Clyde Dam and Schist Landscape Field Trip

28 April 2026

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Contents

1. Overview

This field trip traverses the Queenstown–Kawarau–Cromwell Gorge corridor to examine the coupling between Otago Schist rock-mass evolution and a spectrum of slope instabilities from active rockfall to deep-seated gravitational slope deformations (DSGSD) and very large defect-controlled rockslides. The primary case study is the Clyde Dam abutments and the suite of remediated landslides around Lake Dunstan.

Logistics: meet 07:45 for an 08:00 departure (sharp). The route is a full-day excursion with multiple short roadside stops and two extended sessions at Clyde Dam. Expect variable exposure (wind, sun, cold), steep ground at viewpoints, and active traffic hazards at some stops.

Table 1. Fieldtrip itinerary.

Arrive	Depart	Duration (mins)	Location	Description	Toilets
8:15	8:35	20	Shot over Jet	Viewpoint of Arthurs Point Landslide	No
8:55	9:25	30	Skippers Road Lookout at Coronet Peak	Coronet Landslide, introduction to the asymmetrical valley associated with the schist landscape, view of Shotover Valley, discussion of the geological history	No
9:55	10:10	15	Kawarau Bridge	Historic bridge and Twin Bridges Landslide	Yes
10:10	10:10		Nevis Bluff	Rockfall issue, position of the original Kawarau River dam	
10:30	10:40	10	Roaring Meg	K9 landslide	No
10:55	11:10	15	Fruit shop – Jones Family Fruit Stop	Toilet Stop	Yes
11:25	11:40	15	Clutha River Viewpoint	Introduction to the landslides of the Cromwell Gorge	No
12:00	12:45	45	Lunch Break	Lunch - Orchard Garden *	Yes
13:05	13:50	45	Contact - Dam/Adit Session 1	Subdivide the group: Half the group on a tour of the dam slip joint, whilst the other half goes into the drainage drain DR550	No
13:50	14:00	10	Swap over		
14:00	14:45	45	Contact - Dam/Adit Session 2	Subdivide the group: Half the group on a tour of the dam slip joint, whilst the other half goes into the drainage drain DR550	No
15:20	15:30	10	Toilet Break in Clyde		Yes
15:45	16:00	15	Brewery Creek Landslide Buttress	Cairnmuir Slide. View of surface works and Contact Energy tunnel entrance; discussion of Brewery Creek remedial works.	No
16:20	17:35	75	Panners Gold Fields Mining Centre	Ripponvale Slide (optional for those that would like enter the goldfields area)	Yes
18:30			Hotel		

* Please note the field trip fee includes lunch at Orchard Garden and entrance to Panners Gold Fields mining centre.

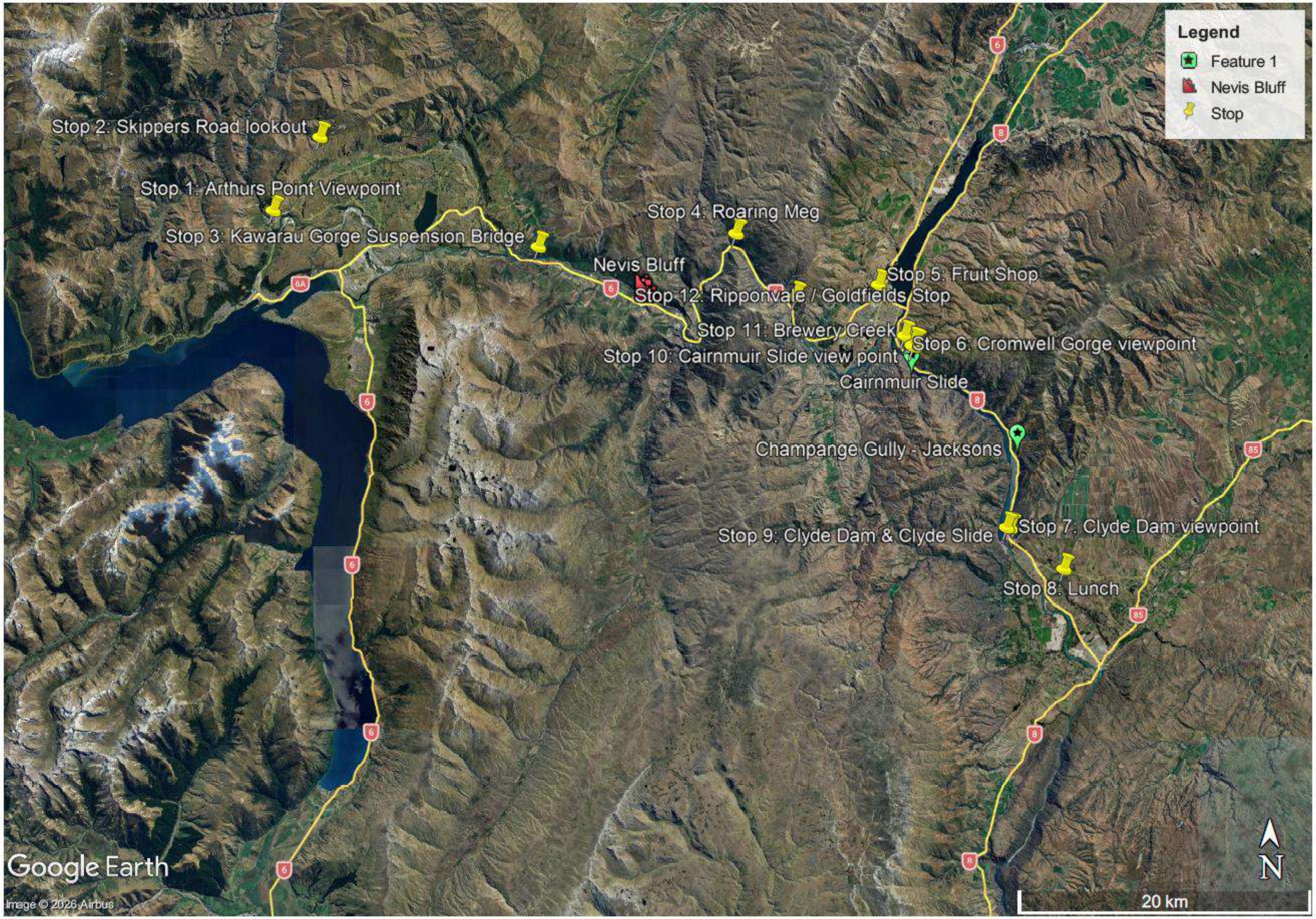


Figure 1. Route map and stop locations.

2. Geological Setting

2.1. Regional Geology

The Otago Schist is a product of multiple deformational phases as summarized in Table 2. Of importance to note are:

- The thrust boundary of the Caples terrane (volcaniclastic origin) over the Rakaia terrane (turbidite accretionary wedge origin) which passes along the south flank of the Cromwell Gorge.
- The multiple deformation cycles resulting in numerous generations of folds and faults,
- The currently active Kaikoura Orogeny with the oblique compression which has resulted in uplift and warping producing the basin and range landscape characterised by active faults
- Climatic variations defined by several periods of ice advance and retreat resulting in terraces and accelerated erosion within the valleys.

Table 2. Summary of major geological phases (Bishop, 1972; Beanland and Berryman, 1989; Mortimer and Roser, 1992; Thomson, 1993; Bishop, 1994; LeMasurier and Landis, 1996).

Phase (ages)	Description
Origin **(~ 290 to 200 Ma)**	• Caples Terrane: Permian – Triassic marine volcaniclastic sequence deposited as a sequence of submarine fans in a volcanic arc trench. • Rakaia Terrane: a Permian to Late Triassic turbidite submarine sedimentary wedge which was deposited along the margin of Gondwana.
Rangitata Orogeny Convergence **(~ 180 to 120 Ma)**	• Convergence of the Gondwana margin during Middle Jurassic, leading to crustal thickening and metamorphism, which formed the Otago Schist. This period also saw the onset of folding within the schists followed by uplift and mountain building. • Ultimately led to the juxtaposition of the Caples Terrane over the Rakaia Terrane in the Early Cretaceous.
Rangitata Orogeny Crustal extension **(~90 to 25 Ma)**	• Crustal extension during the Late Cretaceous was accommodated by low angle shear zones and further rifting as fault control basins developed. • The region experienced a prolonged period of tectonic quiescence until Middle Eocene. • From the Middle Eocene to Early Miocene (~25 Ma) further crustal extension resulted in rifting and the development of fault-controlled basins. • Throughout the extensional phase following the Rangitata Orogeny, the Otago region was subjected to extensive subaerial erosion which formed a low-relief unconformable surface extending over an area of 20 000 km^2. This surface is referred to as the Waipounamu Erosion Surface (previously known as the Otago Peneplain) and represents a fluvio-marine transgressive environment, which was widespread (~106 km^2) over continental New Zealand.
Kaikoura Orogeny **(~ 22 to present)**	• The onset of the Kaikoura Orogeny in Early Miocene involved crustal shortening accommodated by strike-slip faults, uplift and warping. • The Manuherikia Group deltaic, fluvial and lacustrine sediments were deposited in fault-bound depressions. • From the Late Miocene the tectonic stress regime of the Kaikoura Orogeny shifted to oblique compression with further uplift and warping result in development of folding and the reactivation of northeast-southwest faults. This orogeny involved episodic movement on faults such as the Nevis-Cardrona and Moonlight Fault Systems.
Glacial and inter glacial periods **(~ 1 Ma to 16 k)**	• Climatic variations defined by several periods of ice advance and retreat resulting in accelerated erosion within the valleys.

