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FIELD TRIP 6

AVIEMORE – A DAM OF TWO HALVES

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AVIEMORE - A DAM OF TWO HALVES

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1. INTRODUCTION

1.1 Overview

This excursion provides an overview of the geology and tectonics of the Waitaki valley, including some features of its hydroelectric dams. The excursion highlight is Aviemore Dam, constructed in the 1960s across a major fault, the subsequent (mid-1990s – early 2000s) discovery and quantification of late Quaternary displacement on this fault and the resulting engineering mitigation of the dam foundation fault displacement hazard. The excursion provides insights to the nature and expression of faults in the Waitaki landscape, and the character and ages of the Waitaki alluvial terrace sequences.

Section 1.2 comprises a descriptive guide of the route and stops. Section 2 provides background information on geology and geomorphology, while Section 3 presents a synopsis of hydrological and engineering information. Section 4 gives an illustrated summary of earthquake geology investigations at Aviemore Dam.

1.2 Itinerary and stops (Figure 1)

Depart Oamaru town centre and drive north on State Highway 1. SH 1 lies seaward of an abandoned sea cliff that backs Oamaru township. At the foot of the cliff is the southern fringe of the Lower Waitaki alluvial plain. This alluvial plain originally fanned out north and south from the mouth of the Waitaki valley, but has been greatly truncated by coastal erosion during the Holocene. At Pukeuri, turn left onto State Highway 83 and enter the Waitaki valley. Travel about 8 km, then turn right onto Peebles Road and pull onto the verge just before Seven Mile Rd intersection (15 min drive).

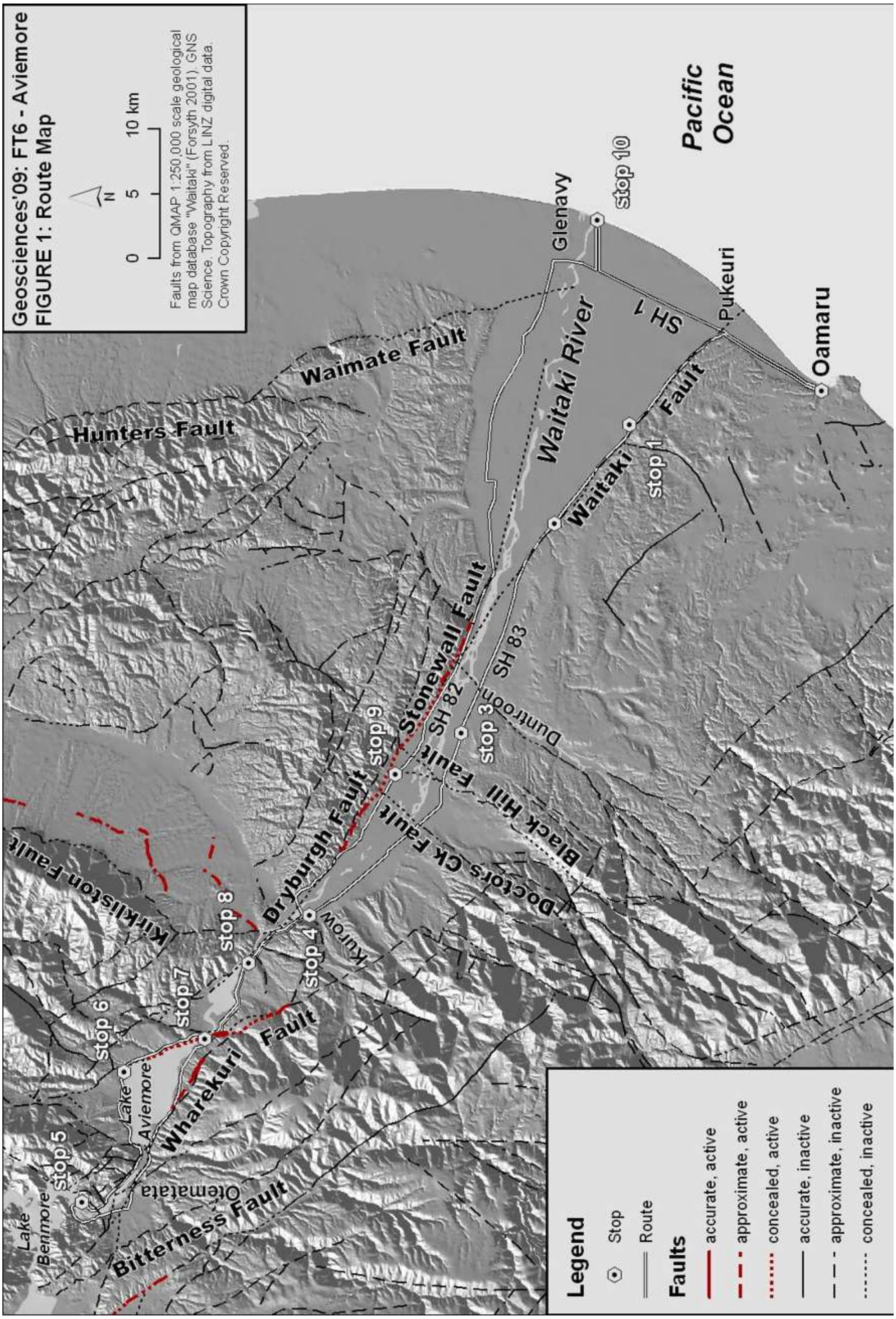

Figure 1: Route map, showing topography and faults

STOP 1: Peebles (44°57.90’S, 170°56.33’E)[1]

We are at the southwest margin of the Lower Waitaki Plain. The main surface (Morven surface) of the plain is underlain by Morven Formation, comprising fluvial aggradation gravel that coastwards forms a large fan that originally spread north to the Waihao River and south to Oamaru. The Morven Formation is younger than the abandoned sea cliff behind Oamaru, thought to be of Last Interglacial age (~125 ka)[2], and older than about 50 ka, based on luminescence dating of a loess sequence overlying Morven Formation gravel at Oamaru (Barrell & Read 1999).

The southwest margin of the Lower Waitaki Plain is the fault-line escarpment of the Waitaki Fault. This fault is downthrown to the northeast by at least several hundred metres, based on stratigraphy and gravity surveys. The fault does not appear to have deformed the Morven Surface.

Note the large fans that have built out over the Morven surface from the fault-line escarpment, mostly from catchments of negligible size. This geomorphic consideration reinforces the dating evidence from Oamaru that the Morven Surface, at least in places, is of substantial age. This has allowed time for sizeable fans to have been constructed from very small catchments.

> *Turn left onto Seven Mile Road, then right onto SH 83.Continue for about 9 km to Georgetown village, pull into parking bay at left (5 min drive).*

STOP 2: Georgetown (44°54.70’S, 170°50.70’E)

At Georgetown, the fault-line escarpment of the Waitaki Fault is expressed much more sharply than it is at Peebles. Its sharper expression reflects the presence of much harder schist basement rock on the upthrown side of the fault, compared to the weaker Tertiary sedimentary rocks on the upthrown side of the fault near Stop 1.

> *Continue northwest on SH 83. The road begins to step down into the incised valley of the Waitaki River. As we descend to lower, younger, terraces, note that the marginal fans are progressively smaller on younger terraces, reflecting lesser time available for fan-building. Approaching Duntroon, note the slump block topography along the Kokoamo Cliffs, where former river erosion undercut the Otekaike Limestone which here overlies much weaker Kokoamu Greensand. At Duntroon, we rise into a higher terrace remnant, possibly Morven equivalent. On this older terrace, note the return of subdued terrace edge form (similar to Stop 1), due to loess cover and presence of small fans built out from minor gullies. Pull into parking bay at Takiroa Rock Art site (15 min drive).*

STOP 3: Takiroa (44°50.57’S, 170°38.70’E)

The Takiroa rock art site sits beneath an overhang in a cliff formed in mid-Tertiary Otekaike Limestone. This location affords good views across the Waitaki valley

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[1] Co-ordinates are latitude/longitude in WGS84.

[2] 1 ka = 1,000 years before present; 1 Ma = 1,000,000 years before present.

landscape, including the Stonewall Fault/Dryburgh Fault uplifted blocks (Station Peak) to the north and the Wharekuri Fault block to the west (St Marys Range).

Continue north on SH 83. Note the large fans built out into the Waitaki valley by its large southwestern tributaries, the Otekaieke and Otiake rivers, and Kurow Creek. Comfort stop in Kurow township (15 min drive).

STOP 4: Kurow (44°44.00’S, 170°28.20’E)
Kurow lies at the mouth of what is sometimes called the Middle Waitaki valley, or Waitaki Gorge. Upstream of Kurow, the valley narrows and is gorged in a few places. Kurow sits on an extensive river terrace, correlated with the Aviemore alluvial terrace of the Mid-Waitaki. At Kurow, this terrace was probably abandoned by the Waitaki River at least 10,000 years ago, judging from luminescence dating of silty cover beds on the terrace. An age of this order is commensurate with the large size of fans built out across this terrace by the large tributary rivers south of Kurow.

There is something of a ‘spaghetti junction’ of faults converging at Kurow. The Dryburgh Fault strikes up the river valley and extends along the eastern side of the Lake Waitaki basin.

Continue north on SH 83 into the Mid-Waitaki valley along its western (true right) side. Pass Waitaki Dam and Aviemore Dam, both of which are stops on the return journey. Note the block fault-controlled landscape of uplifted ranges of basement rock, with downthrown basins in which Tertiary cover rocks are preserved.

In a classic paper, Marwick (1935) described the main geological and structural elements of the Mid-Waitaki valley, building on previous accounts by McKay (1882) and Uttley (1920). McKay had concluded that coal measures near Aviemore were of Miocene age, a point hotly disputed by Uttley (1920) as ‘untenable’ and also not accepted by Marwick (1935). Ironically, palynology has since shown that McKay was correct (Mutch 1963; Mildenhall & Pocknall 1989; Forsyth 2001). However, subsequent mapping indicates that coal measures (Eocene) also occur at the base of the Tertiary sequence in this area, so it turns out everyone was partly right.

