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## Field Trip Guides

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**GEOLOGICAL SOCIETY OF NEW ZEALAND  
ANNUAL CONFERENCE 2003**

**FIELD TRIP 3**

**OTAGO SCHIST STRUCTURE AND  
EXHUMATION**

**Nick Mortimer and Rick Sibson**

**INTRODUCTION**

With the exception of stop 1, the entire trip (Fig. 1) can be followed on NZMS262 topographic maps H45 (Clarendon) and I45 (Taieri Mouth), and the 1:50 000 geological map of Bishop (1994). The 1: 250 000 geological map of Bishop & Turnbull (1996) is a useful for the wider regional context. Tide on the day is optimal: high at 1020hrs, low at 1630hrs. Watch for large waves, seals and sea-lions on the beaches. The weather will either be appalling or excellent.

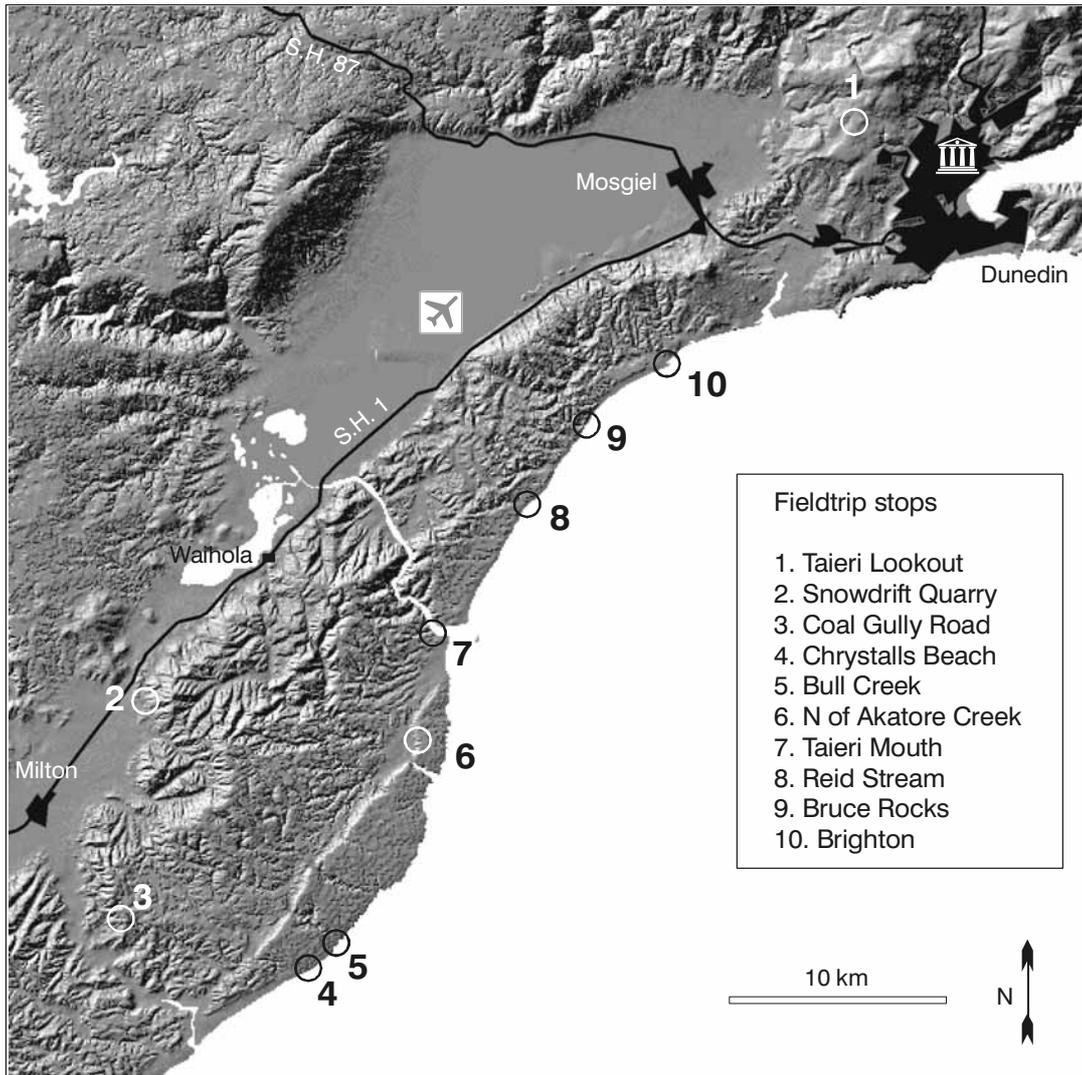
The four aims of the trip are to:

- 1) examine penetrative and non-penetrative (ductile and brittle) meso-scale structures of the Otago Schist in superb 3D coastal exposures
- 2) consider the paleoseismological implications of accretionary wedge melange structures
- 3) review macro- and meso-structural evidence for exhumation of the Otago Schist
- 4) provide an overview of local East Otago geology and tectonics

En route will we cross traces of the Holocene-active Akatore Fault. Time permitting, some brief photostops will be made to view this feature. More information on the Akatore Fault can be obtained from the Coastal Otago Quaternary fieldtrip 2 in this volume, and from Norris & Turnbull (1996).

