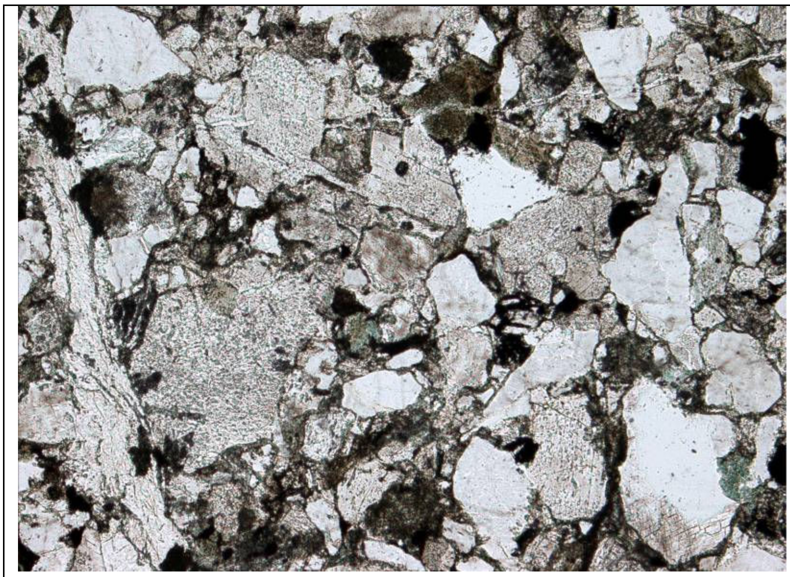


Figure 4
Thin section image of Spillway Formation sandstone P29217 from near the Benmore Dam. Quartz (white), feldspar and lithics (greys), plant fragments (black). Laumontite vein on left of image.
Plane polarised light, image width 2 mm

Peak metamorphic temperatures of Torlesse metamorphism are crudely bracketed by the Frey et al. (1991) temperature limits for prehnite-pumpellyite facies of 175-280°C. Eight zircon fission track ages in TZI rocks of the Waitaki valley range from 114-216 Ma (median 164 Ma), and two apatite ages are 108 and 113 Ma (Tippett and Kamp, 1989; Kamp 2001). Most zircon ages were partially reset in an Early Cretaceous partial annealing zone; cooling below 230-280°C was complete by the late Early Cretaceous. The apatite ages indicate that the Waitaki valley Torlesse sandstones cooled below 70-90°C in the early Late Cretaceous. Thus the Benmore Dam sandstones have always been in a brittle crustal regime, in accord with the lack of foliation and strong veining.

In the field, the sandstone beds are disrupted into lozenges by dominantly dextral shear on a series of NNE to N-striking structures that generally only displace individual beds, and sole out into the adjacent mudstones. The lozenge-bounding faults are sharp, implying the sandstones were reasonably well lithified at the time of this deformation. Similarly, the presence of extensional zeolite(?) veins in lozenge tails suggests a brittle response to deformation, in the presence of fluids. Small-scale thrust duplexes and imbricate thrust stacks are locally evident.
In parts of the sequence, faulting of the thick sandstone beds is accompanied by asymmetric folding of thinner interbedded sandstone and mudstone (Fig. 5). In other words, bed thickness influenced deformation style as the stresses required to cause buckling of the thickest beds exceeded the yield strength of this material. The folding was probably accommodated by a

macroscopically ductile mechanism such as solution-accommodated creep and grain or particle boundary sliding. The structures are consistent with formation in the toe of an accretionary prism. The primary bedding and lozenges are displaced on a sequence of later faults striking NW-SE and dipping moderately to gently to the SE and NW.

Figure 5: Folded and thrust faulted sandstone layers in a mudstone matrix. Torlesse Terrane outcropping on the true R bank of the Waitaki River, immediately downstream of the Benmore Dam. Note the different response of thin and thick sandstone beds to shortening. Field book is 20 cm long. Viewed towards the SW.