Pass through Otematata, then turn right to Benmore Dam (30 min drive).

STOP 5: Benmore Dam (44°34.25’S, 170°11.95’E)
The carpark at the crest of the Benmore Dam spillway affords excellent views of the dam and surrounding landscape. Complexly deformed greywacke/argillite is exposed in adjacent road batters.

Dam construction started in 1958 and that power station was commissioned in 1965. At full capacity of 540 MW, Benmore Power Station is New Zealand’s second largest hydro-electric station after Manapouri. At the time the dam was constructed, it was the largest in the Southern Hemisphere. It impounds New Zealand’s largest artificial lake.

Benmore marks the ‘start’ of the ‘Cook Strait cable’, a high-voltage DC line conveyed directly to the North Island.

Continue southeast down Te Akatarawa Road, around the northern (true left) shore of Lake Aviemore. Extensive camping reserves are a popular summer holiday venue for people throughout the region. Aviemore occupies a tectonic depression bounded to the northeast by the Waitangi Fault and to the southwest by the Wharekuri Fault. Close to the Waitangi Fault is a thick succession of Miocene coal measures. Preferential erosion of the weak coal measures has produced the spectacular fault-line escarpment of the Waitangi Fault, with much harder greywacke and schistose greywacke standing proud on the eastern (relatively upthrown) side of the fault. Stop on the lake side of the road close to where the road meets the Waitangi fault-line escarpment (10 min drive).

STOP 6: Waitangi fault-line escarpment (44°36.21’S, 170°19.58’E)
In a low cliff along the lake shore are scruffy exposures of the coal-measure deposits. These may have been disturbed by deep-seated landslide movement. The fault itself is obscured by colluvium and is nowhere exposed in this area. In-situ greywacke is seen in batters farther along the road.

The purpose of this stop is to gain an appreciation of the rocks upon which Aviemore Dam is founded, and the general nature of the Waitangi Fault.

Continue southeast down Te Akatarawa Road to Aviemore Dam. Beware fallen ‘sump-breaker’ rocks on the road. Stop first on the true left (east) abutment for an overview. Then cross the dam and park near the switchyard (10 min drive).

STOP 7: Aviemore Dam (44°39.40’S, 170°21.20’E)
Although the first geotechnical investigations of the Aviemore dam site were carried out in the late 1920’s, preference was given to building a dam farther downstream at the Waitaki site. Construction of Aviemore Power Station began in 1963 and it was commissioned in 1968. At full capacity it generates 220 MW, and boasts the largest diameter (7 m) steel penstocks of any power station in New Zealand.

The design of the c. 50 m high dam reflects the contrasting foundation conditions on either side of the Waitangi Fault. The fault strikes upstream/downstream (NNW) and dips steeply to the west (true right). It juxtaposes Mesozoic greywacke on the east against Tertiary sediments on the west, implying normal faulting with down-to-the-west displacement. The 340 m long concrete dam is founded on hard, jointed, greywacke east of the fault. The adjoining 390 m long earthfill embankment to the west is founded on relatively soft Tertiary claystone, sandstone, coal, and a zone of sheared greywacke adjacent to the fault.

No evidence of late Quaternary movement was documented on the Waitangi Fault during construction. However, dam safety review investigations in the mid-1990s uncovered evidence of late Quaternary deformation on the fault, prompting a suite of detailed paleoseismological investigations. Between 1998 and 2001 sixteen trenches were excavated across geological faults within 6 km of the dam. The materials exposed in the trenches, the largest of which was 190 m long and up to 10 m deep, were logged in detail and more than 25 samples from the trenches were dated, primarily by luminescence techniques.

The Waitangi Fault shows clear evidence for at least two, possibly three, surface ruptures in the last 25,000, with the most recent surface rupture event between about 11,000 and 14,000 years ago. These most recent ruptures were located at, or up to 6 m west of, the bedrock fault contact. Measurement of offset deposits showed a reverse component of fault movement, and fault slip indicators, such as slickenside lineations, indicate an oblique sense of slip, with vertical displacement greater than right lateral (Barrell et al. 2005a,b).

Late Quaternary movements on the Waitangi Fault are best characterised as up-to-the-west, right-lateral reverse with a horizontal to vertical displacement ratio (H:V) between 1:4 and 1:1, on a fault plane dipping 70° to the west. An interesting finding is that the vertical sense of late Quaternary movement differs from the net late Tertiary offset, of downthrow to the west. The simplest explanation is that an earlier history of normal faulting has given way to a new regime of reverse faulting.

Trench exposures provided constraints on the sizes of single-event displacements. Field data show that the last two fault movements had different vertical offsets (~0.5 and ~1.5 m). An expert panel reviewed the data and agreed on low, medium and high median estimates of vertical single-event separation (0.8, 1.2 and 1.6m respectively) each with agreed coefficients of variation. Weightings, which reflect the assessed likelihood the values would be representative of the next surface rupture of the fault, were heavier for the medium and high values. For the recurrence interval the medium estimate of 12,000 years was assigned the greatest weighting (Barrell et al. 2006).

The Safety Evaluation Earthquake (SEE) for Aviemore Dam has been evaluated as an M_w7.0 event on the Waitangi Fault, associated with a vertical fault displacement of 1.2 m at the dam. The responses of the dam and appurtenant structures to earthquake shaking (peak ground acceleration of 1.07g), permanent displacement (1.2 m vertical: 0.4 m horizontal) and reservoir seiche waves following a fault rupture were analysed (Mejia et al. 2005a,b), with reference to a guiding criterion that the dam is required to withstand the SEE without catastrophic failure.

The safety assessment included a detailed investigation and review of the internal structure of the zoned embankment fill. Analyses showed that even though the embankment was not designed for a fault rupture, its core and filter structure is sufficient to accommodate a Waitangi Fault surface rupture without catastrophic failure. Engineering analyses also showed that the spillway and sluice gates would not fail catastrophically as a result of the associated earthquake ground motions, although the sluice gates were strengthened as a precaution against deformation or leakage (Walker et al. 2004). Most of the water mass of Lake Aviemore lies on the upthrow side of the fault, so a major consequence of fault rupture will be upward displacement of the lake bed and most of its water (Webby et al. 2007). The main remedial measure was construction of a low protection wall along the lake side of that part of the crest of the earth embankment dam that lies on the downthrown side of the fault (i.e. for up to 30 m west of the concrete gravity dam section). This wall, whose appearance is one of breath-taking simplicity, is designed to direct water flow over the concrete dam, rather than over the earth dam, mitigating the possibility of catastrophic erosive scour of the earthfill materials. As Aviemore Power Station is operated remotely from Twizel, the occurrence of a surface-rupture earthquake on the Waitangi Fault may be difficult to recognise immediately. To overcome this, an underground ‘trip-wire’ has been constructed across the fault, and if it breaks, an alert is transmitted.

A potential concern following a surface-rupture event on the Waitangi Fault is increased seepage through the embankment, possibly leading to the development of piping (erosive scour). An underground water monitoring system has been established, following baseline studies, to identify seepage changes that may indicate foundation piping following earthquake movement on the Waitangi Fault. High-precision measurement of water temperature is the main monitoring indicator, supported by discrete water chemistry and isotopic analyses (Amos et al. 2007).

Finish with a circuit back over the dam and back again, before rejoining SH 83, turn left and return down-valley towards Kurow. Pull in at Waitaki Dam lookout parking bay (5 min drive).

STOP 8: Waitaki Dam (44°41.44’S, 170°25.47’E)
Waitaki Dam was constructed between 1929 and 1934, and was notable for being built without diverting the natural river flow. Constructed in two parts, a cofferdam (temporary dam used to exclude water during construction) diverted water to the Otago (south) side of the river, while the Canterbury (north) side of the dam was built. Eleven sluice gates built into the Canterbury dam carried the river flow while the Otago side of the dam was built. It was also the last major dam in New Zealand to be built primarily using manual labour (picks, shovels and wheelbarrows). A thorough historical account of Waitaki Dam by Natusch (1984) is recommended reading.

Continue back to Kurow (5min drive; Comfort stop). Turn onto SH 82, cross the Waitaki bridge and proceed down the left (northeastern) side of the Waitaki valley for about 10 min, then pull onto the verge at the end of the long straight (9 km from Kurow).

STOP 9: Station Peak (44°47.74’S, 170°36.11’E)
This location affords good views of the major fault-line escarpments. To the west is St Marys Range, a large block of basement rock thrown up on the western side of the Wharekuri Fault. The highest peaks are 1900 to 2000 m, attesting to km-scale late Cenozoic vertical displacement. To the south, on the far side of the valley, is the prominent escarpment of Black Hill Fault, which strikes NE-SW and is upthrown to the southeast. Beside the highway, to the northeast, the low river terraces meet the foot of the hill at the eroded escarpment of the Stonewall Fault. Just beyond is the Dryburgh fault-line escarpment, at the base of the steep range-front. Evidence for late Quaternary surface rupture on the Stonewall Fault is preserved at a site about 4 km up-valley from here, where an alluvial fan has been displaced. Investigations there showed the

Stonewall Fault to be a steeply-dipping reverse fault. Its most recent rupture had a vertical component of between 0.9 and 2.2 m, and luminescence dating showed that this occurred sometime between about 46 ka and 15 ka.

Terraced fans along the margin of the valley indicate that the Waitaki River has episodically re-occupied this part of the valley floor. Periods of river activity have eroded the toes of the fans, while fan-building has occurred at times when the active river channels were elsewhere on the valley floor. Several episodes of trimming/rebuilding are preserved in the fan landforms in this area. The relatively small sizes of fans currently building on this terrace suggest that the river abandoned this terrace quite recently, perhaps within the last 1,000 years or so.