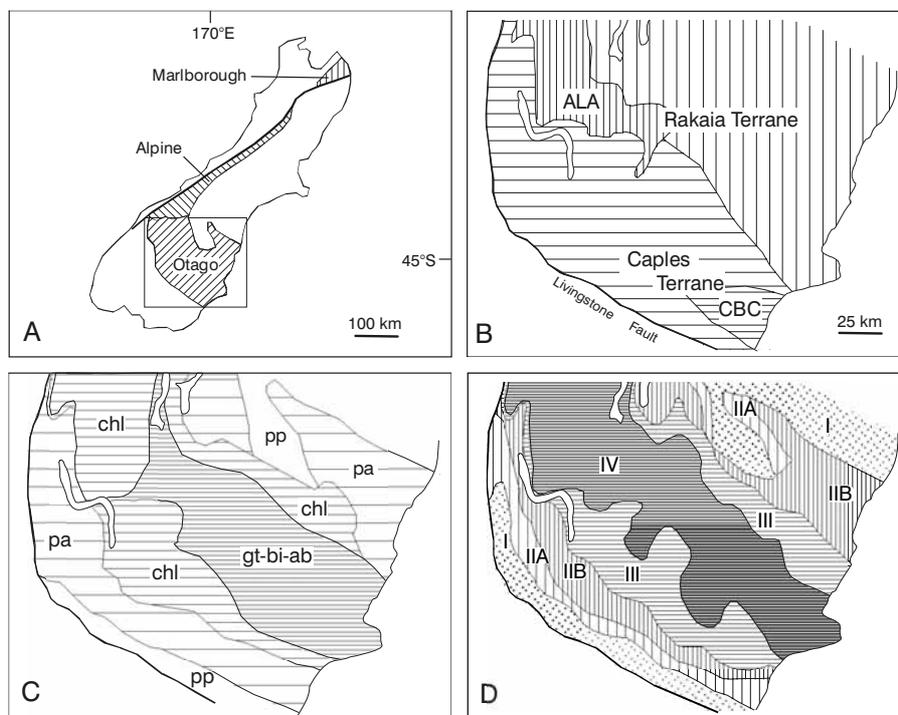
**THE OTAGO SCHIST**

The Otago Schist is a major feature of New Zealand's Eastern Province. The schist forms a c. 150 km-wide, two-sided arch with prehnite-pumpellyite facies nonschistose greywackes on its flanks and greenschist facies rocks (peak temperature and pressure 350-400°C and 8-10 kbar) in the centre (Mortimer, 2000). Along with the increasing metamorphism there is an increase in deformation towards the centre of the Otago Schist as defined by the progressive development of a penetrative foliation, different textural zones and successive fold generations (Figs. 2, 3, 4). The schist is thought to have formed during accretion of the Permian-Triassic Caples and Rakaia terranes in a Jurassic-Cretaceous accretionary wedge.

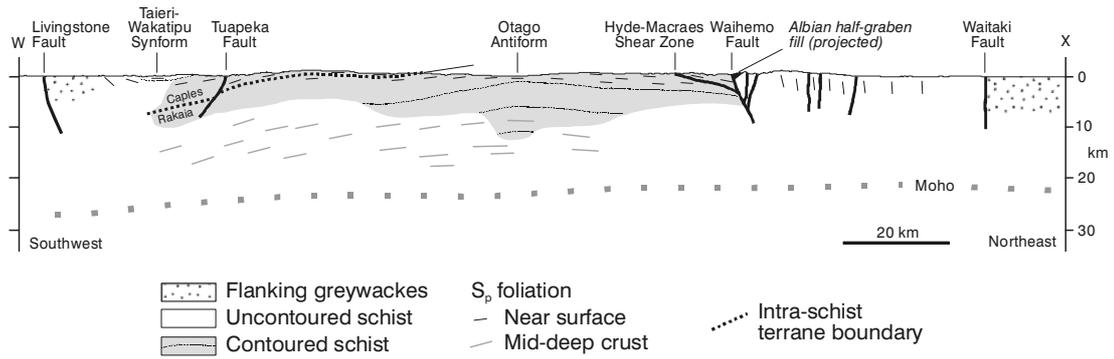


**Figure 1:** Fieldtrip route. The Taieri Plains are bounded on the southeast side by the Titri Fault. The Akatore Fault is the lineament extending SW from stop 6. The highest point is Maungatua (hill west of airport) at 895 m.

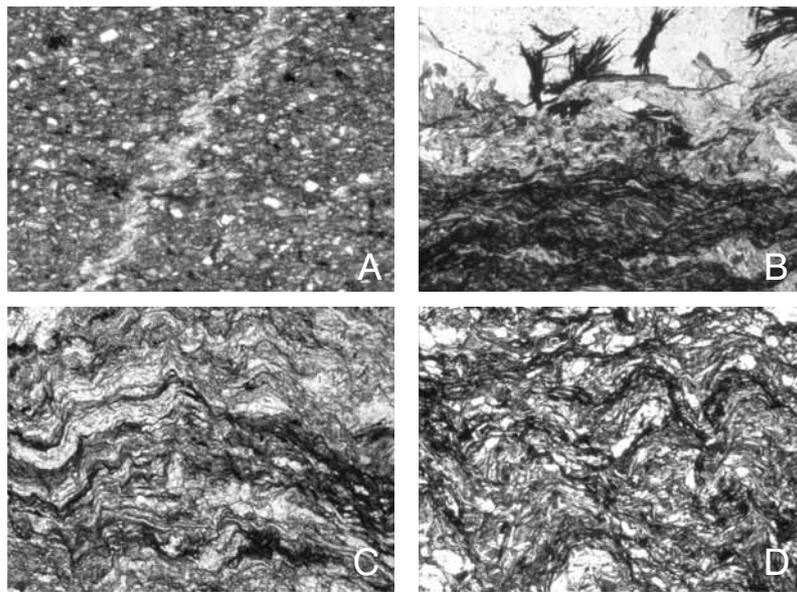
Peak metamorphism of the Otago Schist occurred at 170-180 Ma (Fig. 5). Subsequent exhumation either occurred very slowly and continuous at a rate of c. 0.2 km Ma<sup>-1</sup> (Adams & Robinson 1993) or was punctuated with a phase of more rapid exhumation at rates of 0.6-1 km Ma<sup>-1</sup> after 135 Ma (Little et al. 1999). Rocks from the schistose parts of the Mesozoic wedge finally reached the surface at c. 100 Ma, as indicated by the first appearance of schist fragments in Albian graben sediments (e.g. Henley Breccia which we will see on the trip). Widespread erosion of the Otago Schist and Albian graben sediments started in the Late Cretaceous. The Otago Peneplain (Waipounamu Erosion Surface) is expressed as an unconformity at the base of Haumurian sediments (~85 Ma). Lying above the peneplain surface are Late Cretaceous and Tertiary passive margin cover rocks. Miocene and younger compressional deformation folded the peneplain and gave the Otago its present range-and-basin topography.