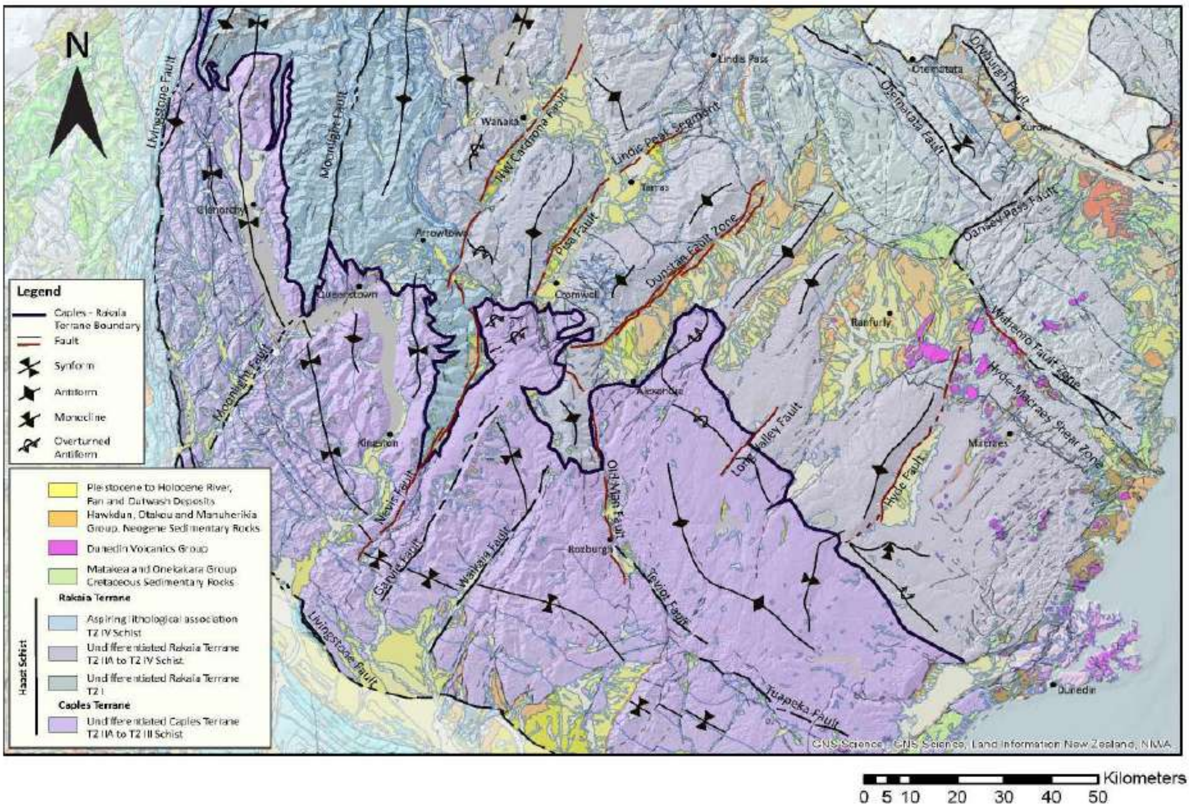


Figure 2. Regional geological map of Central Otago (Gnesko, 2020; GNS Science, 2018; Turnbull, 2000).

2.2. Active Faulting

The field trip traverses part of Otago's 'basin and range' topography which is characterised by block mountains formed against active faults. The Otago region has seen very few earthquakes over the last two centuries, largely due to the region being well to the east of the main (Alpine Fault) boundary of the Australian and Pacific tectonic plates. Previous studies (e.g. Norris & Nicholls 2004) have proposed that large earthquakes recur episodically, with individual faults going through active and quiescent phases, making the region an important case study of earthquake recurrence in low seismicity regions.

In general, the blocks are uplifted on their eastern margin and back tilted to the west. Range heights increase westward, particularly west from Clyde, while the valleys become narrower. The inland Otago "range and basin" region to the east of Clyde is quite different from the area we have crossed during the morning. It has relatively gentle topography, and its dominant geomorphic feature is a peneplain surface, formed on the basement rock, that is warped or broken into a series of 15 to 20 km-wavelength parallel ridges and valleys by folds and reverse faults trending NE-SW.

The basement rocks are schist with a relatively flat-lying foliation, exposed in the ridges/ranges, while top of the basement rock, and the peneplain, is commonly obscured by Tertiary and Quaternary sediments in the basins.

The range-forming structures are active but collectively probably accommodate only a few mm/yr. Where the basement rock is well-foliated schist, large-scale landsliding is typical along the range fronts. Barrell (2019) provides a comprehensive review of the active tectonics in the region.

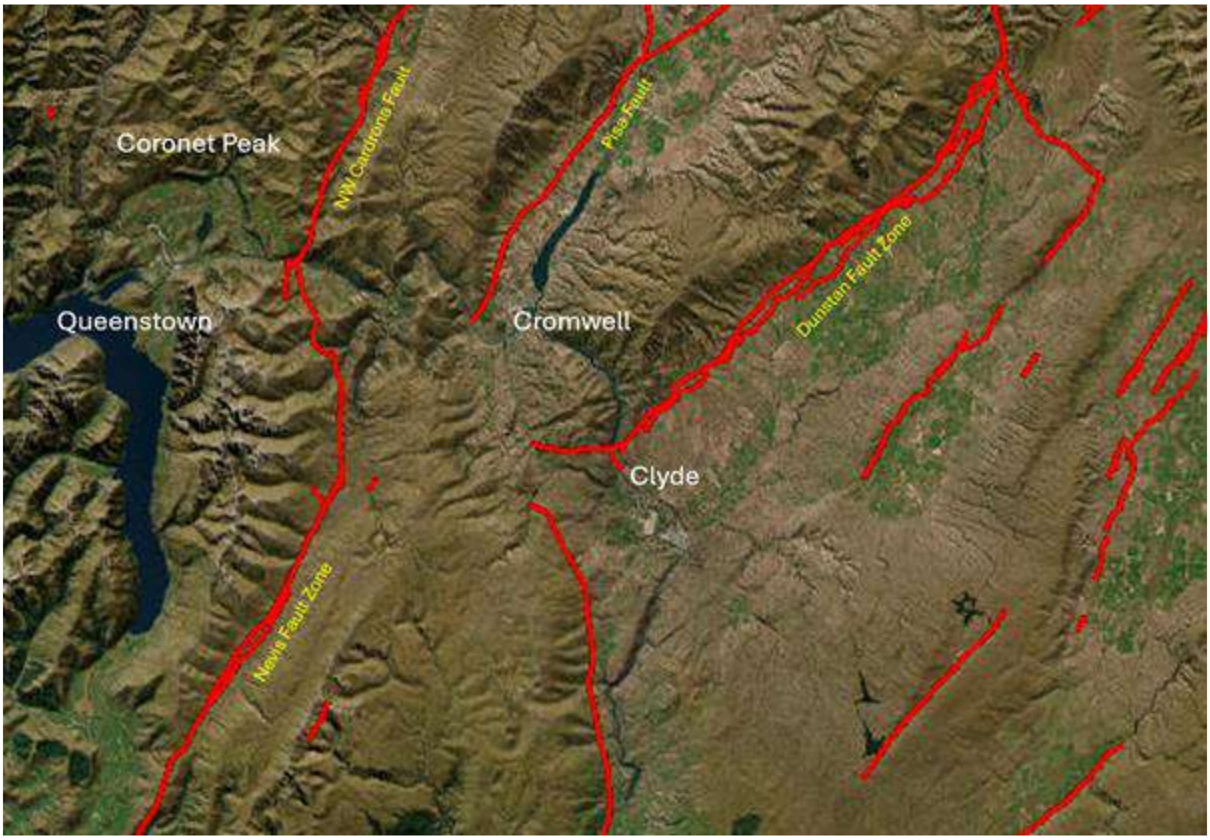


Figure 3. Active faults of Central Otago (GNS Science - Active Faults Database).

2.3. Glacial History

Central Otago's valley network was repeatedly modified during multiple glaciations. The extents of the last major glaciations are shown in Figure 4. Progressive tectonic uplift, successive glaciations and postglacial base-level fall have carved out overdeepened basins with drainage patterns that have evolved over time. Noteworthy shifts in drainage directions are as follows:

- Lake Wakatipu initially drained south before headwater capture of the Kawarau River near Frankton (Turnbull and Forthsyth, 1988; Bell 1992).
- For a time, the Shotover River flowed down Gorge Road Valley into the Wakatipu basin near Arthurs Point before incising into bedrock and becoming constrained to the current position in the lower Shotover Gorge.
- The Clutha River initially flowed through Thomson Saddle north of the Cromwell Gorge. Deglaciation and rise of the antiformal Dunstan range resulted in the shift in position and progressive incision of the Cromwell Gorge.

Subsequent deglaciation has progressively lowered lake levels leaving prominent shorelines and deltas. The geotechnically soft, laminated lake and deltaic silts retain high water contents and low cyclic resistance; thus, posing a risk of settlement and liquefaction susceptibility under strong shaking.

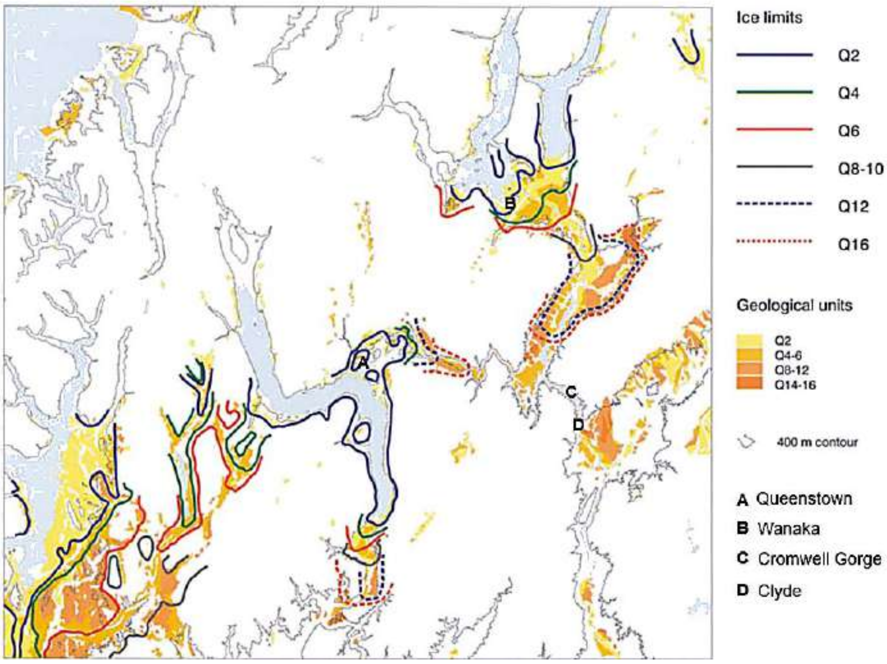


Figure 4. Terminal moraines of major ice advances in Central Otago (Turnbull, 2000).

2.4. Schist landslides

The anisotropic nature of the schist bedrock has a strong control on the topography of Central Otago resulting in valley asymmetry typically with gentle sloping cataclinal (dip-slope) on one side of the valley and a steeper anaclinal slope (anti-dip) on the other side of the valley. Prolonged gravitational stresses from the uplift and warping compounded with successive glaciations have led to the widespread occurrence of landslides in the Central Otago region (Figure 5). The largest landslides are foliation and/or shear controlled translational failures located along the cataclinal flank of the valley that are typically characterised by various deformational zones (Table 3).