Continue down-valley on SH 82. After about 5 minutes, the road begins to step up onto progressively higher, therefore older, river terraces. Note the somewhat larger sizes of alluvial fans on the older terraces. The road then hugs the Stonewall fault-line escarpment, before climbing on the extensive Lower Waitaki Plain (Morven surface). Continue down SH 83, cross the Elephant Hill Stream bridge, then turn right into Ikawai Middle Road towards Glenavy. After rejoining Tawai-Ikawai Road, turn right down Glenavy-Tawai Road and proceed to Glenavy. Turn right onto SH 1 and cross the Waitaki River bridge. About 1 km south of the bridge, turn left onto Kaik Road, and proceed to the to the Waitaki river mouth. Go through the gate at the Waitaki huts, and continue down to the end of the road at the gravel barrier ridge (about 45 min drive).

STOP 10: Waitaki River mouth (south bank) (44°56.75'S, 171°08.50'E)
The river terrace is at about river level, and the true height of the beach gravel bar (6 to 8 m above sea level) can be appreciated. This gravel beach extends the full length of the coast from Oamaru, and apart from the occasional breaks at river mouth channels, and the headlands and port breakwaters of Timaru, extends all the way north to Banks Peninsula, a total distance of about 220 km. The gravel beach is built by long-shore drift of gravel that has been eroded out of the cliffed Lower Waitaki Plain, with some input from rivers and streams.

At this stop, the gravel ridge is of composite age. The landward part of the ridge is several decades old, and is a notably darker colour due to growth of lichens on the stones. The young and active ridges seaward are a fresh light grey. Note the presence of a number of slightly weathered brown-weathered clasts, reworked from the at-least 50 ka deposits of the Morven Formation, exposed in the eroding sea cliffs farther southwest.

Return to SH 1, turn left and travel to Oamaru (20 min drive).

2. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

2.1 Regional Setting

The Waitaki valley lies in a region where Mesozoic basement rock of greywacke and schist is overlain by Tertiary sedimentary cover rocks, including coal measures, marine sandstones, mudstones and limestone, and alluvial conglomerates (Figures 1 & 2; Tables 1 & 2). In the Late Tertiary and Quaternary[3], the basement and cover bedrock was affected by tectonic movements associated with evolution of the plate boundary through New Zealand. In the Waitaki area, movement of large fault-controlled blocks resulted in uplift, tilting and folding and offset of basement and cover rocks. Much of the cover rock sequence was eroded off the uplifted blocks, exposing the basement rock while in the downthrown basins, cover rocks remain preserved to varying extents. As the landscape evolved, the Waitaki River and its main tributaries deposited veneers of Quaternary alluvial gravel that form high-level terraces on valley flanks, with lower terraces and modern floodplains near the valley axes. Tributary streams have built fans of alluvial sediment out into the valleys. In many cases the terrace and fan alluvium, along with superficial deposits of colluvium and loess, obscure the bedrock geology and faults.

Geological maps presented here are based on the GNS 1:250 000 scale QMAP (Quarter million scale map) digital database (Forsyth 2001), with some minor amendments. More detailed information comes from Gage (1957) and reports targeted at hydro-electric development (e.g. Macfarlane 1988).

The Waitaki area lies within a region of New Zealand that has low to very low rates of historical earthquake occurrence and contemporary strain (e.g. Beavan and Haines 2001; Stirling et al 2002). This is compatible with only a few of the faults in the area having clear evidence for displacement of relatively young (i.e. Late Quaternary) deposits or landforms.

2.2 Waitaki geological timeline

The geological evolution of the Waitaki valley area comprised the following main components, listed from oldest to youngest.

- Formation of the greywacke & schist basement rocks during the Permian to Jurassic periods (between 300 and 145 million years ago (Ma)), when New Zealand was still part of the Gondwanaland supercontinent.

- Formation of a nearly flat erosion surface (‘peneplain’) across the basement rocks during the Late Cretaceous (< 100 Ma), and in the west extending into the Tertiary Period (<65 Ma), after NZ had split from Gondwanaland due to opening of Tasman Sea and Antarctic Ocean.

[3] The Tertiary Period spanned from 65 Ma through to 1.8 Ma, succeeded by the Quaternary Period (1.8 to 0 Ma). In 2009, the base of the Quaternary was redefined at 2.6 Ma; it comprises two epochs, the Pleistocene (2.6 Ma to 11.7 ka), and the Holocene (11.7 to 0 ka). Late Quaternary is generally taken as the period from 125 ka to 0 ka. Late Pleistocene is generally taken as 125 ka to 11.7 ka.

- Deposition of a sedimentary sequence, many hundreds of metres thick, including quartz sandstones, mudstones and limestones, resulting from subsidence and submergence of the peneplain beneath the sea, during the Tertiary Period. The Aviemore area marks the westernmost known extent of Tertiary marine deposits in the Waitaki valley.

- Onset of compression across the NZ region in the Late Tertiary (<24 Ma), with the commencement of uplift, emergence from the sea, mountain-building, erosion and widespread deposition of greywacke gravels derived from the main areas of uplift.

- Progressive elevation of the fault block ranges, relative to downthrown basins, by faulting and folding. Development of drainage systems was accompanied by erosion and dissection of higher parts of the landscape, while alluvial sediments accumulated and buried lower-lying areas. The main elements of the present landscape were approaching their present form by the middle of the Quaternary Period (1 Ma).

- Landscape evolution from the mid-Quaternary to the present day has been influenced by cycles of warm (interglacial) to cold (glacial) climates, with associated cyclic variation in rates of sedimentation and erosion (e.g. Alloway et al. 2007). Particularly during glacial phases, accelerated erosion in catchments led to widespread deposition of gravelly sediments forming alluvial fans and river plains in the lowlands. During interglacial phases (such as the present day), erosion lessened and most rivers and streams cut incised valleys into their glacial-phase fan and terrace surfaces. Wind-blown silt (loess) is widespread on abandoned fan and river terrace surfaces.

- Throughout these climate cycles, occasional large earthquakes on the active faults have ruptured or deformed the ground surface, progressively offsetting or buckling stream deposits and landforms. Along the active faults, older, higher, terrace landforms typically have larger offsets (scarps) than lower, younger, terrace landforms.

2.3 The fault block landscape

Most of the major faults of the region have, during the late Tertiary-Quaternary, undergone movements totalling many hundreds of metres and in some cases up to around two thousand metres. The upthrown sides of these faults (‘fault blocks’) form prominent features in the landscape (fault-line escarpments) due to the juxtaposition of rocks of differing types and contrasting susceptibilities to erosion. Relatively young river and stream deposits and their associated terrace and fan landforms obscure the surface traces of these faults to a considerable extent, creating uncertainty as to their exact locations.

The main elements of the Waitaki landscape may be regarded as of tectonic origin, although greatly moulded and enhanced by erosion and other landscape processes.

Table 1: Lower Waitaki Valley - geological units

Regional geological units (after Forsyth 2001)	Lower Waitaki geological units (Macfarlane 1988)	Geological description
River alluvial deposits & fan alluvium. Subdivided as: Holocene Late Pleistocene Mid- to Early Pleistocene	 Recent (r) Aviemore (av), Waikaura (ik) Morven (mv) Duntroon (dt), Georgetown (gt) and Smillie (sm)	Greywacke and/or schist gravel, sand and silt associated with terrace and fan landforms Relatively young deposits (r, av, ik and mv) are generally unweathered and lie at low to mid levels in river and stream valleys Older deposits (gt, gt and sm) are moderately to highly weathered and occur as isolated fan or terrace remnants high on valley sides or as a capping on ridges
Late Tertiary to Early Pleistocene non-marine sediments	Kowai Formation and Elephant Hill Gravel (Kurow Gravel equivalents – see Table 2)	Typically brown, weathered greywacke or schist conglomerate, sand and clay, generally well compacted. In places with quartzose white or brown sand, silt or clay near the base of the deposit
Late Tertiary marine sediments	Rifle Butts Formation	Greyish sandstone and siltstone, in places with fossil shells
Mid-Tertiary limestone and greensand	Otekaike Limestone	Light brownish white sandy or silty limestone
	Kokoamu Greensand	Highly glauconitic greensand containing fossil shells
Early Tertiary marine sediments	Earthquakes Marl	Brownish fine sandy siltstone, highly calcareous and with large green glauconite grains
	Tapui Sandstone	Brownish gritty sand and calcareous silty sandstone with disseminated fine glauconite and tabular concretions
Early Tertiary non-marine sediments	Papakaio Formation	Quartz gravel, sand, clay and lignite, with zones of very hard silica-cemented sandstone or conglomerate
Greywacke, schistose greywacke and semischist	Torlesse Composite Terrane	Greywacke: hard, fractured sandstones and weaker fissile mudstones. Schistose greywacke: sandstone and mudstones with incipient non-planar metamorphic layering. Semischist: thinly parallel-layered schist

Note: Otekaike Limestone and Kokoamu Greensand were originally named before the official name of the place names were changed to Otekaieke and Kokoamo. According to standard geological practice, the original spelling of the name is retained for the geological unit.