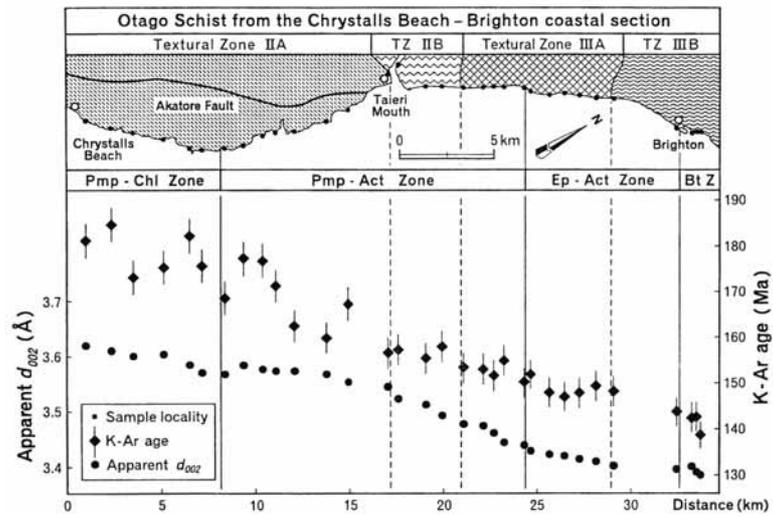
**Figure 2:** Regional subdivisions of the Otago Schist. **A.** Haast Schist in South Island consists of Marlborough, Alpine and Otago Schists. **B.** Caples and Rakaia Terranes and constituent lithotectonic units. **C.** metamorphic zones (prehnite-pumpellyite, pumpellyite-actinolite, chlorite and garnet-biotite-albite). **D.** Textural zones (I=unfoliated greywacke and argillite, IIA=weakly foliated greywacke and argillite with metamorphic micas <5µm thick and <75µm long, IIB=well foliated semischists with micas 5-15µm thick and <75µm long, III=thinly segregated greyschists with micas 15-25µm thick and 75-125µm long, IV=thickly segregated greyschists with micas 25-50µm thick and 125-500µm long; Turnbull et al. 2001).



**Figure 3:** SW-NE cross section through the Otago Schist in East Otago. The coast section affords examination of a structural cross-section through the Caples Terrane from near the Livingstone Fault (stop 4) to near the Otago Antiform (stop 10). In simple terms, the Livingstone Fault forms the backstop to the Mesozoic accretionary wedge, the schist is the deeply-exhumed part of the wedge which tapered NE towards the Pahau Terrane. From Mortimer (2003) with Moho projected from Mortimer et al. (2002).



**Figure 4:** Microscope images (all plane polarised light and 1 mm wide) of pelitic rocks seen on the fieldtrip, illustrating progressive increase in textural and metamorphic grade. **A.** Bull Creek area, very weakly foliated TZIIA sandy siltstone with ptygmatically folded quartz vein (P50665). **B.** Taieri Mouth, well foliated TZIIB phyllite with stilpnomelane sprays in quartz vein (P8661). **C.** Reid Stream area, foliated and crenulated, but unsegregated, TZIIB schist (P50676). **D.** Brighton, thinly segregated and strongly crenulated TZIII schist; rodding is perpendicular to plane of photo (P50678).



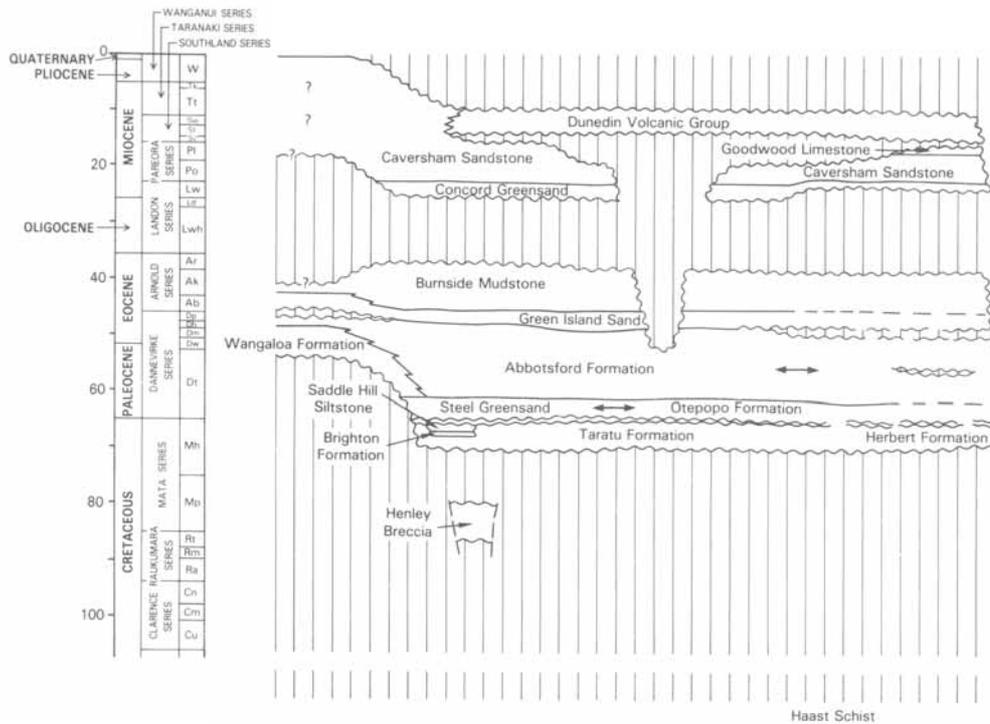
**Figure 5:** K-Ar ages and graphite crystallinity along the coast section from Chrystalls Beach to Brighton (Nishimura et al. 2000). Note the good metamorphic gradient from Taieri Mouth to Brighton, and the less well-defined gradient between Chrystalls Beach and Taieri Mouth.