A prominent SE-dipping structure at this location appears to have the greatest offset since it places different packages of sediment (i.e. mudstone-dominated package to the N against sandstone-dominated package to the S), whereas beds can be matched back across the NW-dipping structure, which accommodated dm-scale displacement. Proceeding SW along the river bank, the beds are cross-cut by apparently conjugate sets of brittle strike-slip faults with associated zeolite mineralisation. Note that if the vertically dipping strata were restored to the horizontal, the structures would represent a conjugate set of normal faults. Did they form early or late in the deformation sequence?

Stop 2b: Loch Laird Recreation Reserve, immediately downstream of the Benmore Dam, facing across the stream
E 2286660 N 5622436
Walk SW (downstream) 300 m from the previous exposures, approximately along strike of bedding. Here the sedimentary sequence is deformed into asymmetric tight to isoclinal folds. These structures, which have steep N-S striking axial planes and mostly near vertical fold hinges probably mirror the form of larger structures in the area as mapped by Retallack. In places within the outcrop, the hinges of folds with similar appearance plunge only moderately to the N. Either the fold hinges are bent around a second fold phase, or the N-plunging hinges belong to a separate phase. Other folds with N-plunging axes are kink or box-style, consistent with them representing a more brittle response to shortening. Steeply plunging folds are widespread over vast tracts of the Mt Cook region (e.g. Lillie and Gunn, 1964) and pose a problem as to whether they formed steep or represent the refolded hingelines of originally subhorizontal fold structures.
12:30pm

Stop 3: SE abutment of the Benmore Dam. E 2287562 N 5622547.
1.5-2 hours, including lunch break. Depart 2:00-2:30pm
In contrast to the subhorizontal rock platforms at stop 2, the main views of the Torlesse here are in subvertical cut faces at the SE abutment of the Benmore Dam. De Ronde et al. (2001) have made a detailed study of the deformation and veining at this locality. The rocks are again a steeply E-dipping but folded sequence of dm to m-bedded Spillway Formation sandstone and mudstone. The bedding is displaced on conjugate sets of shallowly and moderately NE-dipping thrust and reverse faults that apparently formed as conjugate Coulomb shear fractures (Fig. 6). Slickenfibres on fracture surfaces plunge almost directly down-dip, suggesting a sub-horizontal principal shortening direction. On the lower bench this is also the intersection line of the faults and bedding, so it is difficult to make clear interpretations of shear sense from offsets observed in the outcrop face (Fig. 7).

Figure 6: Braided reverse faults decorated by quartz + prehnite + calcite + epidote veins, SE abutment of Benmore Dam. Notice also that veining in the host rock is mostly concentrated in more competent sandstone layers. Viewed towards the SE.