Table 2: Middle Waitaki Valley - geological units

Regional geological units (after Forsyth 2001)	Mid-Waitaki geological units	General geological description
River alluvial deposits & fan alluvium. Subdivided as:		Greywacke and/or schist gravel, sand and silt associated with terrace and fan landforms
Holocene	Very young river alluvial deposits (vya) and very young fan alluvium (vyf)	Relatively young deposits (vya, vyf, av, yf, and mf) are unweathered to slightly weathered and occur at low to mid levels in river and stream valleys
Late Pleistocene	Aviemore river alluvial deposits (av), young fan alluvium (yf) Medium-age fan alluvium (mf)	
Mid- to Early Pleistocene	Hydro Village (hv), Akatarawa (ak), Homestead (hm) and Deep Creek (dc) river alluvial deposits; old (of), very old (vof) and extremely old (eof) fan alluvium	These older deposits are generally moderately or highly weathered and occur as isolated fan or terrace remnants high on valley sides or as a capping on ridges
Late Tertiary to Early Pleistocene non-marine sediments	Kurow Gravel	Typically brown weathered greywacke or schist conglomerate, with sand or clay
Late Tertiary coal measures	White Rock Coal Measures	Typically greyish white quartz sand, silt or clay, locally with quartz conglomerate
Late Tertiary marine sandstone & mudstone	Southburn Sand	Greyish sandstone & siltstone, in places with fossil shells (incl. Rifle Butts Formation)
Mid-Tertiary limestone and greensand	Otekaike Limestone Only known southeast of Wharekuri Creek.	Light brownish white sandy or silty limestone
	Wharekuri Greensand	Highly glauconitic, greenish grey weathering to brown, quartz sand containing fossil shells
Early Tertiary marine sandstone & mudstone	Earthquakes Marl	Brownish fine sandy siltstone, highly calcareous, scattered large glauconite grains
	Tapui Sandstone	Brownish gritty sand and calcareous silty sandstone with disseminated fine glauconite and tabular concretions
Early Tertiary coal measures	Lower Coal Measures	Quartz gravel, sand, clay and lignite
Mesozoic greywacke, schistose greywacke and schist	Torlesse Composite Terrane	Greywacke: hard, fractured sandstones and weaker fissile mudstones. Schistose greywacke: sandstone and mudstones with incipient non-planar metamorphic layering. Schist: layered fissile metamorphic rock

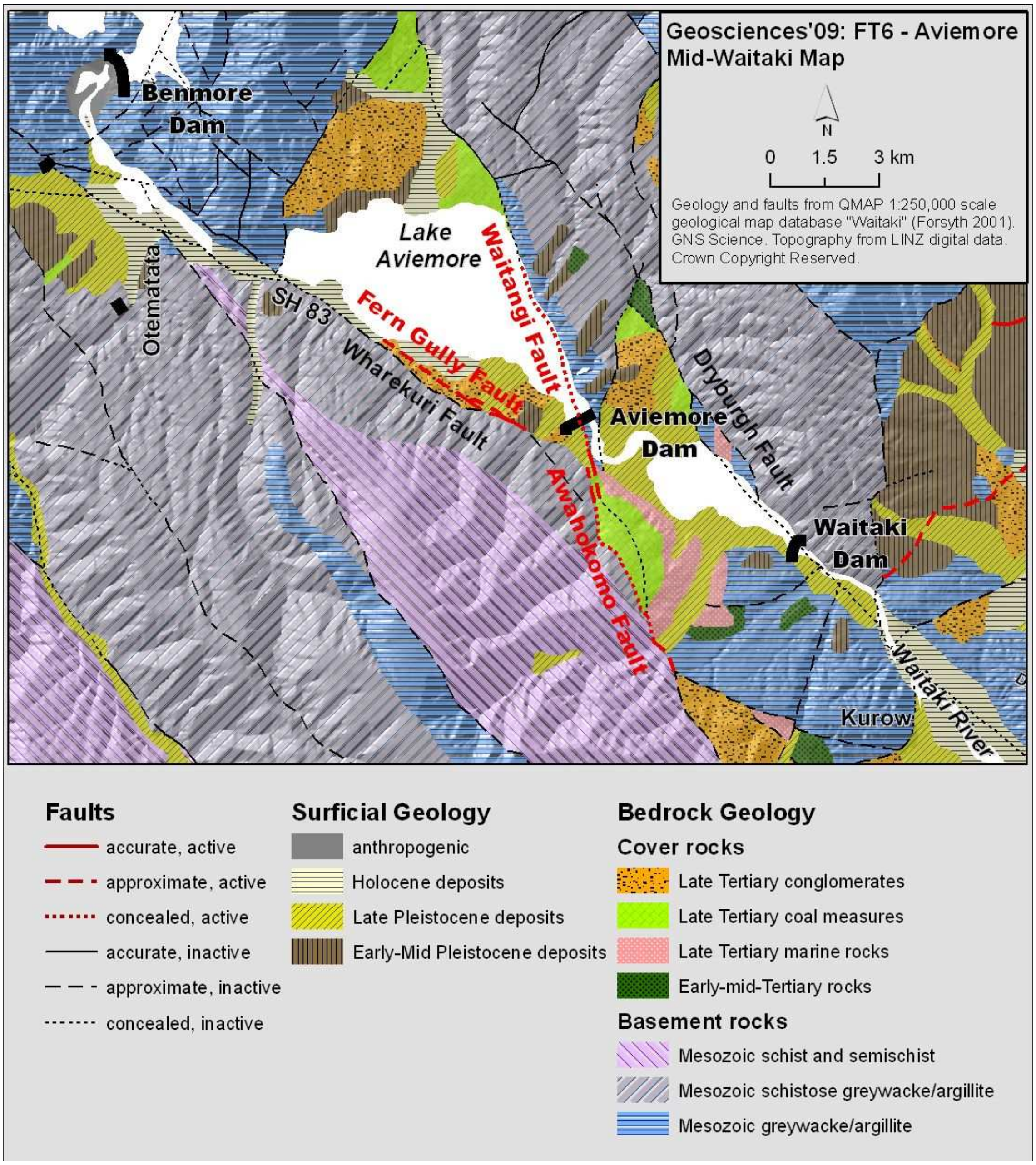


Figure 2: Geology of mid-Waitaki valley, from Forsyth (2001).

3. HYDROLOGY AND ENGINEERING

The Waitaki is the South Island's fourth largest river, reaching the Pacific Ocean with a mean discharge of ~360 m^3/s. The Waitaki River is formed at the confluence of its three main tributaries, the Ohau, Pukaki and Tekapo rivers, draining a 100 km length of the highest part of the Southern Alps. Drainage from the lakes exits the Mackenzie Basin through the Benmore Gorge, now occupied by Lake Benmore, which marks the start of the middle Waitaki valley.

The Waitaki catchment is extensively utilised for hydro-electric power generation with three dams, Benmore, Aviemore and Waitaki, on the Waitaki River, in addition to the canals and power stations of the Mackenzie Basin. The natural glacial lakes Pukaki and Tekapo have been dammed and raised, and are controlled to provide seasonal water storage for power generation. The power stations of the Waitaki Power Scheme represent about 20% of the electricity generation capacity in New Zealand (Table 3).

Table 3: Electricity generating capacity (megawatts - MW) of the Waitaki Hydro-electric System power stations (Meridian Energy brochure).

Power Station	Generating Capacity (MW)
Tekapo A	25.5
Tekapo B	160
Ohau A	264
Ohau B	212
Ohau C	212
Benmore	540
Aviemore	220
Waitaki	105
TOTAL	**1738.5**

In the middle Waitaki Valley, the Waitaki and Aviemore dams are constructed across major faults (Dryburgh and Waitangi respectively) associated with fault-angle depressions, while major faults are not known in the Benmore Gorge where the Benmore Dam is located. The following section describes Aviemore Dam and in-depth dam safety reviews related to its location on the Waitangi Fault.

4. AVIEMORE DAM

4.1 Setting, design and construction

Aviemore Power Station, owned and operated by Meridian Energy Ltd (Meridian), was constructed between 1963 and 1967. It has a four unit powerhouse, a 3,400 cubic metres per second capacity spillway, and the impounded Lake Aviemore has a surface area of 29 km^2. The dam is a composite structure with a 340 m long, 56 m high, concrete dam adjoined to a 390 m long, 48 m high, earthfill embankment (Figure 3).

The dam straddles the Waitangi Fault, and its design reflected the differing foundation conditions on either side of the north-south (upstream-downstream) trending fault. The concrete gravity dam across the former channel of the Waitaki River is founded on unweathered to slightly weathered, 'hard', closely jointed, Mesozoic-age, interbedded sandstones and mudstones (greywacke). The earthfill embankment on the western side of the valley ('true' right, i.e. looking downstream) has a core mainly founded on lower quality, 'soft', unweathered, Tertiary claystones, sandstones and coal, with shoulders largely founded on coarse-grained alluvial deposits. The Waitangi Fault crosses the embankment foundations approximately 30 m from the west (true right) end of the concrete dam so that greywacke, including some sheared mudstone, is also present in part of the embankment foundations.

Reflecting engineering standards and practice of the time, the concrete dam included an upstream grout curtain and drainage relief holes, while the earthfill embankment with an upstream sloping clay core included a sand filter and drainage layer between the core and downstream shoulder. In addition to abutting against the concrete dam, the embankment also wraps around it for some distance.

During construction the Waitangi Fault was mapped as a sharp contact associated with a narrow (<50 mm) fault gouge and a zone up to 5 m wide on its western side primarily composed of tectonically-mixed Tertiary materials. The fault plane had a very steep to subvertical dip to the west implying a normal fault juxtaposition of greywacke and Tertiary bedrock materials. No evidence of recent (estimated last 20,000 years) fault movement was documented, and no specific allowance for fault movement was included in the dam design (Barrell et al. 2006).

Figure 3: Aerial view NW across Aviemore Power Station. The powerhouse lies in front of the concrete gravity dam, with the grass-covered embankment dam to the left. Downstream of the dam are remnants of the 'Aviemore' alluvial terrace, with terraced alluvial fans to the far left. Note the approximate position of the Waitangi Fault (red line) and the large 'Pinetrees' (T01/1) fault investigation trench (white arrows). Photo: D.L. Homer, GNS Science.

4.2 Dam safety evaluations

Under New Zealand Society on Large Dams (NZSOLD) dam safety guidelines (NZSOLD 2000), Aviemore Dam has a high potential impact category (PIC) in terms of failure consequences. Key elements in the dam safety assurance programme operated by Meridian, in particular for high PIC dams, include the identification of potential deficiencies, their evaluation and where judged necessary, their remediation (Walker et al., 2004).

A review of the geology and active faulting within a 100 km radius of hydro-generation facilities in the Waitaki valley was initiated in 1998 by the then owners, Electricity Corporation of New Zealand, and continued by Meridian, owner of the Waitaki hydro-system since April 1999. At Aviemore, the mid-1990s recognition of late Quaternary (last 125,000 years) movement on the Waitangi Fault highlighted a need for more specific seismic performance evaluation parameters (Walker et al., 2004).