**START. ST MARGARET'S COLLEGE, OTAGO UNIVERSITY**

*Drive to The Octagon and follow Stuart Street uphill. Keep on the main road which leads over the summit of Three Mile Hill. Pull off on the left hand side about 1 km after the crest of the hill.*

**STOP 1. TAIERI LOOKOUT, THREE MILE HILL. I44/102810**  
**Local stratigraphy and compressional Taieri Graben**

From here we get a good view looking WSW straight along the axis of the Taieri Plains which occupy a compressional graben flanked by outward-dipping reverse faults. This is a good place to review the Dunedin area stratigraphy (Fig. 6) and tectonics.



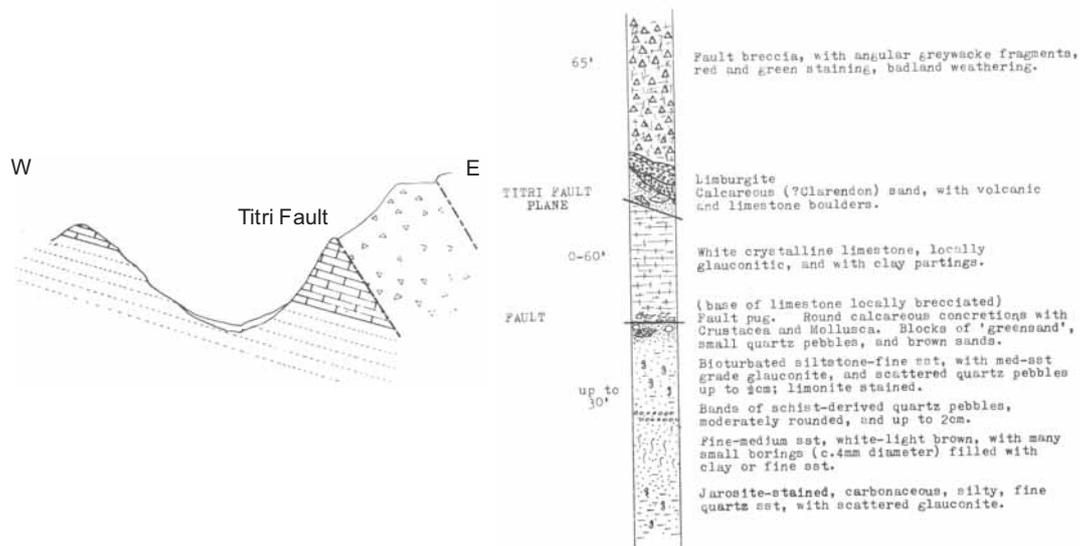
**Figure 6:** Dunedin and Coastal Otago stratigraphy.

*We proceed to Dunedin Airport to pick up extra members of the trip, then continue south on State Highway 1 to Milburn. Turn left at Milburn and proceed to a gate at the road bend.*

**STOP 2. SNOWDRIFT QUARRY. H45/797544**  
**Titri Fault, Henley Breccia and Milburn Limestone**

*Permission to enter Snowdrift Quarry can be obtained from J.R. Finch & Sons, Hawthorne Lodge, West Road, Milburn. The geological information is reproduced from Bishop (1994).*

This is one of the rare exposures of the Titri Fault. In the quarry (Fig. 7), red Henley Breccia (poorly dated but Cretaceous, possibly Raukumara Series, 85-95 Ma) is thrust over white Milburn Limestone (Miocene, Waitakian, 19-26 Ma). The thin-bedded limestone is locally chevron-folded in the immediate footwall of the fault. Two small basanite dikes of the Dunedin Volcanic Group (Miocene, 10-22 Ma) are present on the fault plane which here dips  $\sim 60^\circ$ NE.



**Figure 7:** Cross section and stratigraphic column for Snowdrift Quarry. After Meder (1962). Approximate dimensions of cross section 70 m long by 30 m high.

The Titri Fault has had a long and complex structural history reflecting the compressional inversion that gave rise to much of the present Otago landscape. It was first active in the Late Cretaceous (Mutch & Wilson 1952), probably as a listric normal fault when the uplifted western side (now the Taieri Graben) provided the source area for the fanglomerates and conglomerates of the Henley Breccia. Subsequent, late Cenozoic, movement on the Titri Fault has been in the opposite (reverse fault) sense e.g. the relationship seen in the quarry. Evidence of compressional deformation associated with the Titri Fault continues into the Quaternary but no direct evidence of Holocene activity has yet been recognised (Litchfield 2001).