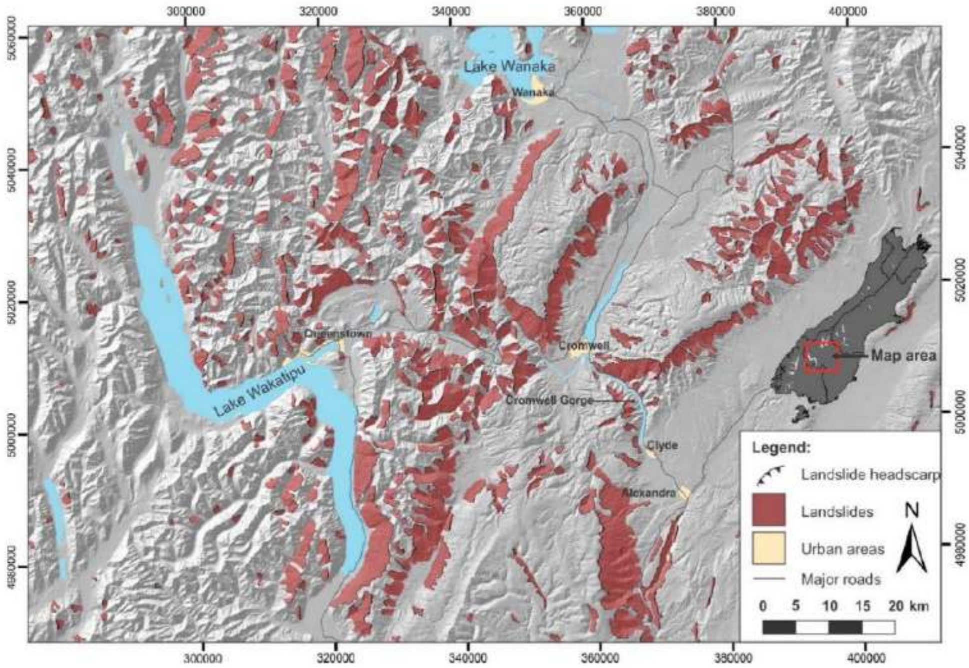
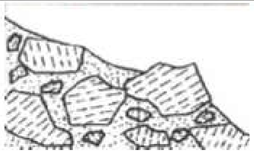
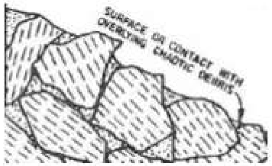
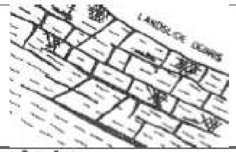
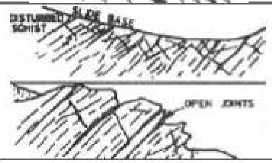
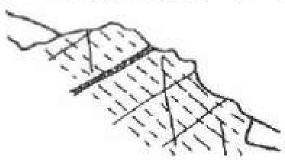


Figure 5. Mapped landslides in Central Otago (Turnbull, 2000).

Table 3. Typical characteristics of internal zones associated with DSGSD within Cromwell. Zones listed in vertical order as encountered from slope surface progressing with depth (Beetham and Fergusson, 1990; Macfarlane *et al.,* 1990; Smith *et al.,* 1990; Bryant and Watts, 1991).

Zone	Terminology	Illustration of appearance	Description	Surface Characteristics	Type of movement
Upper (landslide)	Chaotic debris		Gradation from large competent rock blocks to fine grained material (commonly intensely sheared and crushed) with gouge seams. Foliation attitudes of blocks normally highly variable. Slickensided downslope-dipping internal or basal failure zones.	Laterally impersistent breaks in slope (hummocks). Well-developed slide scarps where active. Blocks on surface	Rotational, translational, or complex slide (displacement: 10's – 100's m)
	Displaced Schist (to blocky debris where displacement is greatest)		Large competent rock blocks either in contact or separated by open and/or infilled joints or by zones of sheared/crushed material. Foliation either parallel or oblique to undisturbed rock, and adjacent blocks may be slightly rotated relative to one another. Slickensided near downslope-dipping internal or basal failure zones, typically sub-parallel to foliation or pre-existing rock defects.	Laterally persistent break in slopes (broadly irregular). Forms outcrops locally.	Translational slide (displacement: m's – 10's m)
	Basal Failure Zone		Crushed zones and gouge seams with some sheared and shattered schist of variable thickness. Fabric may be subparallel to boundaries, contorted, or totally disrupted. Gouge seams typically thin but persistent with slickensides, oriented downslope	Outcrops rare	Slide (displacement: mm's – 100's m)
Transitional	Disturbed schist		Sub-slide rock mass with partly open defects often infilled. Termed "relaxed schist" in the near-surface situations.	Relaxed schist forms prominent outcrops similar to undisturbed schist	Stress relief processes (displacement: mm's – m's)
	Deformed schist		Sub-slide rock mass, fissile with discrete sheared and crushed zones sub-parallel to flexurally deformed ("buckled") foliation, steepened to overturned locally.	Prominent outcrops with foliation dipping at moderate to high angles to undisturbed schist	Bedrock flow, by stress relief and/or gravitational processes. (displacement: mms to 10's of m)
Undisturbed	In situ schist		In situ rock mass with closed defects	Forms prominent outcrops	None

2.5. Landslide framework for Otago Schist terrain

Along this corridor, slope instability is best understood as a continuum from intact rock-mass deformation (DSGSD) to fully developed rockslides. Field evidence commonly includes uphill-facing scarps, grabens, tension cracks subparallel to slope crests, kink-banding/chevron folding of schistosity, bulging toes, and localised rock-mass weakening within deformation zones at depth.

The field trip notes use the following working kinematic groupings:

- Translational rockslides: planar/step-path sliding on schistosity and associated shear zones, often initiated or reactivated by glacial debuttressing and ongoing river incision.
- Toe-buckling and deep-seated gravitational slope deformation (DSGSD): progressive folding/overturning of steep schistosity beneath a basal rupture surface, producing anomalously oversteepened foliation and characteristic extensional–compressional zoning.
- Wedge/compound failures: structurally controlled by the intersection of schistosity, joint sets, and local fault zones; often expressed as narrow, elongated failures in gorge walls.
- Debris-flow and rockfall systems: episodic, rainfall-triggered processes on colluvial/alluvial fans and steep rock faces; these dominate short-term risk to infrastructure and land-use in parts of Queenstown.

3. Queenstown Area

3.1. Stop 1: Arthurs Point Viewpoint (20 mins)

Geotechnical Risk to Queenstown

The Queenstown Lakes District has one of the fastest growing populations in New Zealand. Between 2018 and 2023 the population grew 22 % roughly 3.5 times the growth of the New Zealand rate. This rapid urban expansion has increased exposure to a multi-process hazard environment (rockfall, debris flow, shallow landsliding, and large deep-seated rock-mass deformation). Recent work for QLDC integrates susceptibility and risk modelling into land-use planning policy, including scenario-based loss estimation for debris-flow and rockfall hazards QLDC (2021).

As we drive from Queenstown's town centre through to the first stop observe the narrow development corridor constrained by the Lake and surrounding mountains. Notice how newer residential developments are being built further up the mountains.

At the first stop we will be looking at the Arthurs Point residential area located where the Shotover River debouches the mountains marking the southern flank of the Coronet Peak Landslide (more details of the Coronet Peak Landslide are provided in Stop 2 description). This stop will coincide with the Landslide Risk Workshop.

The focus of this stop will be to observe the geomorphology with respect to development in the area, particularly to changes in land use as shown in Figure 6.

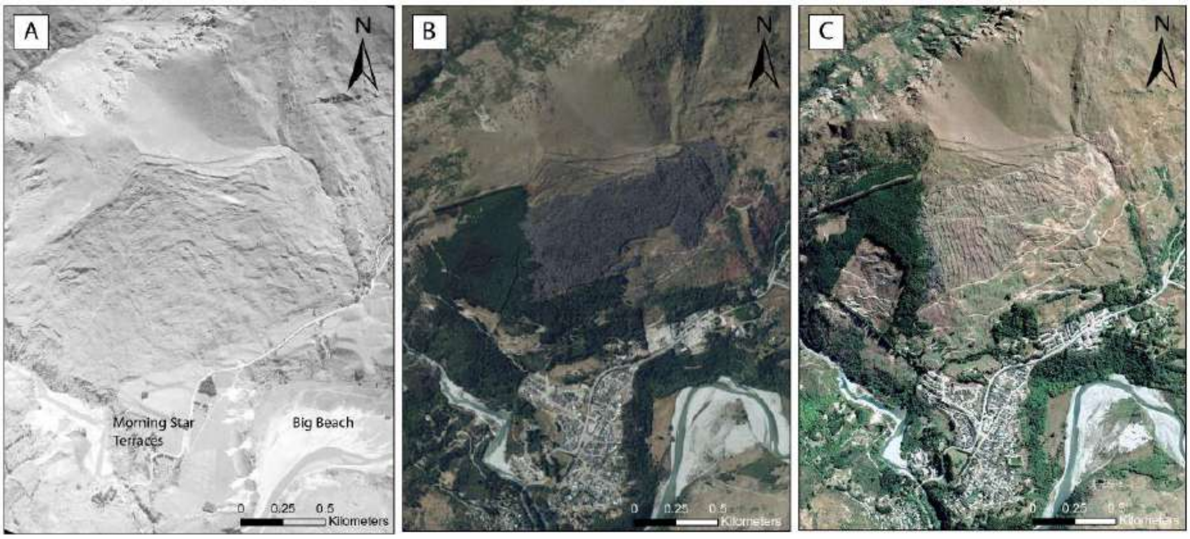


Figure 6. Aerial images of the Arthurs Point area in A) 1956, B) 2019 and C) 2022 (Rozmus, 2023).

3.2. Stop 2: Skippers Road Lookout (30 mins)

Coronet Peak Landslide

The Coronet Peak Landslide is a classic example of a foliation controlled translational planar failure. The landslide is > 1 x 10^9 m^3 in volume extending from the ridge crest (1651 m at Coronet Peak) to the toe of the slope (450 m at the valley floor) with a thickness of ~ 150 m (Willets, 2000). The landslide exhibits classic foliation-controlled kinematics, with displacement accommodated along schistosity-parallel shear surfaces and deformation zones, and a surface expression of scarps, tension cracks, hummocks and disrupted drainage. Ongoing slow movement has been reported in parts of the slide (mm/yr scale).


Figure 7. Skippers Road Lookout is the perfect vantage point to view the Coronet Peak Landslide and glacial geomorphological features of the Wakatipu Basin.