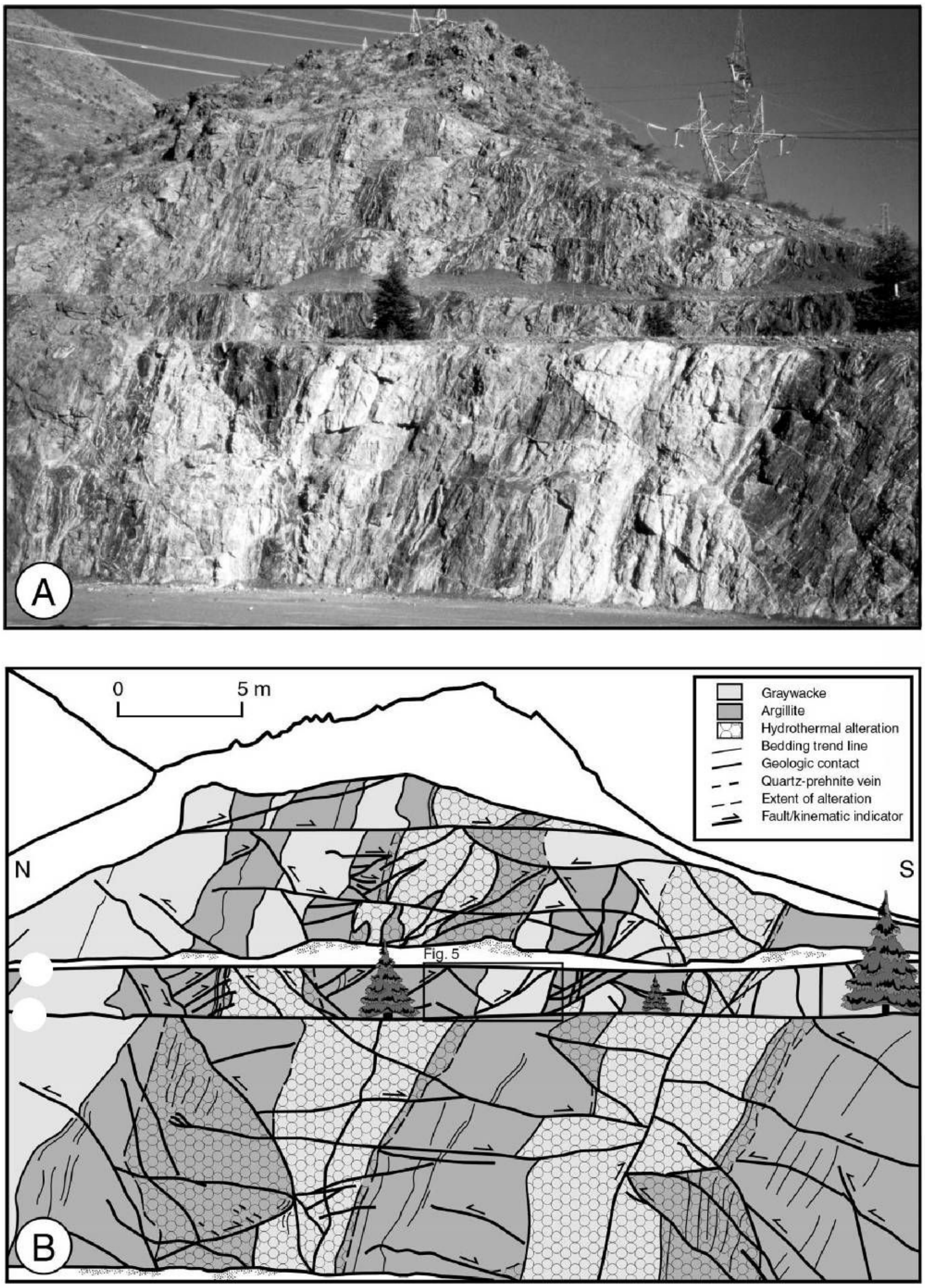


Figure (A) Photograph looking approximately southeastward toward the southern abutment outcrop to Benmore Dam, 3.5 km north of Otematata (see Fig. 1). Hydrothermal alteration (circle ornament) is more pronounced in the lowermost outcrop than in the two higher walls and is best developed in graywacke. (B) Line drawing of photograph shown in A. Zones of hydrothermal alteration extend on either side of the faults but are more pronounced in the hanging wall to these faults.

Figure 7. Photograph and interpretation of structures outcropping in the SE abutment of Benmore Dam. From de Ronde et al. (2001).

Within thick competent sandstones, there are also abundant gently E-dipping extensional and extensional shear veins of quartz + prehnite +/- epidote +/- calcite. Larger, en echelon arrays of these veins (Fig. 8) bisect the acute angle between the shear fractures, indicating all these structures were formed coevally. Microveins are most common in the more competent sandstone layers, and it is interesting to consider how a more deformed version of this rock may compare to foliated TZ II Otago Schist that we will see at stop 4.

Figure 8: En echelon array of extensional veins in sandstone. SE abutment of Benmore Dam. Field book is 20cm long. Viewed towards the SE.

Vein textures indicate incremental opening, which led de Ronde et al. (2001) to the interpretation that they formed during a micro-earthquake swarm. There are few precise constraints on the timing of faulting, however it is unlikely that there has been significant tilting of the sequence since formation of the fractures because, regionally, the Late Cretaceous-Cenozoic unconformity generally dips less than 20 degrees. Hence, fluid pressures must have at least equalled overburden pressures (i.e. $P_f > s_v$) so that the 'flat' extensional veins could form, and that the steep reverse faults could be re-activated, despite their unfavourable orientation (Fig. 9). When veins opened they likely formed an interlinked, permeable pathway for fluids – ie. a 'fault-fracture mesh' (cf. Sibson, 1996). Note, however, that the conjugate sets of minor faults is again consistent with extension along the bedding - did they form in a compressional regime in their present attitude or in an extensional regime when the strata were horizontal?