This is the only exposure of Henley Breccia we will see on the trip. Henley Breccia is one of four fault-bounded, Late Cretaceous coarse grained non-marine units that are the oldest sedimentary rocks to unconformably overlie the Otago Schist (Fig. 6; the others are Kyeburn Formation, Horse Range Breccia and Blue Spur Conglomerate). The

metamorphic and textural grade of clasts increases towards the top of the Henley Formation (from TZIIA-B to TZIII), reflecting exposure of progressively deeper schist levels in the source area. (U-Th)/He dating of a TZIIA-B schist clast (not from this quarry) has given an age of  $103 \pm 8$  Ma (Mark Brandon et al. work in progress), suggesting a cooling rate of at least  $10^\circ\text{C}/\text{m.y.}$

*Drive south to Milton, turn off State Highway 1 and follow signs to Toko Mouth. Turn left onto Coal Gully Road and immediately cross the Tokomairiro River. Continue for about 2 km to a hairpin bend on the hill.*

**STOP 3. COAL GULLY ROAD BEND. H45/778452**  
**Taratu Formation quartz sand and lignite**

Taratu Formation is considered by most to be the basal unit of the well-stratified Late Cretaceous-Cenozoic sedimentary sequence (Fig. 6). It comprises quartzose coal measures that overlie the Otago Peneplain and Henley Breccia.

At this locality, a good section through quartz gravel, sandstone, mudstone and lignite is exposed, dipping  $160/10^\circ\text{E}$ , but nearby faults do not allow full appreciation of the stratigraphic relations. From the crest of the hill above us, the peneplain dips seaward and is offset by the Akatore Fault which strikes parallel to the Titri Fault (Fig. 1, Photostop A) and also dips seaward at  $\sim 60^\circ\text{SE}$ .

*Continue up along Coal Gully Road which turns into Bull Creek Road. Outliers of Taratu Formation cap the ridges hereabouts. At Glenledi Farm junction either continue along Bull Creek Road to Chrystalls Beach, or divert to the photostop on Irishmans Road.*



**PHOTOSTOP A. GLENLEDI. H45/841435 & H45/844431**  
**Active trace of Akatore Fault.**

Pull off on Irishmans Road to view a 2.5 m fault scarp across the Holocene river flat of the antecedent Nobles Stream. The offset on the Otago peneplain is about 75 m.

*Return to the junction at Glenledi and turn north into Bull Creek Road. The Akatore Fault is crossed again. Near the top of the hill turn right into Chrystalls Beach Road.*

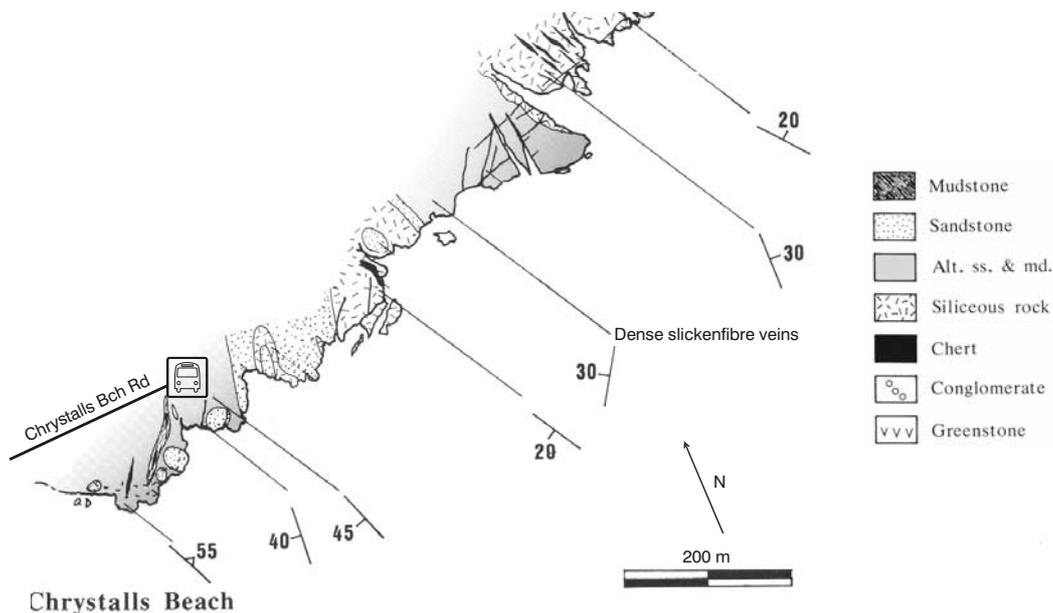
**STOP 4. CHRYSTALLS BEACH. H45/867423 to H45/871425**  
**Argillite-matrix melange; sandstone and chert lenses; slickenfibres vein arrays**

*Park opposite the last cribs. We will examine the rock platforms from here to a particularly dense array of veins about 500m NE of the vans (Fig. 8).*

The rocks at Chrystalls Beach are the southernmost coastal exposures of Otago Schist and Caples Terrane. Cooks Head Rock, an isolated exposure of columnar jointed Dunedin Volcanic Group, is 2.5 km to the SW along Chrystalls Beach. The next exposures of basement are near Kaka Point, Triassic Willsher Group sediments (Campbell et al. 2003), possibly of the Maitai Terrane.

The rocks between Chrystalls Beach and Taieri Mouth have been the subject of intense study by various groups over the last few years, though much remains to be done, particularly from a structural point of view.

Although most simply considered part of the Caples Terrane, the petrography and geochemical composition are somewhat atypical of normal Caples (Coombs et al. 2000). The melange structure and presence of chert and metavolcanics (Nelson 1982; Hada et al. 1988) is also unusual for Caples Terrane. Along coast to the north, Triassic tube fossils are present in sandstones and Triassic radiolarians have been obtained from cherts and phosphatic nodules (Campbell & Campbell 1970; Hada et al. 1988; Ito et al. 2000). K-Ar ages range from 170-190 Ma (Nishimura et al 2000, Figure 5) and may reflect a mix of metamorphic and detrital ages.