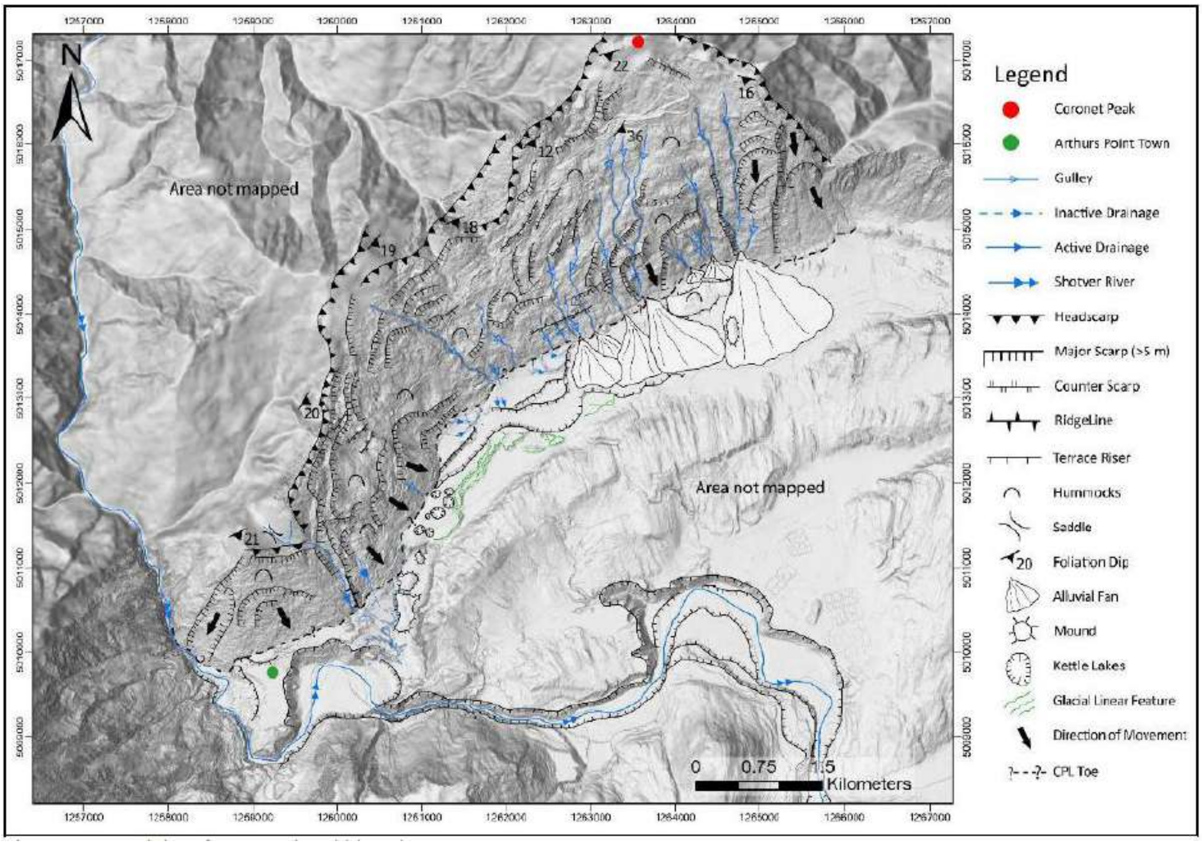


Figure 8. Geomorphology of the Coronet Peak Landslide (Rozmus, 2023).

4. Kawarau Gorge

4.1. Proposed hydropower schemes in Kawarau Gorge

Hydro development options for the Kawarau River were investigated in the 1980s as part of the Clutha Valley Development which proposed a total of five dams on the Clutha and Kawarau rivers. The investigations in the Kawarau Valley comprised limited mapping and drilling. Very early in the process, landslides were identified as a problem for the originally proposed dam options due to narrow valley, steep slopes, obvious activity (scarps, rapids) and likely adverse effects of toe inundation (Figure 9). As a result, alternative schemes involving tunnels and canals were investigated.

The investigations (and associated landslide monitoring) were stopped by a Conservation Order in mid-1985. No remedial works were done on any of the landslides. Monitoring was by survey only and the total monitoring history is quite short (late 1970s to early 1980s), except at Ripponvale.

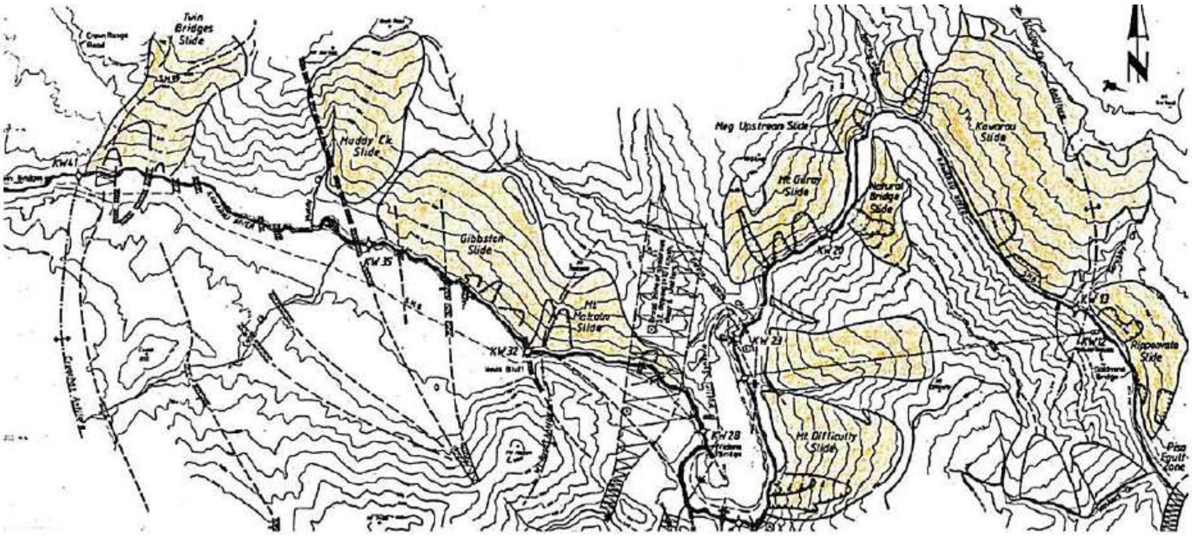


Figure 9. Landslides in the Kawarau Valley (NZGS, 2021).

4.2. Stop 3: Kawarau Bridge - Bungy site (15 min)

Twin Bridges Landslide: structural control and gorge-wall kinematics

Kawarau Gorge Suspension Bridge was completed in 1880 to replace the ferry system across the Kawarau River and provide improved access to the Otago goldfields. Due to increased traffic demands, in 1963 the suspension bridge was decommissioned and replaced with the current Kawarau Bridge. It has subsequently been recognised by IPENZ as an engineering heritage site.

From this vantage point, the Twin Bridges landslide provides a useful contrast to the very large Coronet Peak rockslide: it is a narrow, elongated failure following a major regional fault (the NW Cardrona fault) and, as expressed on a steep gorge wall, shows the effects of interaction between foliation orientation, persistent joint sets, and local fault structures combining to generate a preferential failure corridor. Use binoculars to trace (i) lateral margins; (ii) internal benches and scarps; and (iii) toe interaction with the river (erosional undercutting vs buttressing).

The fault scarp (NW Cardrona Fault) crosses the terrace between road and river just downstream (looks like a step in the surface at right angles to the river). It was trenched in 1980's as part of the seismic hazard studies for the Clyde project.

Figure 10. Kawarau Suspension Bridge from ~ 1900 (Lakes District Museum and Galley).

Figure 11. The replacement bridge was built in 1963.

4.3. Nevis Bluff (no stopping)

High risk to SH6

We are unable to stop at this site due to rockfall hazard and ongoing construction to develop the cycleway through the Kawarau Gorge.

One of the originally proposed dam sites on the Kawarau River was at the western (upstream) end of the bluff. The site was abandoned due to an unstable left abutment and deep sediments in the river channel. The rapid below the bluff is due to the river crossing/undercutting the active Mt Malcolm landslide.

In 1972 the slope was cut back 30 m and steepened to an angle of 75° to widen SH6. A joint controlled slope failure (30,000 m^3) blocked the highway for 6 weeks in 1974. Since then, there has been an ongoing history of scaling and stabilisation works, including another slope failure of 10,000 m^3 which caused road closure for 5 days in 2000.

Remediation methods included drill and blast, use of monsoon buckets, hand scaling, hydraulic and pneumatic drilling and most recently lateral support with rock bolts.

Figure 12. Rockfall closed the SH6 in 2000.

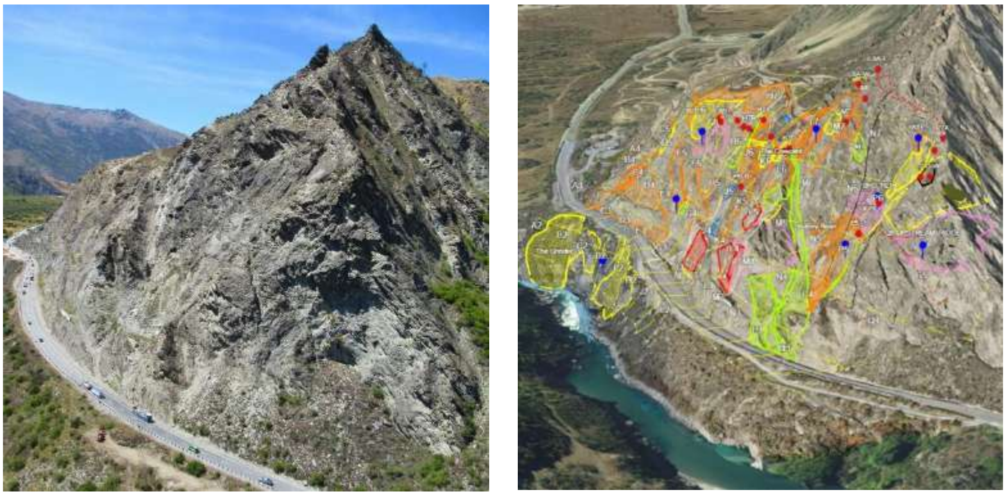


Figure 13. Drone image of Nevis Bluff and the digital twin developed to identify and manage risk (WSP, 2025).

4.4. Stop 4: Roaring Meg (10 min)

The rivers were incised into rock along both the Kawarau and Cromwell Gorges and this can be seen at this stop. Interestingly there is a natural rock bridge 300 m upstream of the Roaring Meg power stations. This was used as a crossing point for early Māori and explorers. A flying fox was used during the engineering investigations of the 1980s.

We can also look down valley to see the asymmetric profile caused by the geological controls on slope geometry. On the left, the whole slope is one large landslide known as the K9 or Kawarau Slide, a dip-slope failure along the foliation in the schist. On the right the steeper slopes form where the schist dips into the slope and the main control on the slopes is jointing so slope instability is generally limited to small, shallow rockfalls or rockslides, a marked contrast.