De Ronde et al. (2001), used fluid inclusion and stable isotope data to constrain the sources of vein cements. dD_{H2O} vs. $d^{18}O_{H2O}$ indicate a meteoric fluid source was modified to some extent by interaction with the surrounding Otago Schist. Vein quartz was formed from relatively saline fluids at elevated temperatures (c. 280°C based on the co-existence of epidote+prehnite). Trapping pressures were c. 160 MPa, consistent with a minimum trapping depth for lithostatic conditions, of 6km. Later calcite cements (with quartz and pumpellyite) were deposited from much less saline fluids (<1wt% NaCl) at lower temperatures. Fluid inclusion gases contain methane in addition to water, indicating exchange occurred between the organic-rich sediments of the Spillway Formation and the fluids during passage through the rock mass.

2:30-3:00pm

Note that as we drive up the Maraewhenua River from near Duntroon, we cross at least 15 km of vertically foliated Otago Schist with no obvious change in metamorphic grade. This contrasts with much of central Otago where it is commonly inferred that metamorphic isograds lie subparallel to the generally subhorizontal foliation. The cover sequence overlying the subhorizontal unconformity truncating the schist foliation consists of Late Cretaceous non-marine quartz gravels of the Taratu Formation at the base (extensively sluiced for gold) overlain by marine Eocene sandstones (intruded by the basaltic Tokarahi Sill) followed by Oligocene calcareous greensands and limestones.

Stop 4: Maraewhenua River, Dansey's Pass Holiday Park E 2299608 N 5582000

2.0 hours. Depart 5:00pm

Note first that the Waipounamu Erosion Surface overlain by Taratu quartz gravels, is visible across the river from the schist outcrop. River-worn outcrops beneath the Dansey's Pass Holiday Park expose typical TZ IIA / IIB Otago Schist. As at Benmore Dam, the protoliths are mainly sandstone and mudstone, with occasional horizons of pebbly mudstone. Original sedimentary layering (S_0) is locally recognisable but is mostly transposed into a well-developed S_1 foliation defined by a cleavage that lies axial planar to F_1 fold hinges in bedding. In places this cleavage is paralleled by mm-thick quartz veins. The foliation in pelitic lenses is oblique to that in the matrix mudstone, probably due to cleavage refraction.

Some thicker quartz veins are present. These can be both lozenged and disharmonically folded into tight F_2 structures with near vertical hinge lines and steep E-W striking axial planes (Fig. 10). These folds are then affected by a set of open F_3 folds with NE-SW striking axial planes. The schist foliation affected by the F_3 folds is sometimes smoothly deflected, but at other times is fractured, indicating this deformation occurred under conditions favouring brittle behaviour.

The schist lineation, defined by stretched conglomerate pebbles, rakes c. 60°W on near vertical, NW-SE striking foliation planes. The lineation is parallel to the dominant F_2 fold hinges; an observation also common elsewhere within the Otago Schist. In TZ II schist elsewhere in this area, deformed conglomerate pebbles indicate shortening of c. 50% with development of a plane strain to slightly oblate strain ellipsoid (Norris & Bishop, 1990).

Figure 10: Lozenging and disharmonic folding of variable thickness chloritic quartz veins, Maraewhenua River. Field book is 20cm long. Viewed towards the S.

Swarms of quartz veins up to a few cm thick occur throughout the outcrop. These are mostly regularly orientated, with NE-SW strikes and moderate NW dips. Some are planar features while others are folded and boudinaged. Some exploit the weak hinge planes of F_3 kink folds (Fig. 11).

Figure 11: Quartz tension gash parallel to the hinge plane of a kink fold, Maraewhenua River. Field book is 20cm long. Viewed towards the N.

Microscopically the schist can be seen to have been derived from similar rock types to those at Benmore Dam (compare Figs. 4 and 12). Both sandstone and mudstone protoliths show a throughgoing foliation or cleavage. Graded bedding may occasionally be recognised, especially in mesoscopic fold hinges. Metamorphic temperatures of schist metamorphism here are crudely bracketed by the Frey et al. (1991) temperature limits for pumpellyite-actinolite facies of 210-310°C. Thus, unlike the Benmore Dam sandstones, the Torlesse rocks at this locality passed into a ductile deformational regime deeper in the Mesozoic accretionary wedge before being exhumed in the Cretaceous beneath the Waipounamu Erosion Surface.