**Figure 8:** Sketch geology of the coast platform at Chrystalls Beach. From Hada et al. (1988)

The Chrystalls Beach subduction complex rocks are composed predominantly of sandstone phacoids set in a sheared and cleaved pelitic matrix. Rocks within the *mélange* have likely undergone a mixture of ‘soft-sediment’ deformation as well as ‘hard-rock’ deformation in a subgreenschist environment ( $P = 3\text{-}6$  kbar;  $T = 250\pm 30^\circ\text{C}$ ). The *mélange* is disrupted by a cellular shear zone mesh comprising innumerable slip surfaces subparallel to cleavage coated with incrementally developed quartz/calcite slickenfibres. Sliding surfaces splay and amalgamate and are also commonly interlinked by sets of extension veins localised within dilational stepovers (Fig. 9). The slickenfibres commonly curve or change growth direction abruptly, suggesting that the *mélange* of phacoids enveloped within a mesh of anastomosing slip surfaces functioned as a ‘dead-fish’ shear zone. Multiple generations of slip-surfaces were apparently active at different times. ‘Sense-of shear’ is highly variable but top-to-the-north indicators predominate.

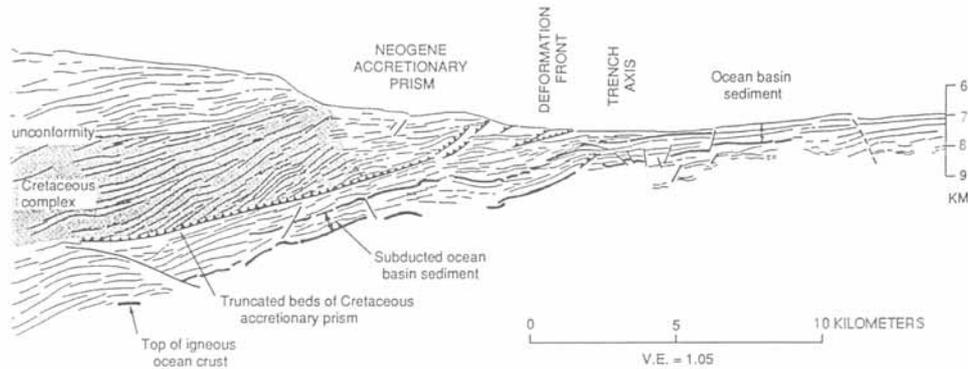


**Figure 9:** Dilational stepover linking *en echelon* slickenfibre sliding surfaces, Chrystalls Beach.

There is clearly a strong influence of parent lithology on rheological response. The combination of slickenfibre sliding surfaces interlinked with extension veins, plus numerous extension veins cutting the more competent sandstones, suggests that the *tensile overpressure condition* ( $P_f > \sigma_3$ ) was widely achieved with deformation occurring under near-lithostatic fluid overpressures. Note also the evidence for continual competition between permeability creation along faults and fractures, redistribution of hydrothermal fluids, and fracture sealing by hydrothermal precipitation - a ‘permeability combat zone’.

Individual slip surfaces extend for metres to many tens of metres while reconnaissance petrography suggests that the slickenfibres developed incrementally in submillimetre to millimetre slip ‘crack-seal’ increments, indicating that the mesh may have been active at the microseismic level. These scaling relationships may be compared with recent

studies of microearthquake clusters along creeping segments of faults where repeating ‘characteristic’ microearthquakes occur with  $10 \text{ m} < L < 1000 \text{ m}$  and  $0.1 \text{ mm} < u < 10 \text{ mm}$  (Nadeau & McEvilly 1977) and microearthquake lineations form parallel to the fault slip vector, possibly along boudin trails.



**Figure 10:** Line drawing of a seismic section across the Japan Trench (von Huene & Scholl 1991). The subduction channel lies below the truncated beds of the Cretaceous accretionary prism and above the subducting igneous ocean crust. The Chrystalls Beach section may possibly have been deformed in such a subduction channel.

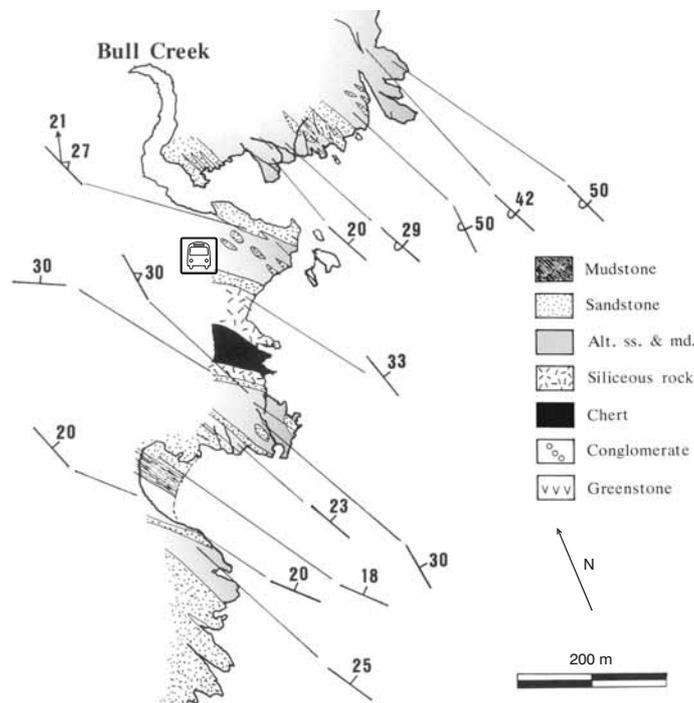
Significant sediment subduction has been recognised along ‘subduction channel’ shear zones of the order of 1-2 km in thickness along many active subduction interfaces (Fig. 10; von Huene & Scholl 1991). Reyners et al. (1999) have identified a zone of comparable thickness defining portions of the active Hikurangi Margin subduction thrust interface characterised by a band of microseismicity associated with anomalous  $V_p/V_s$  ratios diagnostic of extreme fluid overpressuring. One tantalising possibility to be considered, therefore, is that the Chrystalls Beach assemblage represents part of an exhumed subduction channel, formerly overpressured and microseismically active.