The K9 landslide is a large dip-slope landslide (~10^9 m^3) developed in Rakaia Terrane greyschists (psammitic–pelitic quartz–mica schist) with subordinate greenschist (chlorite–epidote schist). It is ~9 km long with maximum displacements ~100 m and grabens up to ~100 m wide. At the scale of the gorge, deformation includes prominent lateral shears and internal scarps. Bell (1976, 1982, 1987 and 1992) documented anomalously steep foliation dips (60–70°) within the lower (compressional) zone of the K9 landslide in the Kawarau Gorge, contrasting with the regional dip-slope fabric on the SW-facing antiform limb where foliation typically dips ~25–30° to the southwest. This identification of toe buckling/foliation oversteepening and buried megablocks beneath chaotic debris provided a key conceptual analogue for Central Otago large slope evolution and was used to inform interpretation of the Cromwell Gorge geological model during the Clyde Power Project.

Figure 14. Looking upstream to the Roaring Meg Power Station.

Figure 15. Looking downstream with the K9 landslide on the true left of the Kawarau River.

Figure 16. Natural rock bridge used to cross the Kawarau River for centuries (Pole, 2014).

4.5. Stop 5: Fruit Shop (15 mins)

Central Otago is well known for its cultivation of high-quality wine and fruit, particularly stone fruit. This is due to the regions hot, dry summers, big day-night temperature swings and schist derived soil. We will take a short stop at a local fruit shop to allow participants to perhaps purchase some local produce and/or use the rest room.

5. The Cromwell Gorge

5.1. The Clyde Power Project

The Clyde Power Station is a legacy of the New Zealand's government 1980's "Think-Big" projects. Construction of the Clyde Dam commenced in 1977, with the main construction works on the dam site occurring between 1982-1989. Landslides occur along about 40% of the shoreline of the lake in the Cromwell Gorge section (Figure 17).

Commissioning of the power station was delayed due to the identification of high groundwater pressures during reconstruction of the highway above lake level. This led to concerns that the numerous landslides along the valley may have the potential for a "Vajont-like" catastrophic event.

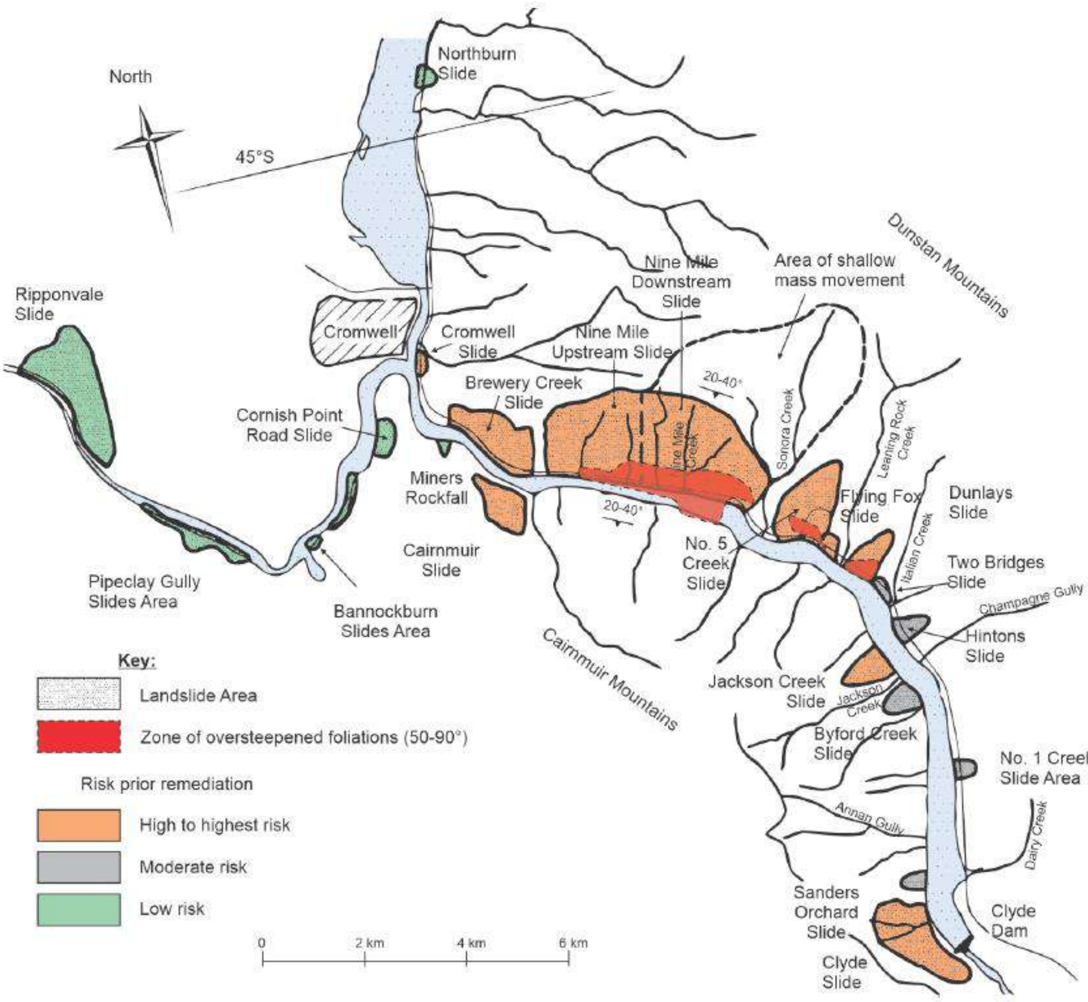


Figure 17. Landslides occur along about 25% of the shoreline of the lake, and about 40% of the shoreline in the Cromwell Gorge section (Macfarlane, 2009; Ridl, 2021).

Figure 18. Historical photograph taken prior to lake-fill from the Cairnmuir Flank looking upstream towards Nine Mile Slide (pers. comm. Thomson, 2015).

5.2. Stop 6: Clutha River Viewpoint - Discussion of the landslides (15 mins)

5.2.1. Controls on landsliding

The Cromwell Gorge developed along the shear zone between the Rakaia Terrane and Caples Terrane Schist. The Leaning Rock Antiform along the Dunstan Range (northeast-southwest trend) locally rotates and plunges westwards in the Cromwell Gorge (Figure 19).

Large-scale translational landslides developed and progressively deepened along the true left flank of the Cromwell Gorge during down cutting as a function of creep deformation along foliation shears and/or low angle shears associated with the terrane boundary between the Rakaia and Caples Terranes (see Figure 20).

Investigations for and construction of the remedial works identified subvertical shear zones (faults) striking upslope at right angles to the river beneath the landslides. Differential movement across the upslope trending faults resulted in stepped slide bases leading to breakout through the deformed rock both above and below the highway in sections of slope between upslope trending faults.

Detailed investigations also identified complex, compartmentalised groundwater systems between the faults and shears in the bedrock beneath the landslides. Analysis showed that some landslides would undergo unacceptable reductions in stability as a result of groundwater changes following lake filling. This was interpreted to indicate a risk of reservoir blockage causing upstream flooding or rapid failure generating an impact wave that could overtop the dam or affect the town of Cromwell during or after lake filling.

5.2.2. Stabilisation works

To offset the reductions in stability, extensive engineering works were undertaken on 10 of the landslides. The stabilisation works included the following:

- 42 km of investigations drilling
- 16 km of drainage tunnels
- 100 km of drainage drilling
- 7.5 Mm^3 of toe buttresses

- 3.4 ha of infiltration protection
- Establishment of an extensive monitoring system of piezometers, inclinometers, extensometers, surveys and flow measurements.

A staged approach to reservoir (Lake Dunstan) filling was carried out over 18 months in 1992-93 and the power station was commissioned in late 1993. During this time the landslides were intensively monitored with frequent supplementary visual inspections.

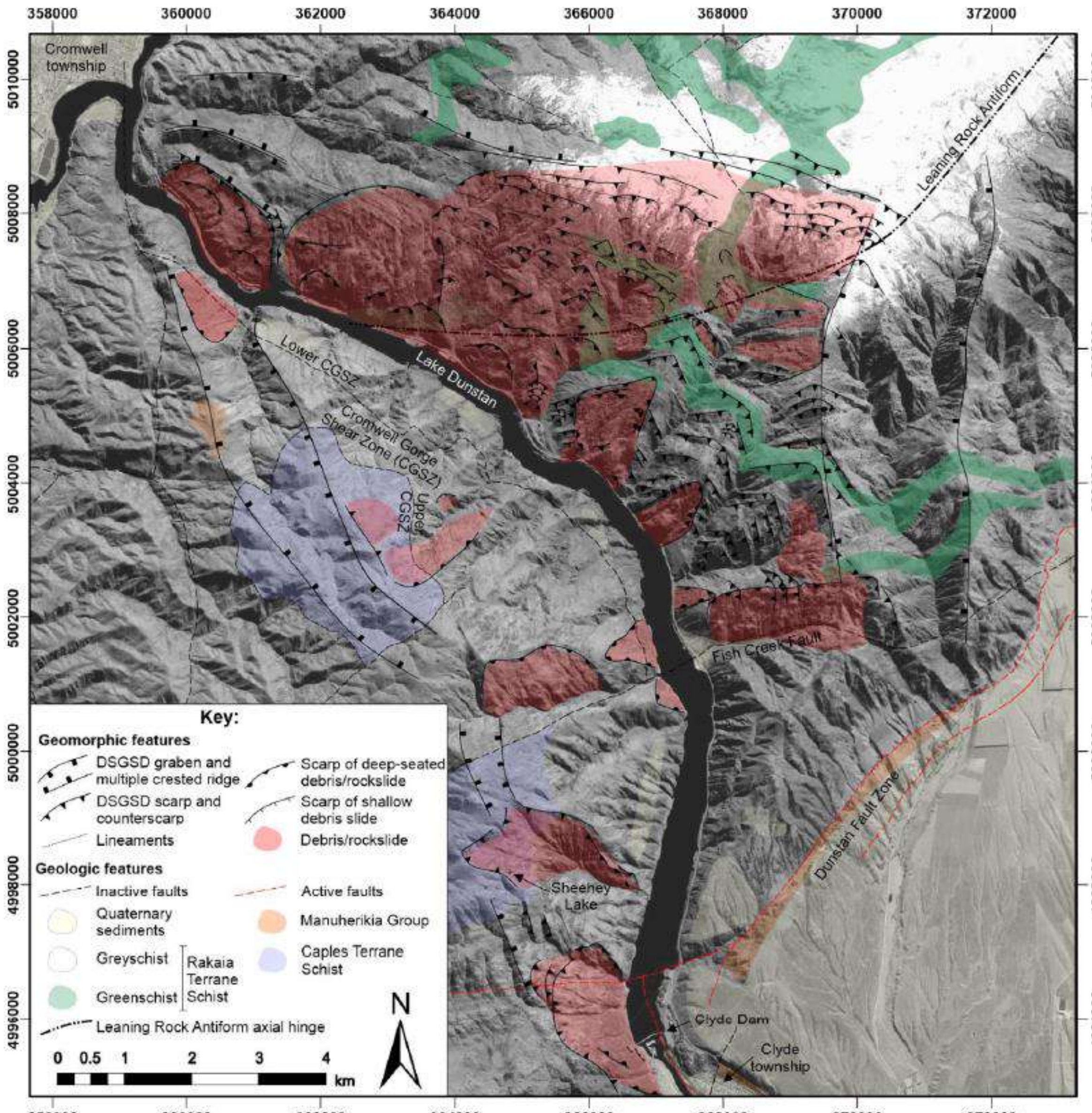


Figure 19. Geomorphology and geology of the Cromwell Gorge (Turnbull, 2000; Ridl, 2021).