A staged suite of detailed paleoseismology investigations was undertaken on geological faults in the immediate vicinity of Aviemore, in particular the Waitangi Fault (Figures 2 & 3). GNS Science (GNS) was primarily responsible for the field studies (Barrell et al. 2005a, 2005b, 2006), with the dam safety assessment under seismic loads undertaken by URS Corporation with advice on seismological and faulting inputs from GNS (Mejia et al., 2005a,b). An international Independent Review Board was also engaged by Meridian (Walker et al., 2004).

4.3 Late Quaternary fault displacement characterisation

Scope of investigations

Field investigations, comprising surface geological mapping, fault trenching and age dating, took place in four stages between November 1998 and February 2001, with the results from one stage defining the work programme for the next. Surface geological and geomorphic mapping, with particular emphasis on late Quaternary deposits and the identification of landforms related to faulting, was a larger component of the first two stages in 1998 and 1999. Twelve trenches (T98/1-2 & T99/1 – T99/10) were excavated within 6 km of Aviemore, and found for the first time, or redefined, evidence of late Quaternary movements on the Fern Gully, Waitangi and Awahokomo Faults (Figure 2).

The later two stages specifically targeted the Waitangi Fault, because of the late Quaternary activity conclusively demonstrated in the earlier investigation stages, and the importance of the fault relative to Aviemore Dam. The four trenches excavated in 2000 and 2001 (T00/1-T00/3 and T01/1) were located within 1 km of the dam (Figure 4), and were significantly larger than those in the earlier stages. Trench T01/1, located about 300 m downstream of the dam, was 190 m long and up to 10 m deep, with an orientation subparallel to the embankment dam (Figures 3 & 4).

Investigation methods

Trenching across faults was the primary paleoseismological investigation method. During and immediately after excavation of a trench, the trench walls were inspected and cleaned down. Detailed logging of the walls (typically at 1:20 scale) was undertaken by pairs of specialist earthquake geologists to document the nature and distribution of the late Quaternary deposits exposed. Particular attention was paid to the locations of the most recent fault displacements, including the amount and sense of slip and terminations where faulted deposits were overlain by unfaulted deposits. Trench walls were also examined by specialist soil scientists to assess the nature and degree of soil profile development in the deposits. On-site peer review was undertaken at the completion of logging, after which the collection of age control dating samples was completed. Trench walls were systematically photographed and, in the case of the later trenches, a guided tour of key geological features in the trench walls was videotaped.

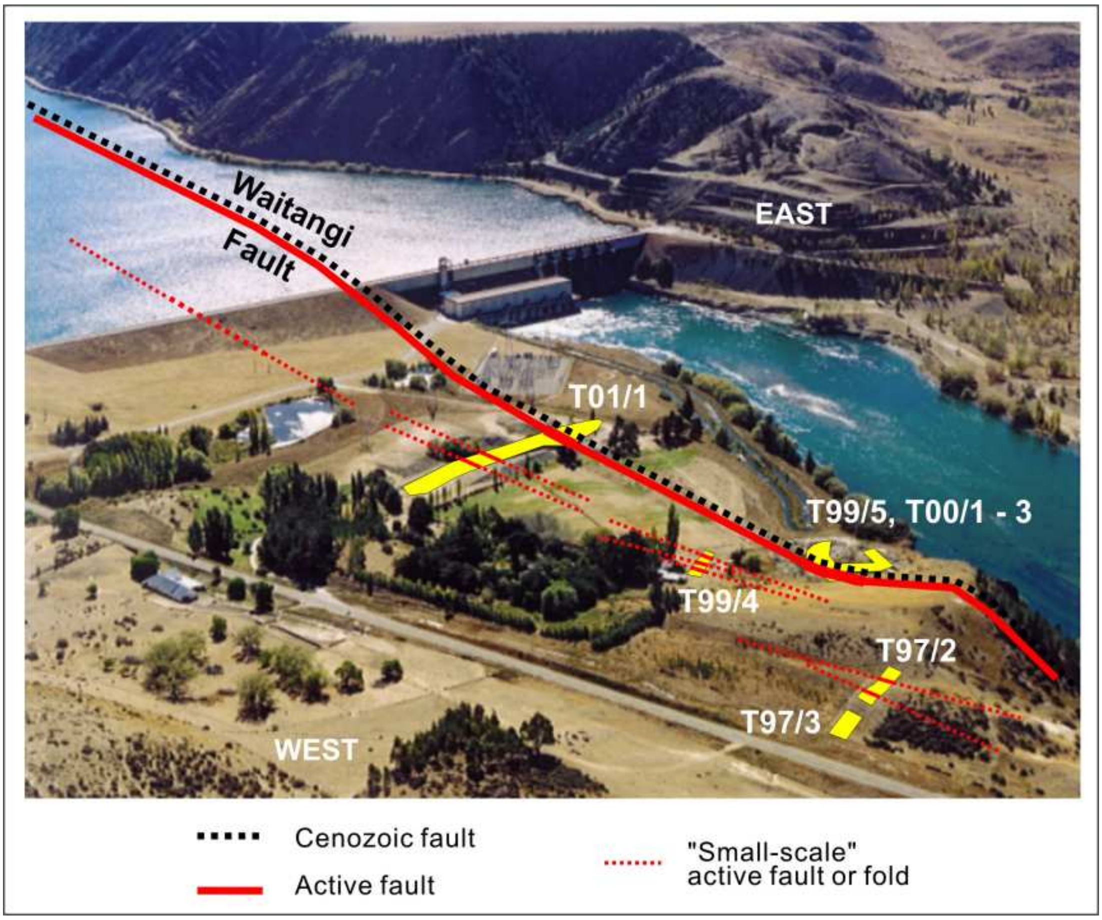


Figure 4: Trenches within 1 km of Aviemore Dam and location of Waitangi Fault.

Geological setting

The late Quaternary geology of the Waitaki valley is dominated by a sequence of alluvial terraces formed by the Waitaki River and fans deposited by local streams (Figures 2 & 3). At Aviemore the Waitangi Fault underlies an extensive alluvial terrace. Terrace stratigraphy comprises a river-eroded surface cut across the greywacke and Tertiary bedrock (bedrock strath) covered by several metres of coarse-grained alluvial gravels with rounded greywacke clasts (Aviemore alluvial deposits). The rounded gravels are overlain by finer-grained materials, with predominantly subangular gravel clasts and silt horizons, deposited by valley side streams (fan alluvium). Colluvium and windblown loess are also locally preserved, particularly adjacent to terrace risers.

The geomorphic expression of the most recent movements on the Waitangi Fault is, at best, subtle, with surface-rupture scarps largely mantled by younger deposits or removed by erosion. Late Quaternary faulting was not recognised definitively from the landforms prior to the trenching, though could be seen retrospectively. In addition the area downstream of the dam had been modified during dam construction in the 1960s, particularly with the spreading of spoil from excavations and subsequent landscaping.

Overview of trenching results

Offset of the bedrock strath and the overlying materials provides the primary evidence for the most recent surface ruptures on the Waitangi Fault. The trench in 1999 (T99/5 – 700 m downstream of the dam, Figure 4) conclusively showed offset of the bedrock strath, but the nature of the late Quaternary deformation was ambiguous. A network of three interconnected trenches was excavated around the T99/5 locality in 2000 (T00/1 – T00/3). This interconnected excavation clarified the positions and nature of the late Quaternary deformation, and allowed the sizes and timing of single-event displacements to be quantified (Figures 5 to 7). The large 2001 trench (T01/1 – Figures 8 to 11) further confirmed the position and nature of late Quaternary deformation, and provided additional opportunities for measuring and dating fault displacements.

Important late Quaternary deformation features observed on the Waitangi Fault include:

- the bedrock strath under Aviemore alluvial deposits has a vertical component of offset of up to 3 m;
- two, possibly three, recent surface rupture events are recognized;
- the ruptures are on fault planes that dip steeply to the west at ≥70º;
- the west side of the fault is upthrown (i.e. the fault now has a reverse component of displacement). This is in contrast to the juxtaposition of bedrock units for which the east side is upthrown;
- the fault plane of the most recent movements may be at the bedrock fault (e.g. T00/2) or up to 6 m west of it within the Tertiary bedrock materials (e.g. T00/3 and T01/1);
- tectonic warping (folding) within a few metres of the fault plane has occurred in association with fault rupture movement, particularly on the upthrown side. Displacements are sharper at the bedrock strath and diffuse upwards into a broader deformation zone in overlying alluvial gravel deposits.

In addition to the deformation at the Waitangi Fault, a number of late Quaternary 'small-scale' (<0.6 m) fault or fold features were noted for at least 150 m west of the fault (Figure 4).

