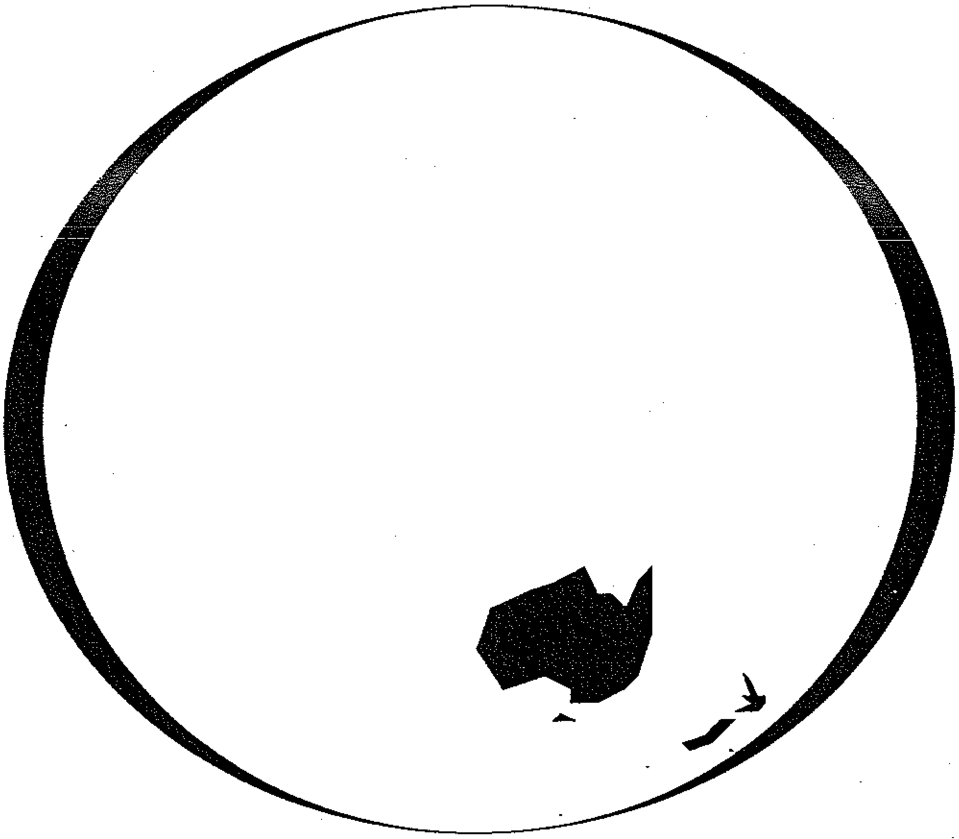
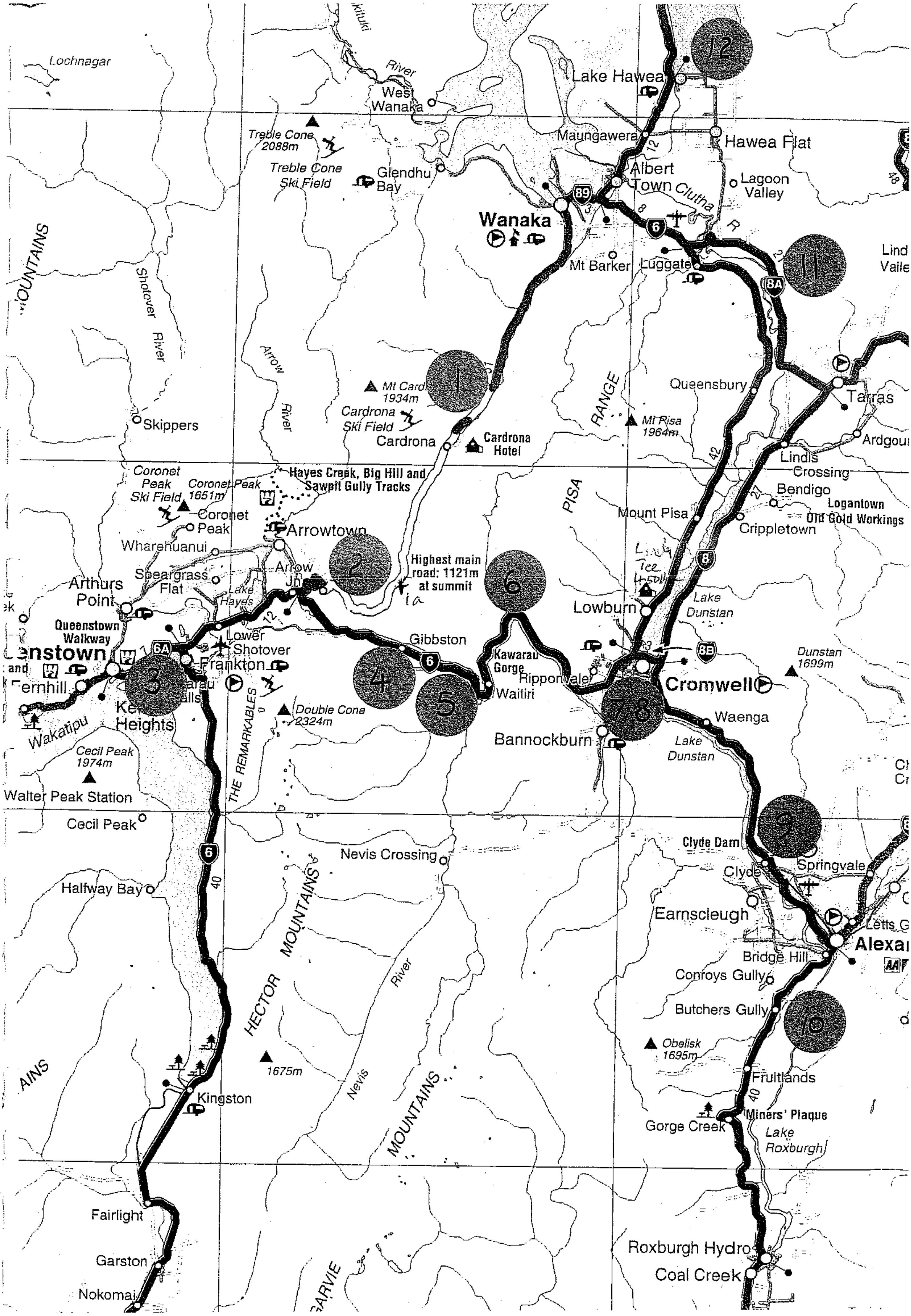
MID-CONFERENCE FIELD TRIP GUIDE