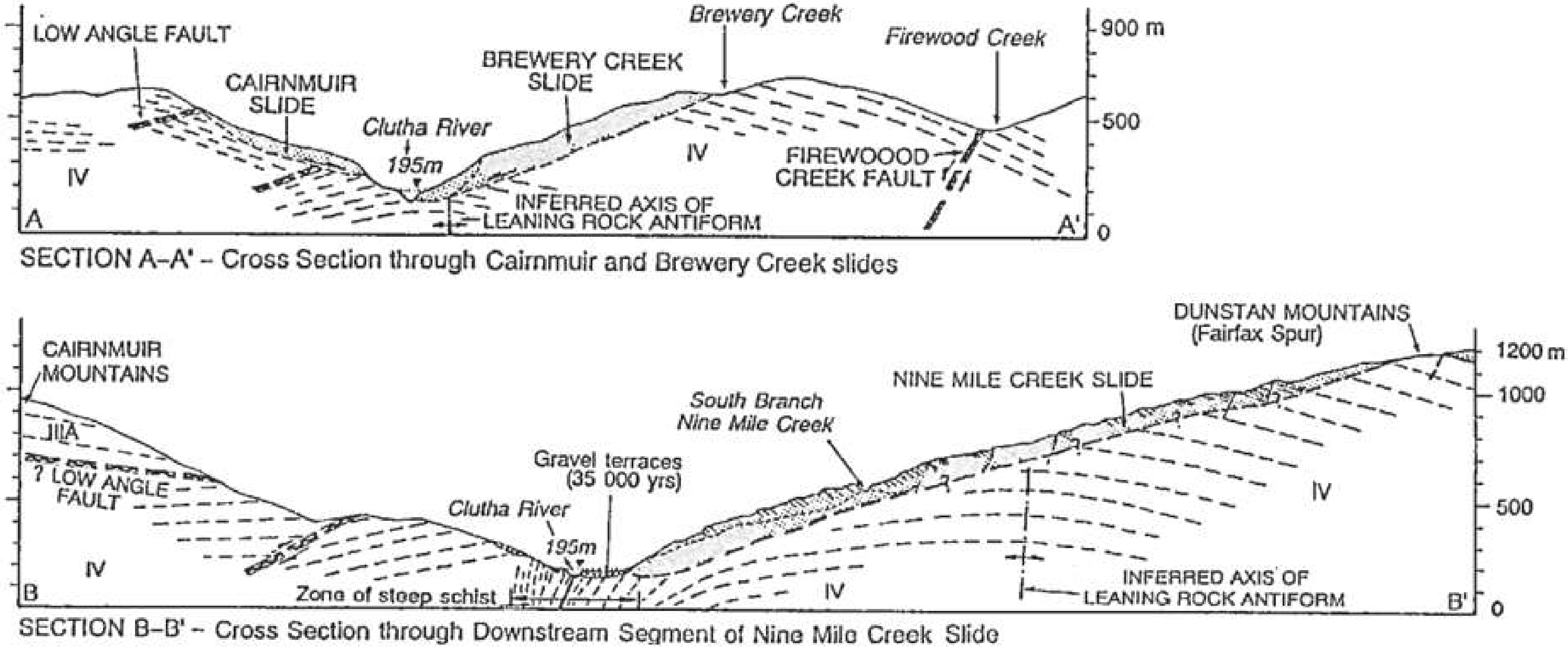


Figure 20. Cross sections illustrating the relationship between landsliding and geological structure (Gillon & Hancox 1992).

5.2.3. Long term monitoring

Contact Energy's dam safety team have continued to monitor the landslides since lake filling and now have performance records spanning more than 40 years. The monitoring requirements have been regularly re-assessed and modified to ensure compliance with NZ's dam safety guidelines. The objectives of the ongoing landslide monitoring are to:

- confirm the continuing functionality of the engineering works, in particular the ongoing reliability and effectiveness of the piezometers, buttress and drainage works.
- provide assurance that the landslide performance remains satisfactory.
- detect warning signs of changes in behaviour that would trigger 'enhanced' (increased) monitoring.

5.2.4. Toe-buckled schist slopes (Nine Mile, No. 5 Creek and Dunlays Slides)

Anomalously oversteepened foliations in deformation zones beneath the basal slide plane were identified at Nine Mile (Upstream and Downstream), No. 5 Creek and Dunlays Slides (Figure 16) were interpreted as a form of buckling deformation associated with Deep Seated Gravitational Slope Deformations (DSGSD). Research suggested the buckling deformation developed with the evolution of the Cromwell Gorge, driven by regional uplift and erosion (Figure 21). The localized nature of the oversteepened foliations is a function of magnitude of in situ stress (> 600 m elevation difference), structural control from the Leaning Rock Antiform, lithological competency contrasts between the competent leucocratic (quartz-rich) and weaker micaceous (mica-rich) laminae result in strain partitioning, upslope-trending fault-controlled steps and hydrological control from the compartmentalized groundwater systems (Ridl, 2021).

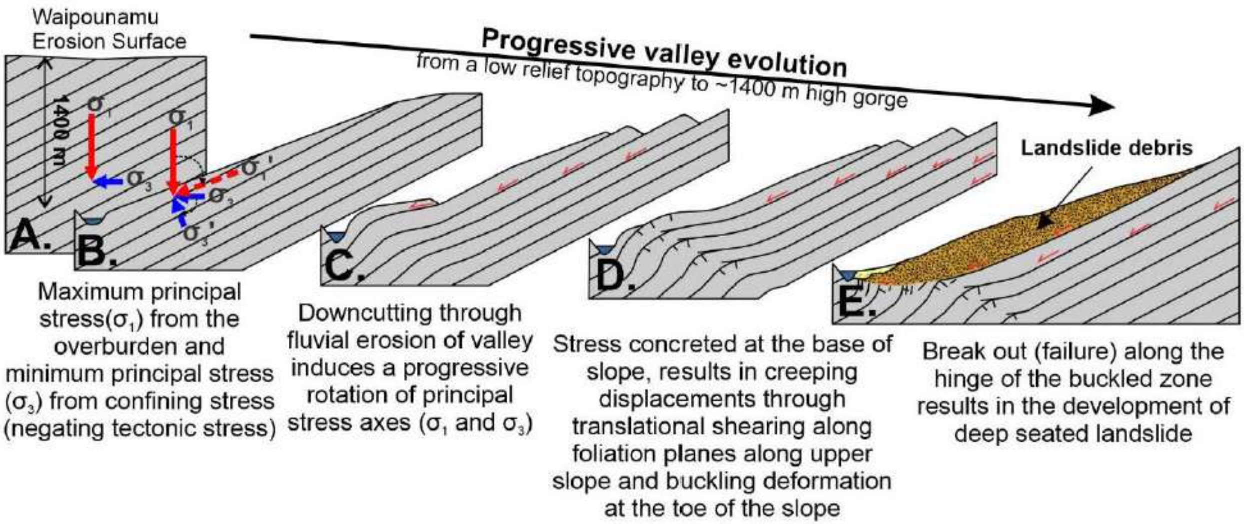


Figure 21. Schematic illustrating the evolution of the Dunstan Flank of the Cromwell Gorge resulting in buckling deformation as the toe of the slope and subsequent breakout with the development of deep-seated landslides (Ridl, 2021).

5.3. Champagne Gully: Overview Jackson Creek Slide (Not a stop)

Jackson Creek slide (Figure 22) is located on the opposite side of Lake Dunstan. The mechanism of failure is wedge failure. Stability analysis indicated that a substantial (25%) reduction in stability would occur as a result of lake filling and toe inundation. Remedial works comprise a 1.2M m^3 toe buttress, 450m of drainage drive and 8000m of drainage drilling plus surface treatment of tension cracks.

The lower slopes were reactivated by stripping for the 60 m high toe buttress, with significantly increased movement rates during construction. The buttress had an immediate beneficial effect on the toe lobes but the upper slope took several years to stop moving. The slide is currently dormant.

Figure 22a. Overview of Jackson Creek Slide (Contact Energy Ltd).

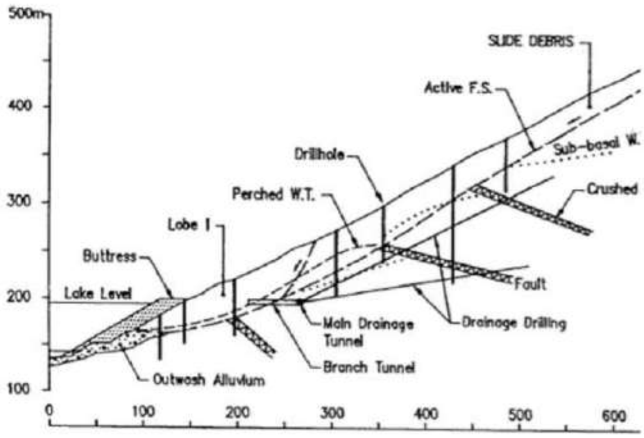


Figure 22b. Cross section of Jackson Creek Slide (NZGS, 2021).

6. Stop 7: Lunch - Orchard Garden café (45 mins)

7. Clyde Dam

7.1. Stop 8: Clyde Dam/Clyde Slide Split Sessions (1.5 hours)

At the dam we will split into two groups each guided by Contact Energy staff. Hard hats will be provided. Half the group will have a tour around the Clyde Dam, powerhouse and slip joint, whilst the other half of the group will be transported a short distance by bus to the Clyde slide and enter Adit DR 550. After 45 minutes the groups will switch over.