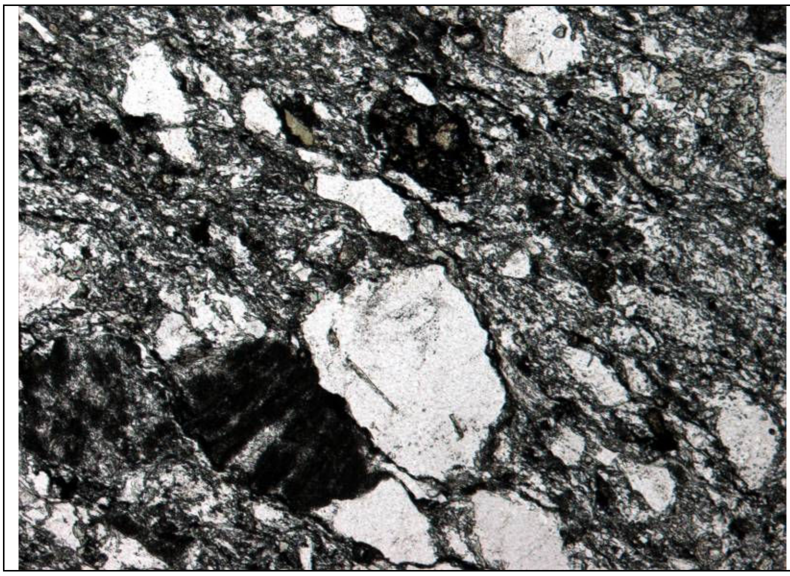


Figure 12a
Image of thin section of TZIIA-B schist P62281 from near the Maraewhenua River fieldtrip stop.
Rock is mix of detrital and neometamorphic minerals. Thin section cut perpendicular to lineation. Plane polarised light, image width 2mm

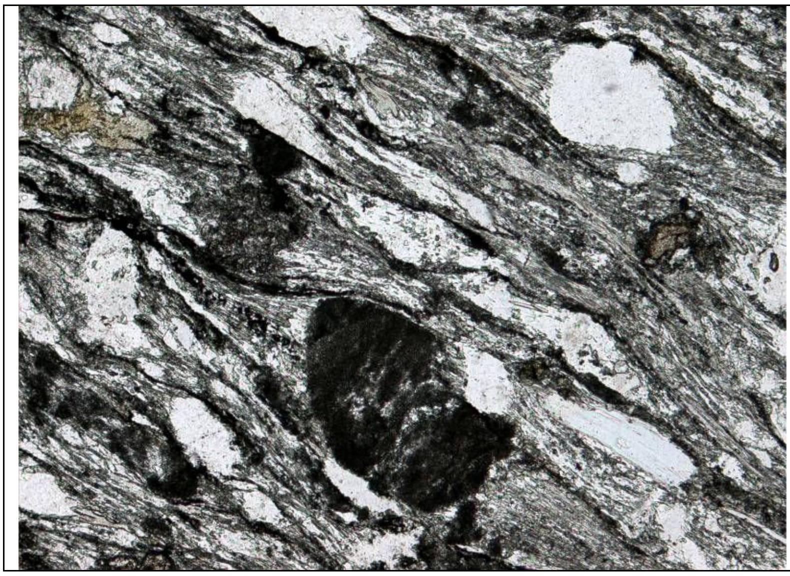


Figure 12b
Same rock as above but thin section cut parallel to lineation.
Note pressure solution beards on detrital grains are far more prominent than in lineation perpendicular view.
Plane polarised light, image width 2mm

Microstructures show that the foliation development was associated with solution transfer processes, perhaps accounting for all or some of the material in the quartz vein arrays. Indications of penetrative strain are more prominent in sections parallel to the pebbles stretching lineation than perpendicular to it (Fig. 12) . This raises the question of which Otago Schist mesoscopic structures - lineation or folds - have the most regional kinematic significance.
As at Benmore Dam, the presence of veins and vein swarms is consistent with movement of abundant silica-bearing fluids through fracture networks within the rock mass. However, the metamorphic grade under which the schists at Maraewhenua were deformed is higher, and it is likely that syn-deformational permeability, controlled by fluid movement on grain boundaries during crystal-plastic deformation, was lower. In similar textural and metamorphic grade Otago Schists on the shores of Lake Hawea, Cox (1993) observed that mass was conserved at the outcrop scale, and extremely large fluid/rock ratios were not required in order for textural reconstitution to occur.