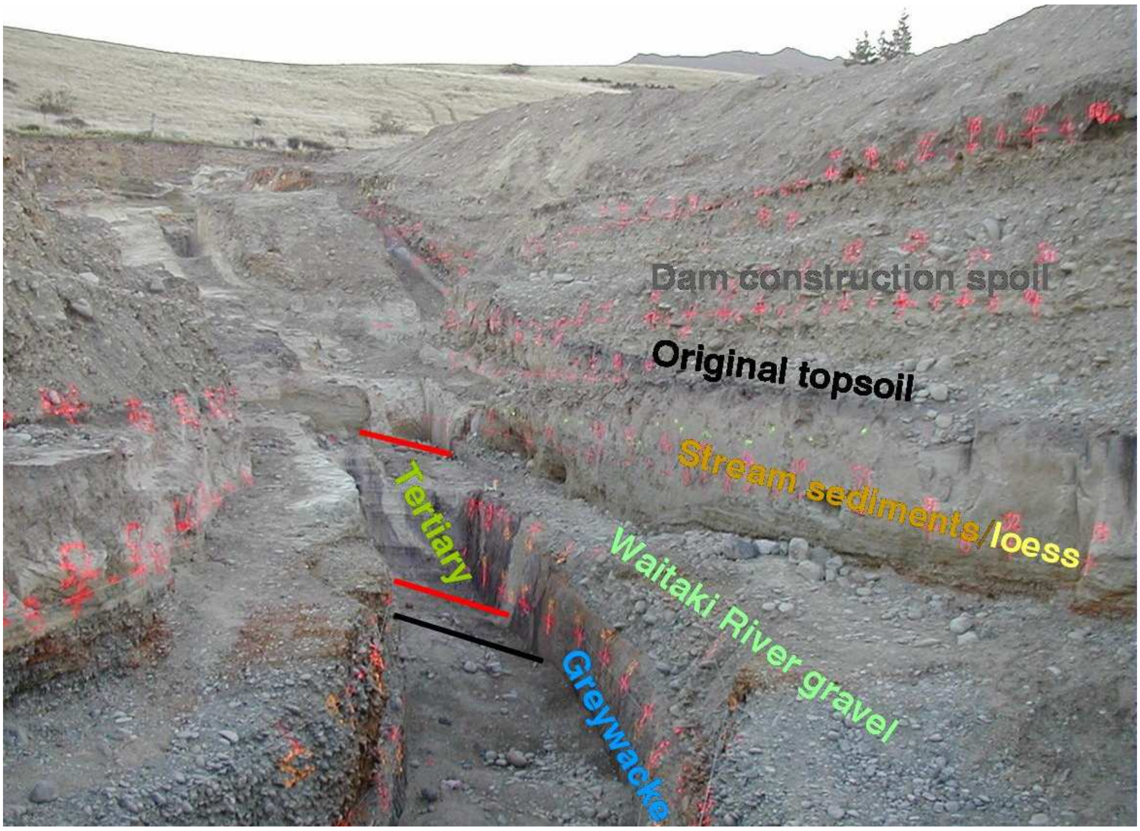


Figure 5: Exposures in trench T00/3, looking south. **Upper**: Beyond the Waitangi bedrock fault (black line) are two late Quaternary faults, Fault 1 (nearer red line) and Fault 2 (far red line). **Lower**: Close-up of the bedrock fault (black line, right) and Fault 1 (red line, left), which has a vertical separation of 0.5 m, defined by Tertiary clay up to the left against Aviemore alluvial deposits.

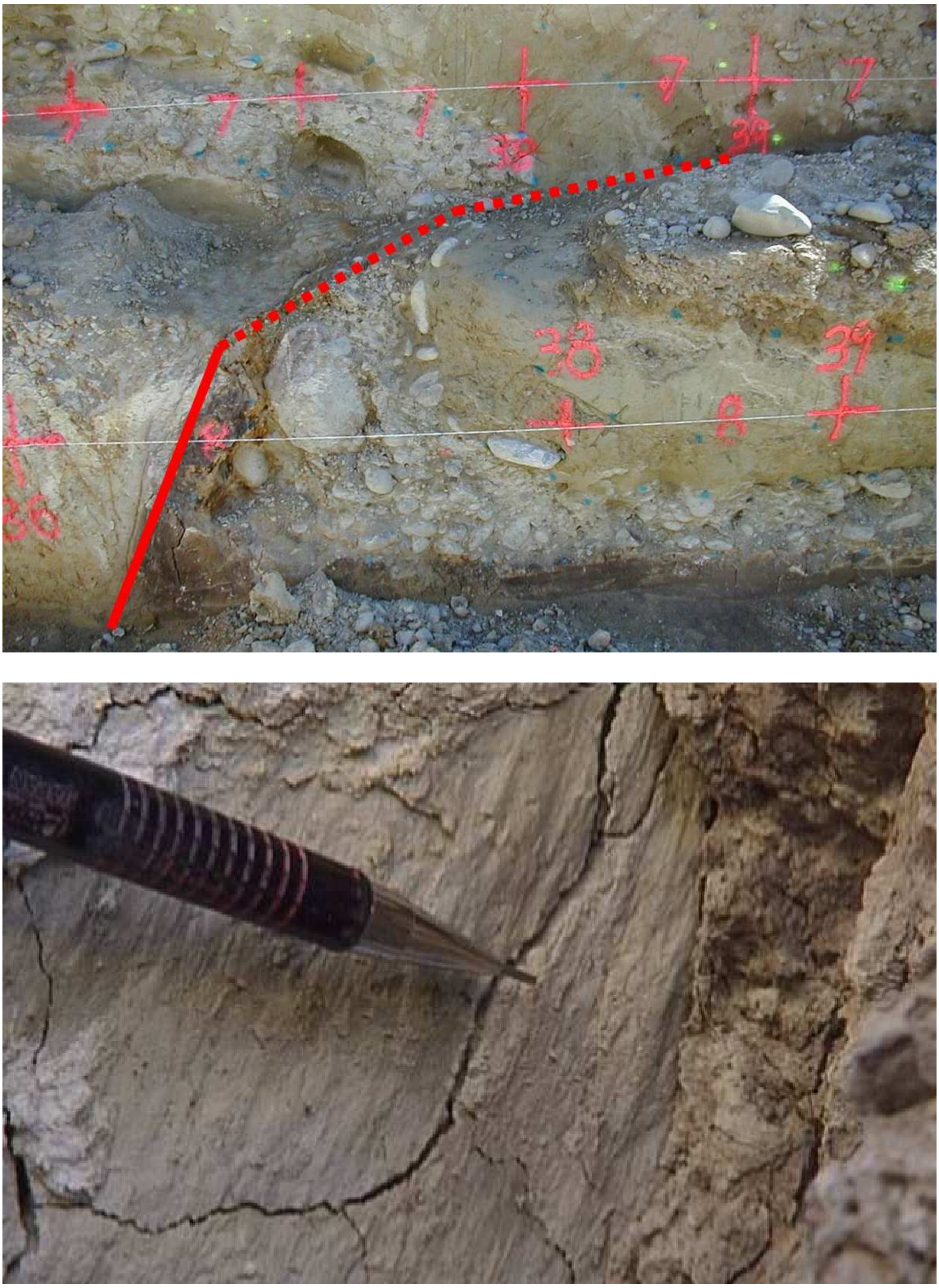


Figure 6: Detail of exposures in trench T00/3. **Upper**: Close-up of Fault 2, with at-fault vertical separation of at least 1.0 m. The fault displacement extends higher into the stratigraphic sequence than does Fault 1, and thus represents a separate, younger, rupture event. **Lower**: The pencil is perpendicular to steeply-pitching slickenside lineations on Fault 2. The lineations indicate oblique reverse-right lateral slip.

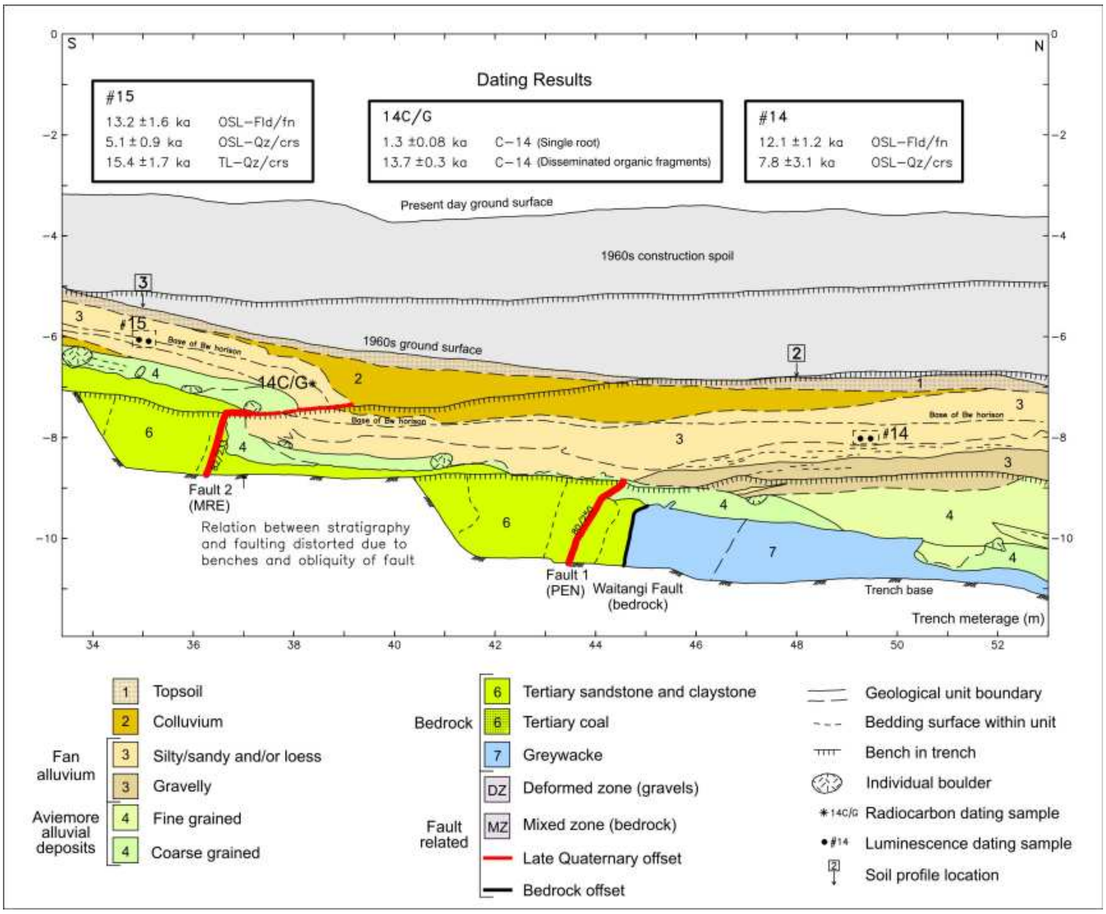


Figure 7: Part of the geological log of the west wall of trench T00/3. PEN = penultimate rupture, MRE = most recent rupture event.