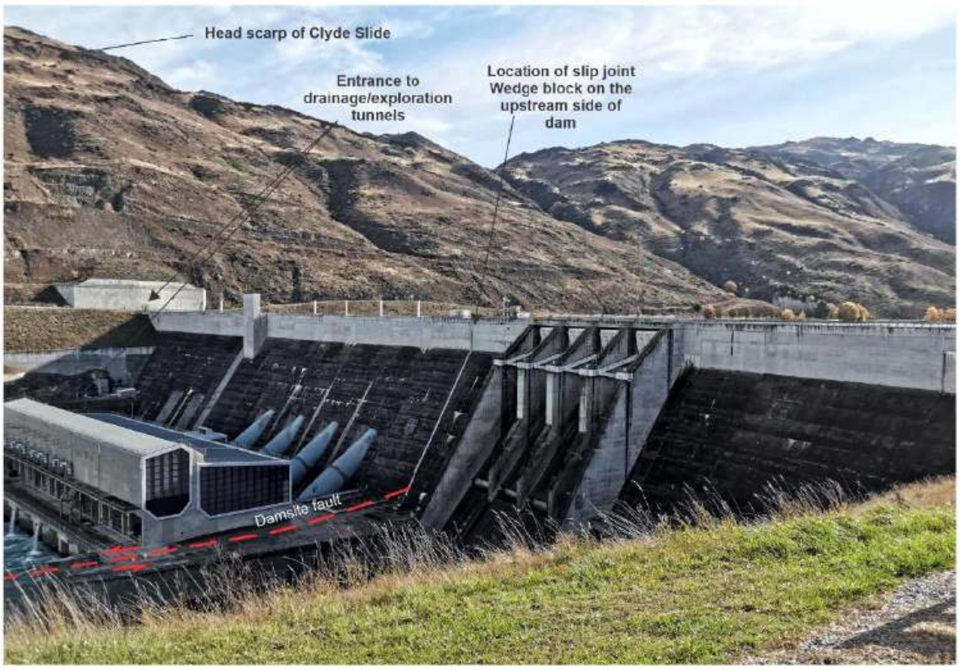


Figure 24. Clyde Dam with the Clyde Slide in the background. Photograph taken in May 2019.

7.2. Clyde Dam

- Clyde is a mass-concrete gravity dam on the Clutha / Mata-Au at the lower end of the Cromwell Gorge.
- The installed plant is four Francis units (consented to 464 MW); two additional penstocks are cast into the structure for possible future units.
- Overall dam length is ≈490 m and height ≈100 m.
- During excavation for the foundations a narrow, slickensided crush zone referred to as the River Channel Fault was uncovered. A slip joint was incorporated into the design to enable the dam to accommodate potential movement (1 – 2 m) along this fault.
- Weak/crushed rock along adverse shears and the River Channel Fault was over-excavated and replaced with concrete. A large programme of foundation cement grouting (consolidation and curtain grouting) was undertaken to reduce permeability and potential leakage paths beneath and around the structure.

Detailed seismic hazard assessment concluded that the River Channel Fault beneath the dam could undergo secondary displacement in a Dunstan Fault earthquake event (Figure 24). For this reason, a 'slip joint' was incorporated into the dam above the fault. The Dunstan Fault (Figure 16) follows the eastern side of the Dunstan Range and crosses the river downstream from the dam. There are well-developed fault traces further north but no evidence of activity close to the dam.

The New Zealand Geotechnical Society (NZGS) Geomechanics News Article from June 2021 provides a great summary of the history of the Clyde Dam (https://www.nzgs.org/libraries/geology-and-the-clyde-dam/).

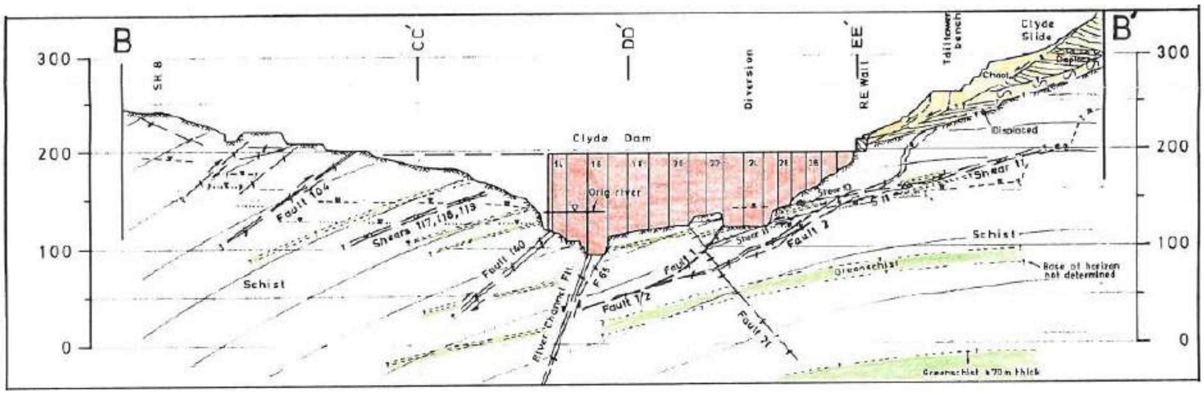


Figure 24. Schematic cross section of the Clyde Dam with the River Channel Fault and Clyde Slide on the true right of the valley (Thomson,1993).

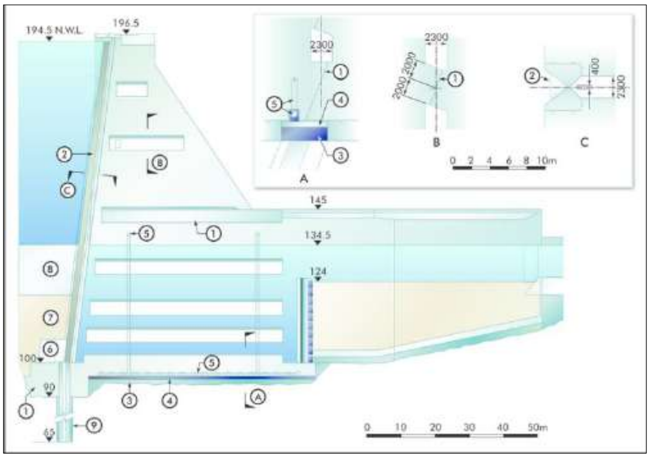


Figure 25. Clyde Dam with split joint. Explanation: 1) Contact surfaces, 2. Wedge plug; 3) Filter zone; 4) Drainage zone; 5) Drainage pipe; 6) Riprap; 7) Gravel blanket; 8) Low permeability blanket; 9) Cutoff shaft (Wieland *et al*, 2008).

Figure 26. Looking upstream along the River Channel Fault, the orange colour excavator is located close to the River Channel Fault cut-off shaft (Thomson, 1993).

Figure 27. Looking upstream along the River Channel Fault remedial excavation (Thomson, 1993).

7.3. Clyde Slide

The Clyde Slide is located on the true right of the Clyde Dam spanning ~2 km of moderate–steep slope and extending from ~RL 190± at the toe up to RL 550± at the head. The slide base developed along foliation shears dipping obliquely downstream and towards the valley and stepping across joints and upslope-trending minor faults. The slide mass comprises chaotic debris with large, displaced blocks (Thomson, 1993) with four distinct zones recognised. In Zone C the slide base is above the dam crest level. This constrained the location of the right abutment.

Figure 28. Clyde Slide taken during construction phase in 1989 (Thomson, 1993).

Because of its proximity to the dam, Clyde Slide has been remediated with a toe buttress, a low-level drainage drive and associated drainage drilling, plus a higher-level drainage drive (DR550) that passes through the landslide and into the underlying bedrock (Figure 29). In addition, the slide is instrumented with inclinometers, piezometers, extensometers, survey and flow measurements. The extensometer and flow data is telemetered to the dam safety team.

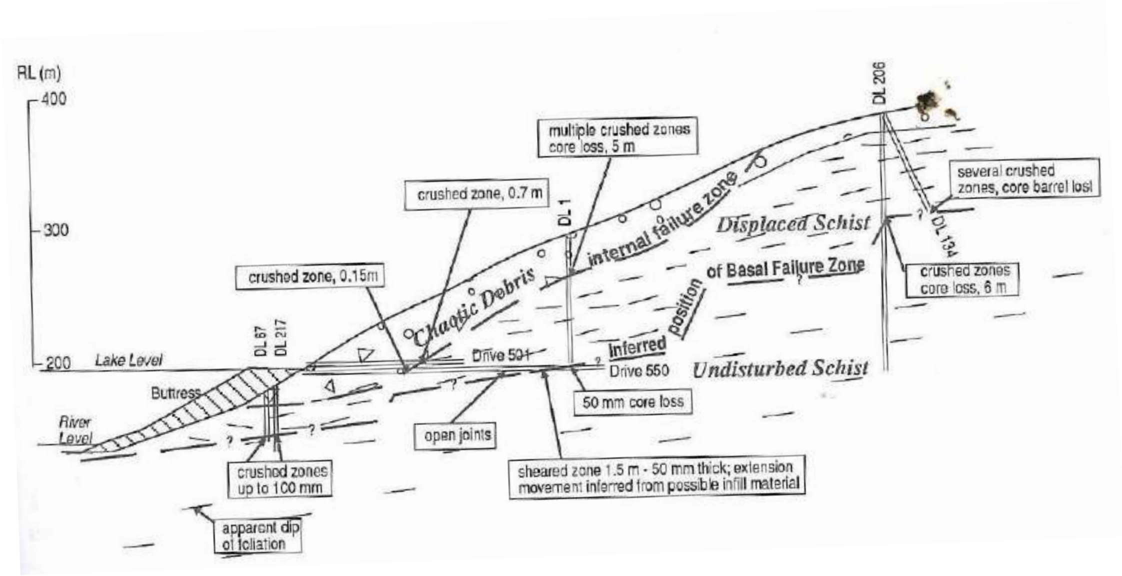


Figure 29. Interpretation of the landslide zones of Clyde Slide (Macfarlane *et al*, 1992).

The inspection of the adit will take us through a concrete-lined section within the landslide and into the in situ rock beneath it. About 700 mm of rock mass relaxation beneath slide base was confirmed by measuring defect apertures when logging the drive.

8. Lake Dunstan Slides

8.1. Stop 9: Cairnmuir Slide and Brewery Creek Slide (15 mins)

8.1.1. Cairnmuir Slide

The prominent geological boundary between the greenish grey volcaniclastic Caples-derived schist and the grey more mica-rich greywacke-derived Rakaia schist is visible about 200 m above lake level.

Cairnmuir Slide, perched about 60m above the lake on the true right of the lake, has formed along foliation drag-folded by movement along the terrane boundary fault. It was the most active landslide in the gorge prior to remedial works with total movement of over 600m and was very sensitive to rainfall. Remedial works consisting of surface protection, drainage tunnels and extensive drainage drilling to intercept infiltrating rainfall have reduced the original movement rate by over 95 % (NZGS, 2021).

Figure 30. Overview of Cairnmuir Slide. The red line is the inferred geological terrane boundary fault (Contact Energy Ltd).