Participants are invited to puzzle out the full history of deformation (folds, fabrics, quartz veins etc) in the schist outcrop. A bottle of wine will be presented to the person who gives the most convincing and comprehensive analysis of the deformation sequence.

5:45pm
Arrive at Burnside Historic Homestead for BBQ dinner, or continue on to Oamaru.

References

Adams, C. J., Bishop, D. G., and Gabites, J. E. 1985. Potassium-argon age studies of a low-grade, progressively metamorphosed graywacke sequence, Dansey Pass, South Island, New Zealand. Journal of the Geological Society of London 142, 339-349.

Cox, S.C. 1993. Veins, Fluids, Fractals, Scale & Schist: An investigation of fluid-rock interaction during deformation of the Torlesse Terrane, New Zealand. Unpublished PhD Thesis, University of Otago.

de Ronde, C.E.J., Sibson, R.H., Bray, C.J., and Faure, K. 2001. Fluid chemistry of veining associated with an ancient microearthquake swarm, Benmore Dam, New Zealand. Geological Society of America Bulletin 113(8), 1010-1024.

Forsyth, P.J. 2001. Geology of the Waitaki area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 19.

Frey, M., de Capitani, C. and Liou J.G. 1991. A new petrogenetic grid for low-grade metabasites. Journal of Metamorphic Geology 9, 497-509.

Kamp, P.J.J. 2001. Possible Jurassic age for part of Rakaia Terrane: implications for tectonic development of the Torlesse accretionary prism. New Zealand Journal of Geology and Geophysics 44, 185-203.

Landis, C.A., Campbell, H.J., Begg, J.G., Mildenhall, D.C., Paterson, A.M. and Trewick, S.A. 2008. The Waipounamu erosion surface : questioning the antiquity of the New Zealand land surface and terrestrial fauna and flora. Geological Magazine 145(2), 173-197.

Lillie, A.R. and Gunn, B.M. 1964. Steeply plunging folds in the Sealy Range, Southern Alps. New Zealand Journal of Geology and Geophysics 7: 403-423.

Mortimer, N. 1993. Jurassic tectonic history of the Otago Schist, New Zealand. Tectonics, 12, 237-244.

Mortimer, N. 2000. Metamorphic discontinuities in orogenic belts: example of the garnet-biotite-albite zone in the Otago Schist, New Zealand. International Journal of Earth Sciences 89, 295-306.

Mortimer, N. 2004a. New Zealand's geological foundations. Gondwana Research 7, 261-272.

Mortimer, N. 2004b. A provisional structural thickness map of the Otago Schist, New Zealand. American Journal of Science 303, 603-621.

Norris, R.J., and Bishop, D.G. 1990. Deformed conglomerates and Textural Zones in Otago Schists, South Island, New Zealand. Tectonophysics 174, 331-349.

Retallack, G.J. 1983. Middle Triassic estuarine deposits near Benmore Dam, southern Canterbury and northern Otago, New Zealand. Journal of the Royal Society of New Zealand 13(3), 107-127.

Sibson, R.H. 1996. Structural permeability of fluid-driven fault-fracture meshes. Journal of Structural Geology 18(8), 1034-1042.

Tippett, J.M., and P.J.J. Kamp 1993. Fission track analysis of the late Cenozoic vertical kinematics of continental Pacific crust, South Island, New Zealand. Journal of Geophysical Research 98, 16119-16148.

Turnbull, I.M., Mortimer, N. and Craw, D. 2001. Textural zones in the Haast Schist -- a reappraisal. New Zealand Journal of Geology and Geophysics 44, 171-183.