*Drive back to the hilltop and continue along Bull Creek Road to the coast. Drive past the first cribs and park in the domain area underneath some trees on the right. This is a sheltered spot for lunch and there are toilets available.*

**STOP 5. BULL CREEK. I45/883436.**

**Penetrative schistosity, transposed bedding, phosphatic nodules**

Here, we are about 1500 m NE of the last stop. The rocks are more penetratively foliated (but still TZIIA) with a cleavage dipping  $110/20^{\circ}\text{N}$  (Figs. 4A, 11). Bedding is locally much steeper and black phosphatic, radiolarian-bearing nodules can be seen. Bedding/cleavage relationships in multi-layer buckle folds have developed within thinly bedded cherts. All tube fossils and most preserved radiolarians have been obtained to the north of Bull Creek, so metamorphic grade and/or strain do not increase uniformly along the coast.



**FIGURE 11.** Sketch geology of the coast platform near Bull Creek. From Hada et al. (1988)

*Return inland and turn north on the Milton-Taieri Mouth Road.*

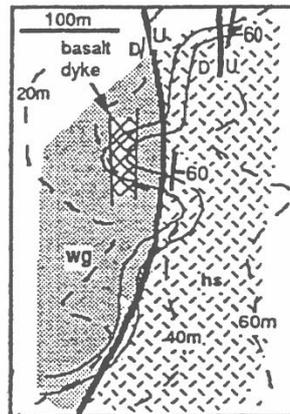


**PHOTOSTOP B. BIG CREEK. H45/869473**

**Pull over as we descend to Big Creek. Akatore Fault Trace. The seaward block is upthrown ~2 m.**

**STOP 6. ROADCUT NORTH OF AKATORE CREEK. I45/918527**  
**Akatore Fault**

*After the tidal Akatore Creek is crossed on a bridge, continue uphill until a hairpin bend is reached. Park as safely as possible.*



**Figure 12:** Sketch of the roadside geology at stop 6. From Norris & Turnbull (1996). hs=Haast Schist, wg=Wangaloa Formation (see Fig. 6).

The Akatore Fault zone here (Fig. 12) consists of about 4 cm of grey plastic gouge overlain by about 30cm of cataclastically deformed schist with numerous thin gouges and shears. The average attitude of the fault plane is  $015/60^{\circ}E$ . The fault juxtaposes fractured TZII semischists in its hanging wall against a footwall of subhorizontally bedded Wangaloa Formation intruded by a basaltic dike.

The Akatore and Titri Faults both dip southeast (seaward). Mortimer et al. (2002) have speculated that these faults merge at depth and are manifested on a deep offshore seismic profile as a 35 km long prominent horizontal seismic reflector at 7 seconds TWT (c. 20 km depth). While there is no definite stratigraphic evidence that the Akatore Fault originated as a Late Cretaceous normal fault like the Titri Fault, its comparable orientation suggests that it too may be an inversion structure.



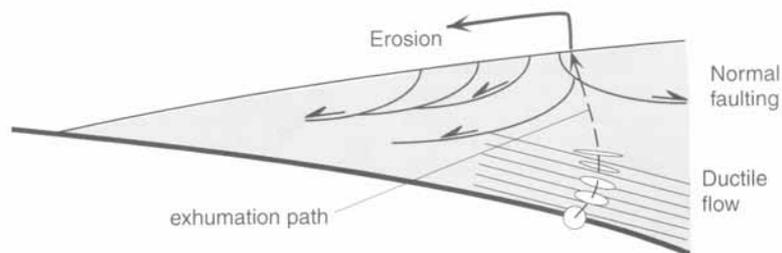
**PHOTOSTOP C. TAIERI MOUTH SCHOOL. I45/929554**  
**Akatore Fault Trace. 2 m vertical offset of a Pleistocene marine terrace in the paddocks opposite the school.**

**STOP 7. TAIERI MOUTH. I45/926578**  
**TZIIB Phyllitic schist, calcite and quartz veins**

*Park opposite old dairy and walk down to examine the low cliff exposures. If the tide is low enough we can walk west along the shore platform to the boat sheds.*

Grey phyllitic schist (Fig. 4B) has a subhorizontal dip. 1-10cm bands of black and green schist represent original bedding - more thoroughly transposed than at Bull Creek. Here we are almost on the axial trace of the enigmatic Taieri-Wakatipu synform, a feature that can be traced through the schist of the Caples Terrane for more than 350 km (Mortimer & Johnston 1990; Mortimer 2003).

It is debatable how much “deeper” into the structural/metamorphic section we have travelled from Bull Creek (see Figs. 1-5). It is likely that the penetrative fabric here is first generation and can be called  $S_1$ . This is about as simple and straightforward as the penetrative fabrics in the Otago Schist get; most of us would argue that the foliation here is little-rotated from its original attitude during formation. Question: is the flat-lying penetrative fabric fundamentally related to crustal thickening and prograde metamorphism during underplating at the base of the wedge, or to ductile thinning and retrograding as material is exhumed through a convergent wedge (Fig. 13)?



**Figure 13.** Illustration of the three exhumation processes that operate in convergent accretionary wedges (Ring et al. 1999). Some generations of Otago Schist foliation could be related to vertical contraction ( $\sigma_3$  horizontal,  $\sigma_1$  vertical) in the ductile regime.