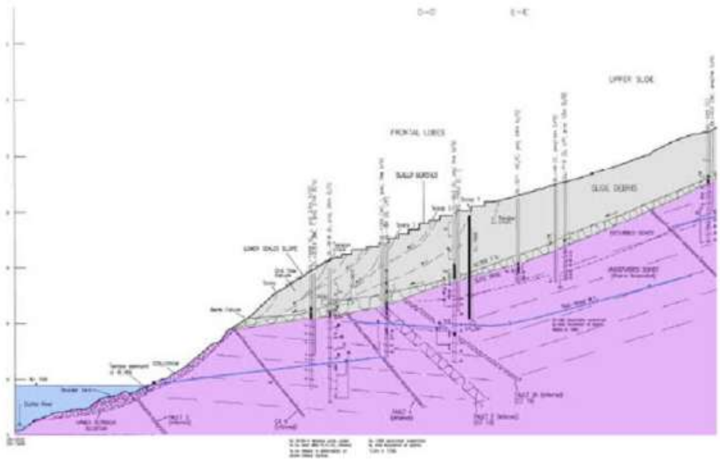


Figure 31. Cross section of Cairnmuir Slide (NZGS, 2021).

8.1.2. Brewery Creek

The slide base of Brewery Creek slide is located well below the Clutha River. Slide base follows a low angle fault (stepped between zones) and it is inferred that the toe of the slide was rotated and ramped up along the Leaning Rock Antiform axial hinge zone (Figure 32).

Stability analysis by the Clyde Power Project indicated that upon lake-fill the landslide would undergo a significant decrease in Factor of Safety. The resulting remedial works implemented included (NZGS, 2021):

- 2 x 10^6 m^3 toe buttress, including an impermeable blanket
- 1.3 km long grout curtain up to 90m deep along the toe
- 1.9 km of drainage drives, including access declines, and a 70 m vertical shaft
- 10,000 m of drains (142 holes) from the drives
- Pumped drainage system from the low-level tunnels installed below the original river level

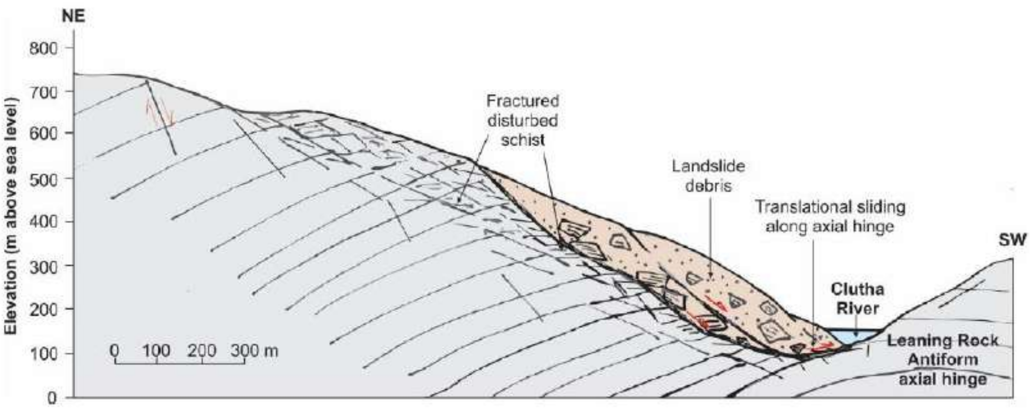


Figure 32. Annotated sketch of the Brewery Creek slide showing the slide base extending below river surface level (Ridl, 2021).

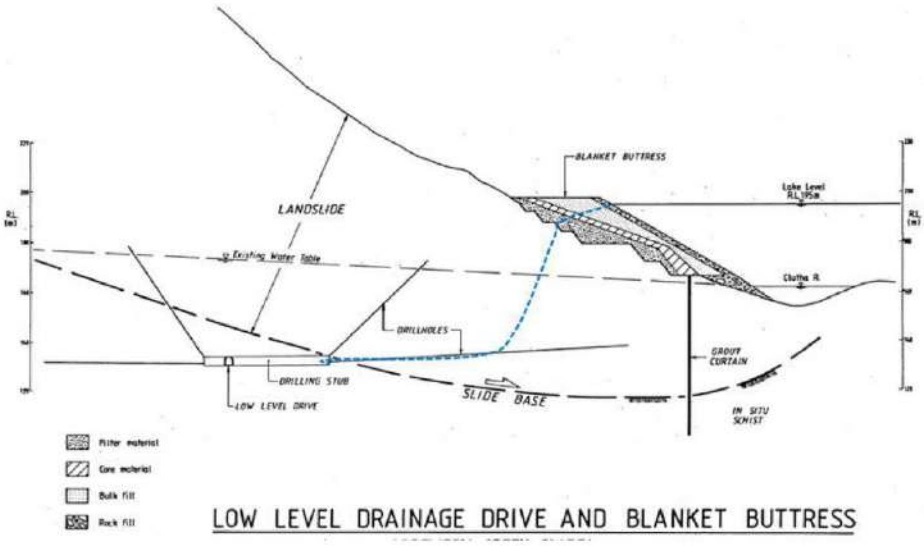


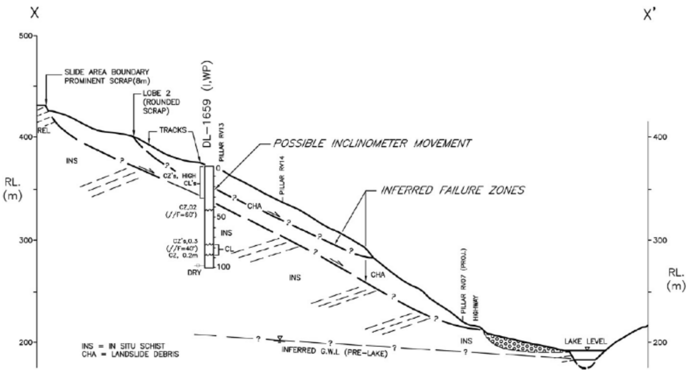
Figure 33. Simplified cross section illustrating Brewery Creek slide remedial works. Blue line is current groundwater profile; dashed line is the original groundwater profile (NZGS, 2021).

Figure 34. Grout curtain under construction at Brewery Creek (Clyde Power Project, unpublished).

Figure 35. Constructing toe buttress, Brewery Creek slide (Clyde Power Project, unpublished).

8.2. Stop 10: Goldfields Mining Centre / Ripponvale Landslide (75 mins)

The Ripponvale landslide is located at the extreme upstream limit of Lake Dunstan (the Clyde dam reservoir) and was not significantly affected by the lake. The headscarp of Ripponvale landslide follows the ridge line ~ 500 m above the lake and it has a volume of ~ 1.2 x 10^8 m^3. The landslide was subdivided into three zones based on geomorphology, outcrop patterns and the position of the slide base relative to lake level.



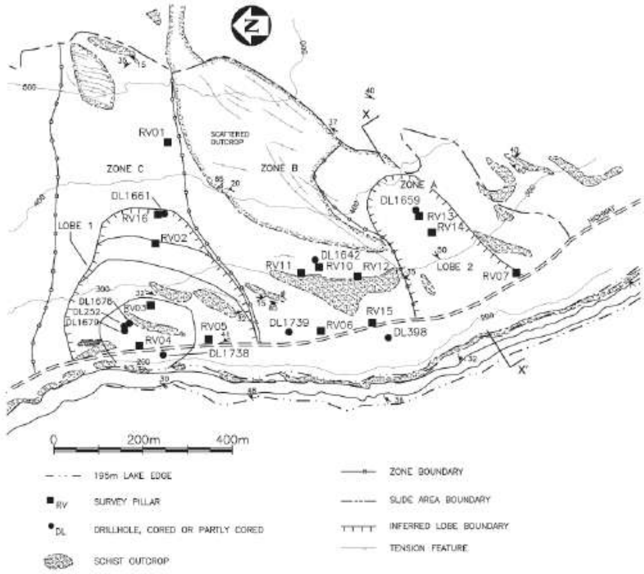


Figure 36. Inferred cross section of Zone A of the Ripponvale Slide (Macfarlane, 2009).

Figure 37. Layout of the Ripponvale Slide (Macfarlane, 2009).

Review of the survey data from Zone A of Ripponvale indicated that the landslide shows that accumulative rainfall of > 300 mm over a period of 3 – 4 months results in landslide acceleration that progressively reduces over a period of 1 – 2 years (Macfarlane, 2009).

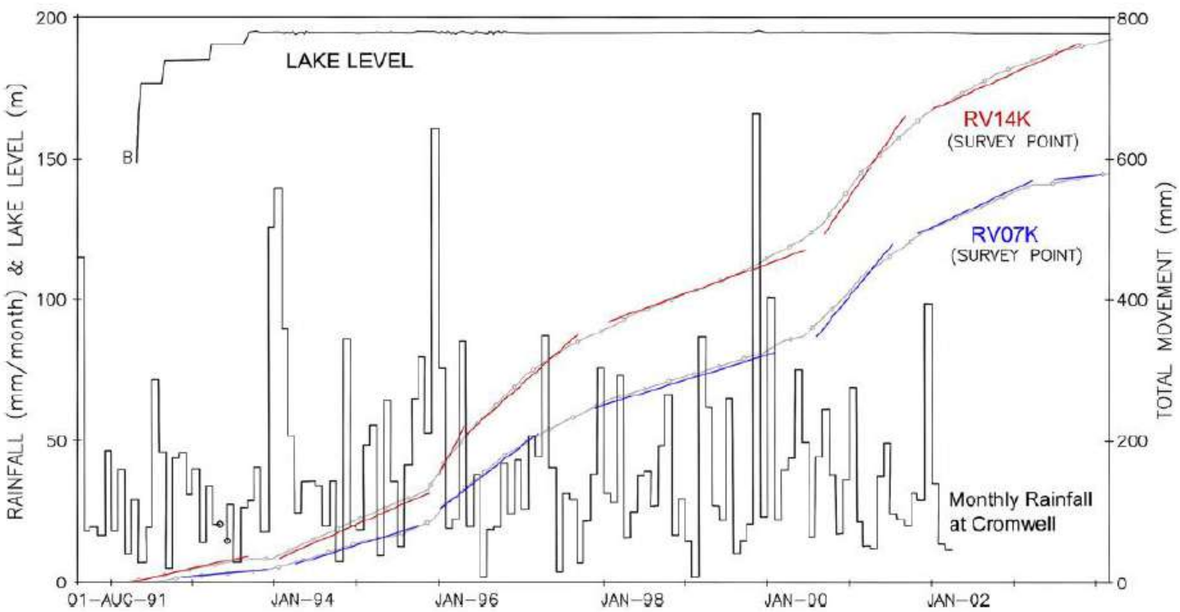


Figure 38. Survey displacement rates at Zone A of Ripponvale Slide and total rainfall for Cromwell (Macfarlane, 2009).

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