geomorphology
wanaka 2000

Royden Thomson
Jane Forsyth


12
Lake Hawea
Lochnagar
River
West Wanaka
Treble Cone 2088m
Treble Cone Ski Field
Glendhu Bay
Maungawera
Hawea Flat
Albert Town
Clutha R
Lagoon Valley
89
Wanaka
Mt Barker
Luggate
6
8A
11
Lind Valle
MOUNTAINS
Shotover River
Arrow River
1
Mt Cardrona 1934m
Cardrona Ski Field
Cardrona
Cardrona Hotel
Queensbury
Tarras
Ardgour
RANGE
PISA
Mt Pisa 1964m
Lindis Crossing
Bendigo
Logantown
Old Gold Workings
Cripplletown
Mount Pisa
42
8
Skippers
Coronet Peak Ski Field
Coronet Peak 1651m
Coronet Peak
Hayes Creek, Big Hill and Sawpit Gully Tracks
Arrowtown
Wharehuanui
2
Arrow Jn
Highest main road: 1121m at summit
6
Speargrass Flat
Lake Hayes
Arthurs Point
Queenstown Walkway
Lowburn
Lake Dunstan
Lower Shotover
Frankton
Gibbston
6A
Queenstown
Fernhill
3
Kelvin Heights
4
5
Kawarau Gorge
Waitiri
Ripponvale
7/8
8B
Cromwell
Dunstan 1699m
Waenga
Bannockburn
Lake Dunstan
Wakatipu
Cecil Peak 1974m
Walter Peak Station
THE REMARKABLES
Double Cone 2324m
Cecil Peak
9
Clyde Dam
Nevis Crossing
Clyde
Springvale
Halfway Bay
6
40
MOUNTAINS
Earnscleugh
Letts G
Alexa
Bridge Hill
Conroys Gully
Butchers Gully
10
River
HECTOR
Obelisk 1695m
1675m
AINS
Nevis
MOUNTAINS
Fruitlands
Kingston
Miners' Plaque
Gorge Creek
Lake Roxburgh
40
Fairlight
Garston
Roxburgh Hydro
Coal Creek
Nokomai
GARVIE