Several late-stage vein arrays are developed in the schist. One set of extensional calcite veins with fibrous crack-seal textures is developed subparallel or slightly oblique to the flat-lying foliation suggesting  $P_f > \sigma_v = \sigma_3$  (i.e. supra-lithostatic fluid-pressures) at the time of their development. Possibly related structures forming under horizontal compression include conjugate kink bands defining box-folds in the foliation and at least one minor thrust fault. Younger quartz veins occur in *en echelon* arrays oblique to foliation, and also as subvertical extension veins associated with steep normal faults forming under horizontal extension with  $P_f > \sigma_h = \sigma_3$ . These vein-sets appear to have become inactive once the normal faults developed as throughgoing structures, as expected from brittle failure theory. More complex quartz veining may possibly be associated with the tip zone of a larger normal fault.

The association in a restricted locality of the two dominant vein sets (subhorizontal calcite veins associated with thrust faults under horizontal compression, and subvertical

quartz veins associated with normal faults forming under horizontal extension) may be entirely fortuitous, but could possibly be related to bending strains associated with the development of the Taieri-Wakatipu synform, with 'outer-arc' extension superimposed on 'inner-arc' shortening as the fold developed and the neutral surface migrated upward.

*Continue north towards Dunedin across the Taieri River bridge. On approach, watch for a partially collapsed octagonal farm building on the left just before Dickson Road. Reid Stream is 0.8 km past Dickson Road; Reid Stream bridge is obvious (duck pond to left) but has no identifying road sign. Pull off on the right just before the bridge.*

### **STOP 8. COAST AT REID STREAM. I45/968635** **TZIIIB deformed conglomerates**

*At the time of writing the sand is high and the oft-visited exposures to the north of Reid Stream are almost buried. We will stay south of Reid Stream and examine the rocks there.*

Metamorphic and textural grade are noticeably higher here than at Taieri Mouth (Figs. 4, 5) and the rocks have a noticeable dip (130/25°SW). Protoliths here are pebbly sandstones on which Norris & Bishop (1990) have done strain studies that indicate up to 80% flattening. Clasts include argillites, sandstones and rare granitoids. A prominent L<sub>1</sub> stretching lineation plunges towards 170 on S<sub>1</sub> surfaces. In addition, mm-scale F<sub>2</sub> crenulations (common) and broad, m-scale F<sub>2</sub> warps are present; fold axes trend 140.

Brittle structures here include quartz tension gash arrays and steep faults. One prominent fault (095/88°S) has a dextral motion based on associated quartz vein geometry. Steep, straight quartz vein arrays strike 045. Although thin and low volume, these are prominent.

*Continue north towards Dunedin. Watch for a long gorse hedge on the left of the road. At the end of this there is a gentle left-hand bend. Pull out on the right hand side of the road immediately after the Hall's letterbox (rapid no. 232). Drive to the north end of the pullout and and walk down to the beach.*

### **STOP 9. BRUCE ROCKS. I45/996675** **Asymmetric F<sub>2</sub> folds, brittle faults**

The rare mesoscopic F<sub>2</sub> folds seen at Reid Stream now dominate the outcrops and have a distinct and consistent asymmetry, verging NE. This asymmetry is seen in mesoscopic folds throughout the lower levels of the Caples Terrane between here and Queenstown (Mortimer 2003). Sandstone and mudstone protoliths can still be readily distinguished as TZIII psammitic and pelitic schists. Thick quartz veins are refolded with fold axial planes parallel to the penetrative foliation. The problematic issue of distinguishing between S<sub>1</sub> and S<sub>2</sub> will be discussed here and at the final stop at Brighton. The relatively abundant thick quartz veins seen here appear to have no counterparts at Reid Stream and Taieri Mouth where early-formed quartz veins are much thinner and rarer.

Late faults are abundant here. One particularly prominent fault zone with a calcite-cemented gouge zone dips 052/45°NW; ancillary faults dip up to 60°. Possibly these are structures that were conjugate to the Akatore Fault during its inferred former extensional phase.

Blocks of rusty, cemented sandstone have fallen from the loess capped cliffs. They are Quaternary terrace deposits.

*Continue north along the road towards Dunedin. Pull off at the Brighton Sports Ground and Domain, just before the bridge. Drive to the far (north) end of the domain and walk down the steps to the beach.*

**STOP 10. BEACH AT BRIGHTON DOMAIN. I45/033699**  
**Strongly rodded schist**

This is the end of our schist traverse. We are now well into the greenschist facies (biotite has been reported from Brighton). The unstepped graphite crystallinity and K-Ar profiles (Fig. 5) give us confidence in interpreting the entire section from Chrystalls Beach to here as being largely unfaulted. Hopefully the party has been impressed by the progressive structural and metamorphic changes (Fig. 4) we have observed up the coast.

The TZIII schist here at Brighton can be recognised as a more deformed version of the schist seen at the last stop. It is more difficult to tell psammitic from pelitic schist, though the mudstone (pelitic) protoliths have thicker, and more, quartz segregations than the sandstones. It has been claimed that graded bedding can be observed! Structurally, the outcrops at Brighton are very strongly rodded (an L<sub>2</sub> stretching lineation) and it is often difficult to measure a penetrative foliation (presumably S<sub>2</sub>). Refolded L<sub>1</sub> lineation can be seen on the surfaces of some deformed quartz veins.

The Brighton foreshore contains still more examples of steep late faults, here striking 030°. The Akatore Fault, which headed out to sea near Taieri Mouth, is believed to come inshore again a few km northeast of Brighton.

*Continue north towards Dunedin. The trip finishes at St. Margaret's College.*

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