Figure 8: The benched, up to 10 m deep, trench T01/1 ('Pinetrees') excavation, looking southwest. The black material is coal on the upthrown (SW) side of the Waitangi Fault.

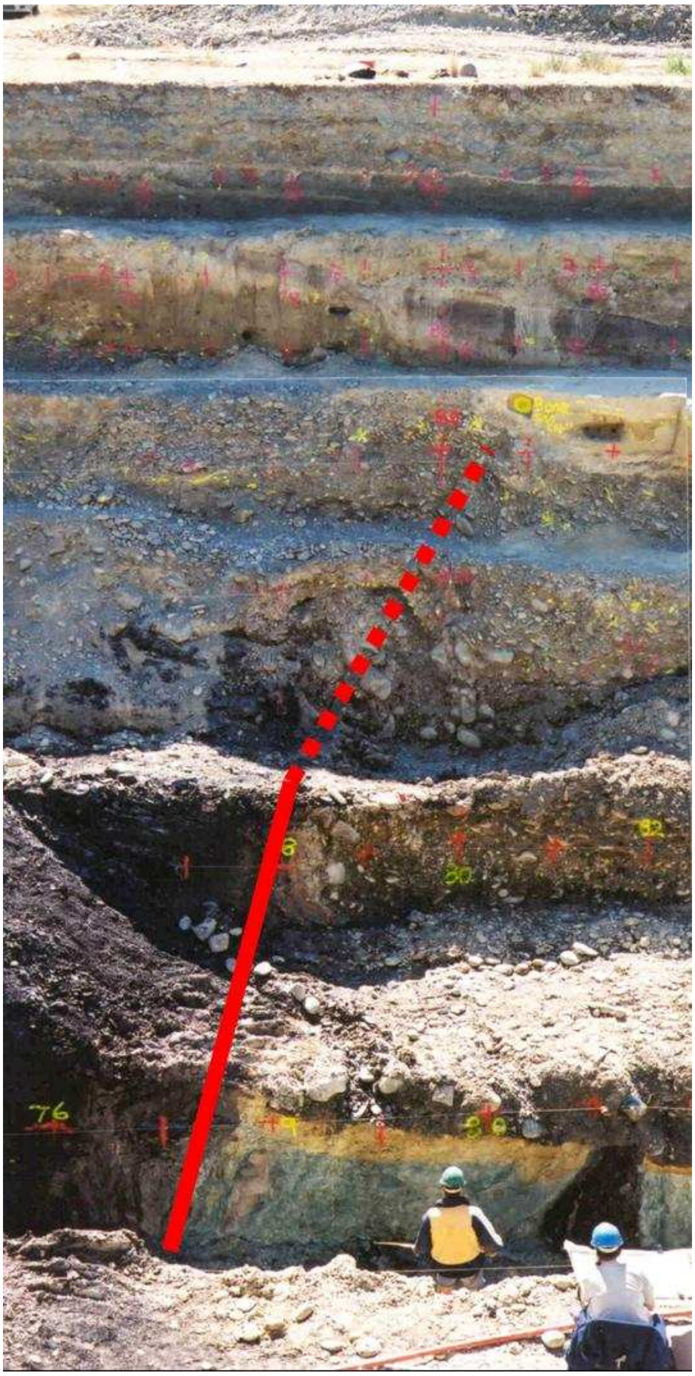


Figure 9: Trench T01/1, looking northwest across the deepest (~10 m) part of the excavation. A Tertiary coal seam (bottom left) has been displaced upwards against subvertical green and dark brown Tertiary clays (weathered yellow directly under the strath) and into the overlying Waitaki River gravel (Aviemore alluvial deposits). Evidence for at least two successive fault displacements is preserved within the stratigraphy of this exposure. The dashed red line denotes more diffused deformation.

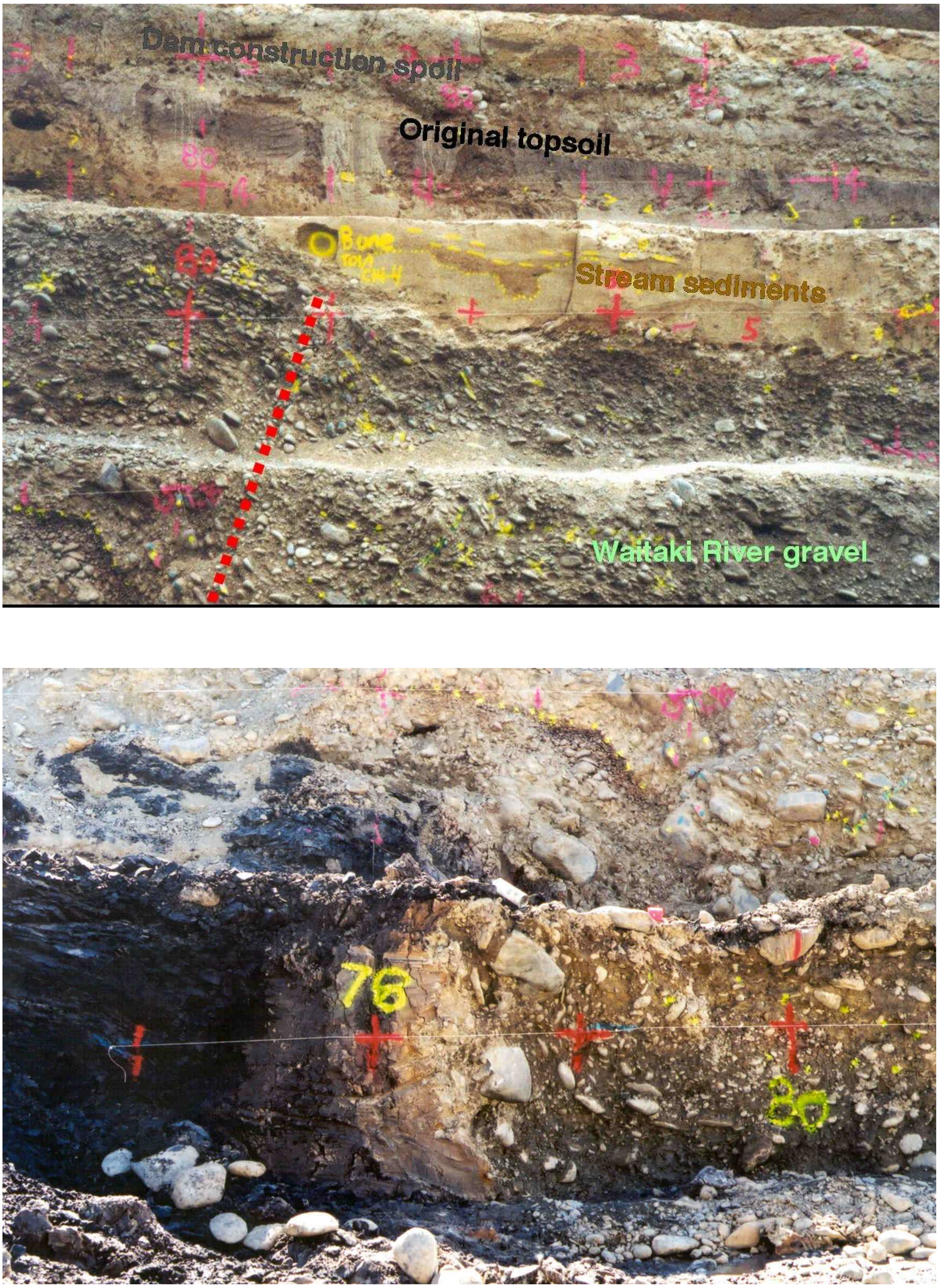


Figure 10: Detail of Waitangi Fault deformation in the northwest wall of T01/1. **Lower**: Close-up of dark claystone and coal upfaulted against alluvial gravels; note the fault drag revealed by gravel clast long-axis orientations. **Upper**: Gravel clast orientations highlight the more diffuse fault deformation within the upper part of the alluvial gravel. The yellow fan alluvium (stream sediments) is unfaulted.

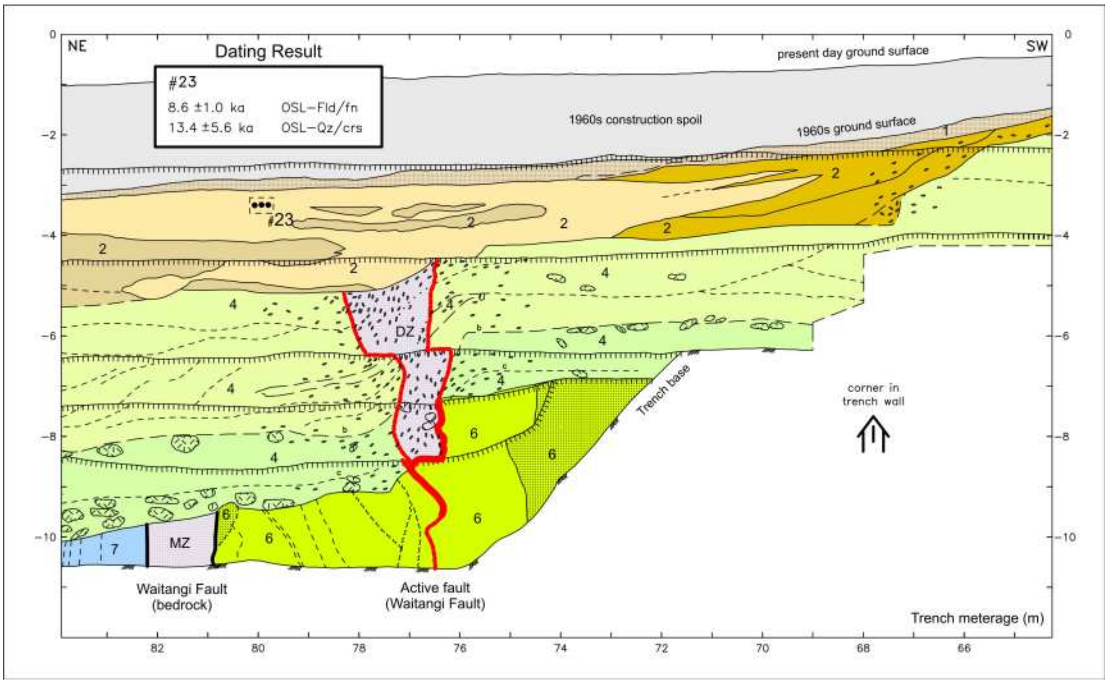


Figure 11: Part of the geological log of the southeast wall of trench T01/1. See Figure 7 for key.