AUSTRALIA NEW ZEALAND GEOMORPHOLOGY GROUP

MID CONFERENCE FIELD TRIP

13 December 2000

Led by R. Thomson and PJ Forsyth

- **Introduction to Central Otago Geology and Slope Stability (Appendix A)**
- **Climate and Vegetation (Appendix B)**
- **Rivers and Flooding (Appendix C)**
- **Victoria Basin Boulders (Appendix D)**
- **Archaeological Sites (Appendix E)**
- **Glacial Limits (Appendix G)**
- **Quaternary Time-scale (End-chart)**

FIELD TRIP STOPS

1 CARDRONA VALLEY

2 photos

Weathered greywacke gravels of fluvioglacial origin, lying within a catchment that is entirely schist, hint at tectonically induced drainage changes. The source of these gravels may have been near the Southern Alps Main Divide at the head of Lake Hawea. An old drainage system may have flowed "up" the Cardrona Valley and into the Kawarau via Tuohy's Gully (Gentle Annie Fault); uplift of the Pisa Range later reversing this drainage. As there is little or no schist component in the gravels, the former drainage system was apparently isolated from the high-grade schist to the west. The gravels are probably early to mid-Quaternary in age but have not been dated directly.

The lower Cardrona Valley is a graben between two faults of the active Nevis-Cardrona Fault System. The valley changes above Tuohy's Gully to a more youthful form with interlocking spurs. A trace on the NW Cardrona Fault crosses fan surfaces aged 19000-18000 years. The reverse Nevis-Cardrona Fault System has influenced the development of this region since at least the Miocene.

1a 3 photos – Quartz

2 CROWN TERRACE LOOKOUT

Views to the Arrow Basin, with Lake Wakatipu and the Remarkables beyond. The glacial landforms below were formed during several ice advances – at times the glacial surface would have been about 300 m above where you are standing. In the Late Otiran, termini of the Wakatipu Glacier were near Morven Hill/Lake Hayes and at the southern end of Lake Wakatipu (Kingston). When the last Late Otiran glacier retreated, Lake Wakatipu was about 60 m higher than at present, and extended into the Arrow Basin. The Shotover River delta built out into this lake, eventually separating Lake Hayes from Lake Wakatipu **(see Sketch 1 – outline plan of Wakatipu Basin)**.

Both Queenstown and Arrowtown had their beginnings as gold mining settlements, servicing the alluvial and lode gold workings in the Arrow and Shotover catchments, but tourism is now their main industry. Controversial urban planning decisions are resulting in intensive subdivision of what was until recently a predominantly rural landscape. Queenstown is one of the fastest-growing areas of New Zealand (as measured by increases in population and building permits). Not everyone thinks this represents progress.

ARROW BASIN CIRCUIT

The tour will meander around the northern fringe of the Arrow Basin to Queenstown and Lake Wakatipu. Significant geological and historical features will be described en route.

FRANKTON LANDSLIDE

On 18 November 1999, after about 4 days of heavy rain, an old landslide was reactivated at Frankton. A Civil Defence Emergency was declared, enabling authorities to evacuate over 30 homes of which 5 were later condemned. Frankton Road, the main route into Queenstown, was closed for a week.

3 FRANKTON

The Shotover River catchment lies in highly fissile mica-rich pelitic schist and contributes a vast amount of sediment to the Kawarau and Clutha river systems. The old Shotover delta, built into a higher Lake Wakatipu (see above), has been stranded by lake fall, which results largely from recent capture of the lake by the Kawarau River. The delta constricts outflow from the lake to some extent, especially during flood events.