Sense of displacement

The trench exposures did not enable the direct measurement of total fault offset (e.g. from piercing points), although they did constrain the vertical component. The orientations of fault slip indicators, such as slickenside lineations (Figure 6) and preferentially-oriented long-axes of gravel clasts, adjacent to or within fault planes were measured where possible. These indirect measures of fault displacement indicated horizontal (H) to vertical (V) movement components ranging from 1H:4V to 2H:1V, with the most reliable (slickensides) indicating that dip slip dominated over strike slip. On this basis the Waitangi Fault was best characterized as an oblique right-lateral – reverse fault.

Size of single-event displacement(s)

There was a reasonable consistency between trenches on the total amount of vertical bedrock strath offset, independent of the number of events recognized. The best information for single-event displacement measurements came from T00/3 where Fault 1 and Fault 2 broke through on separate slip surfaces, as well as terminating vertically against different alluvial deposits (Figures 5 to 7). The rupture on Fault 1 is older than that on Fault 2, and does not appear to have involved rupture of Fault 2.

Fault 1 (penultimate surface rupture) has a vertical separation of 0.5 m on the base of the Aviemore alluvial deposits (bedrock strath), and slickenside lineations indicated a horizontal to vertical slip ratio of about 1H:3V (i.e. 0.1–0.2 m horizontal component). Combining these data on a steeply dipping fault plane (≥70º) indicates a net surface-rupture displacement of approximately 0.6 m.

Fault 2 (the most recent surface rupture event) has a vertical separation at the fault plane is at least 1.0 m, but if warping over a zone up to 5 m west of the fault plane is taken into account, the vertical separation could be as much as 2.0 m. Measured slickenside lineations indicated a horizontal to vertical ratio in the order of 1H:2V and 1H:3V (i.e. 0.3 to 1.0 m horizontal component) indicating a net surface rupture displacement of at least 1.1 m (1.0 m vertical; 1H:3V) and possibly as much as 2.4 m (2.0 m vertical; 1H:2V) on a steeply dipping (≥70º) fault plane.

In other trenches, the most recent ruptures broke through on a single slip surface, and the sizes of individual single-event displacements were difficult to quantify. In T01/1 contrasts in gravel thicknesses provided a possible indication of a third (probably small) fault rupture during deposition of the Aviemore alluvial deposits. However, in high-energy river environments such as the Waitaki valley, coarse-grained alluvial deposits are commonly associated with irregularly eroded bedrock straths, which reduces the opportunities for confident detection of individual smaller events.

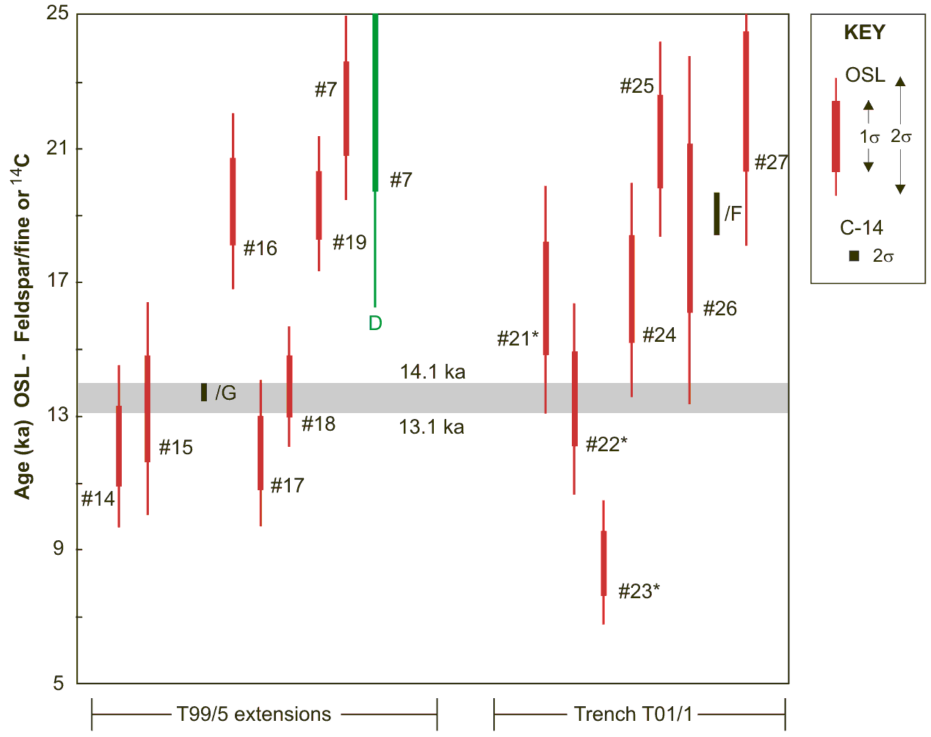
Time since the most recent movement and the surface-rupture recurrence interval

The most consistent luminescence dating results (judged by good corroboration with radiocarbon dating results) came from optically-stimulated luminescence (OSL) utilising feldspar-derived emissions from polymineralic fine silt samples ('OSL – Fld/fn' method – Figures 7 and 11), using a multiple aliquot regenerative technique.

Of these OSL and radiocarbon dating results for samples from the Waitangi Fault trenches, eight of the dates help to constrain the time since the last fault rupture. Five samples came from materials offset by faulting, while three samples came from materials not offset and therefore younger than the last fault rupture (Figure 12). The preferred estimate of 13.1 to 14.1 ka (1 ka = 1000 years before present) is defined by the interval between the older error limits of the youngest faulted samples (#17 and /G) and the younger error limits of the oldest unfaulted sample (#21). The older end of the range (14 ka) is relatively well constrained by 3 dates (#17, /G, #14). The constraint on the younger end (13 ka) is more sensitive; the time since last rupture would reduce to 10.7 ka (#22) in the absence of sample #21 (13.1 ka). It was concluded that the fault has not ruptured since 10.7 ka, and probably not since 13.1 ka.

The age of Aviemore alluvial deposits, which contain a record of at least two fault rupture events, is constrained only broadly, largely because of relatively few finer-grained horizons suitable for luminescence dating. Sample #7 (two standard deviation range (2σ) of 19.5 to 25 ka) was from close to the bedrock strath, while sample #25 (2σ range of 18.5 to 24 ka) was from nearer to the middle of the unit. Given that samples #26, #27 and /F, with a mean age of 20.0 ka (2σ range of 13.5 to 26.5 ka) are from near the base of overlying fan alluvium. By about 15 ka, the Waitaki River had incised into the Aviemore alluvial deposits, and locally-derived fan alluvium was being deposited in places on river-cut surfaces (see Figures 10 and 11). The timing of river incision at Aviemore is broadly compatible with the last major advance and subsequent withdrawal of Last Glaciation ice at Lake Pukaki, about 17.5 ka (Schaefer et al. 2006).

Two, possibly three, surface rupture events on the Waitangi Fault since between about 19.5 and 25 ka gives a recurrence interval between 6.5 and 12 ky (where 1 ky = a time span of 1,000 years), depending on the number of events and the age of the alluvial deposits considered. At least 10.5 ky have elapsed since the most recent surface rupture event, leaving a maximum of 14 ky in the interval between 11 ky and 25 ky when one, or possibly two, surface ruptures occurred.



OSL = Optically-Stimulated Luminescence, measured at Victoria University, except D = Dalhousie University
C-14 = radiocarbon, measured at Rafter Radiocarbon Laboratory, GNS, Lower Hutt
Feldspar/fine = feldspar luminescence from poly-mineral fine silt fraction
* denotes unfaulted sample (samples # 21, 22, 23)
Grey band indicates the timing of the last surface rupture of the Waitangi Fault

Figure 12: Luminescence and radiocarbon dating results for trench T99/5 (and its extensions, T00/1 – T00/3) and trench T01/1.

Slip rate

Vertical slip rates were calculated at each Waitangi Fault trench location using combinations of smaller bounds of offset estimates with older bound ages (to give minima) and larger offsets in combination with younger ages (to give maxima). The fastest minimum and slowest maximum rates were c. 0.1 and c. 0.2 mm/year respectively, leading to a preferred vertical slip rate of between 0.1 and 0.2 mm/year. This implies a net slip rate in the range of 0.1 to 0.3 mm/year for a steeply dipping fault (≥70º) and a 1H:3V to 1H:1V displacement ratio range.

Other 'small-scale' deformation features

'Small-scale' deformation features exposed west of the Waitangi Fault (Figure 4) were typically northeast to northwest striking faults or folds. The nature of individual features varied between trenches, and how they inter-relate was not established. Some of them have moved twice in the last c. 25 ky, but the relatively small offsets imply that their slip rates must be less than those of the Waitangi Fault.

Embankment Dam Foundations

During construction, no significant vertical step indicative of a fault offset was identified in the bedrock strath over the Waitangi Fault at the contact between greywacke and Tertiary bedrock. However, retrospective examinations of construction-time photographs of excavation batters reveal Aviemore alluvial deposits with preferentially-oriented gravel clasts. The location of the zone of aligned clasts was a short distance above and east of a west-side-up sharp rise in the embankment foundations, an estimated 10 to 15 m west of the bedrock fault contact. With the knowledge of the diagnostic characteristics of surface fault rupture deformation from the investigation trenches, it is considered very likely that deformation caused by late Quaternary movement on the Waitangi Fault is present in the embankment dam foundations. Similarly, the 'small-scale' deformation features west of the fault are considered likely to be present in the embankment foundations.

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