In the last 50 years there have been 8 episodes where Lake Wakatipu rose high enough to flood into Queenstown, with 4 of these in the last 5 years. In November 1999 a flooding event lasted for about a fortnight an dcaused major damage and health risks in Queenstown's central business district, as well as affecting other towns on the lake shore. Landslides and flooded streams closed roads around the district, e.g. the Frankton landslide, and almost all the Cardrona Valley road. Downstream, flooding caused major damage to property at Alexandra.

KAWARAU FAULT TRACE

Just east of the bungy-jumping site, the Kawarau trace of the active Nevis-Cardrona Fault System (see above) crosses paddocks on the north side of the highway. The land surface is offset 6 m and buried soils beneath this surface show at least three 2 m displacement events with recurrence intervals of 4000 to 9000 years.

4 GIBBSTON BASIN

Formerly used mainly for sheep and cattle grazing, the Gibbston Basin has been intensively developed for viticulture over the past 15 years.

Hummocky terrain in the central Gibbston Basin was formerly interpreted as a late Otiran glacial deposit. In 1994 it was reassessed as part of a large landslide, Resta Road Slide – this was probably caused by the collapse of the glacially oversteepened schist slope behind, some 500 000 years ago. The schist debris within the slide area is similar to surrounding *in situ* schist and there are no glacial erratics.

High above the Gibbston Basin lies Coal Pit Saddle, where a sliver of Miocene lignite and quatrz gravel is infaulted along the Nevis-Cardrona Fault System. Lignite was mined here until about 1970 and used to fuel the Lake Wakatipu steamer "Earnslaw".

5 NEVIS BLUFF

The bluff is composed of grey and green schist, with a volcanic dyke, and has a history of instability. A rockfall on 17 September this year blocked the highway for a fortnight. Blasting and sluicing with monsoon buckets were used to remove loose and potentially unstable rock from above the road, and scaling is still going on. The rapids in the Kawarau River below consist partly of debris from other recent rockfalls at this site (e.g. a failure in 1972 which occurred during road realignment), and partly of car keys and small change from the pockets of bungy-jumpers further upstream. However, most of the rapids comprise material from the deep-seated Mt Malcolm Slide across the river, a dip-slope failure **(See Sketch 2 – section through Nevis Bluff)**. Nevis Bluff appears to be the downstream limit of glacier ice in the Kawarau Valley.

BOULDERS ON SURFACE OF VICTORIA BASIN (Appendix D).

6 ROARING MEG POWER STATION

The Roaring Meg drains the western Pisa Range, and saddles with Tuohy's Gully (seen earlier). The Kawarau River here has an inner gorge incised into a stepped strath terrace, with a veneer of auriferous river gravels. The river has cut down as the Pisa Range has risen. Landslides along the valley sides include the Kawarau Slide, a dip-slope failure of some 1.6 billion cubic metres **(see Sketch 3 – cross section through Kawarau Slide)**.

CROMWELL

This town at the junction of the Kawarau and Clutha rivers had its beginnings as a mining town, but the most historical parts were drowned below the waters of Lake Dunstan in 1989.

7 BRUCE JACKSON LOOKOUT

The former junction of the Clutha and Kawarau rivers was drowned with the filling of Lake Dunstan behind the Clyde dam.

The view up the Clutha shows a suite of fluvioglacial terraces – the downstream parts of the Upper Clutha sequence – and the inferred terminal positions of some older (Northburn and Lowburn) glacial advances.

Views of the Pisa and Carrick ranges show the form of these uplifted blocks of the Otago Basin and Range province.

8 HARTLEY & REILLY MEMORIAL

Landslides occur on both sides of the Cromwell Gorge, and these became recognised as potential problems during the Clyde Dam construction (see diagram of major landslides in Cromwell Gorge). Some had potential to fall into the newly-created Lake Dunstan, especially with the raising of the water level to wet their toes, and some threatened the new highway. The Brewery and Cairnmuir slides, and associated works, are seen from this stop.

The memorial commemorates early gold discoveries.

9 CLYDE DAM LOOKOUT

Studies of possible hydro-electric power development in Cromwell Gorge dated from the early 1960s. By the 1980s, up to 30 geologists were involved in investigation and construction of the Clyde Dam. In addition to landsliding in the reservoir area, there are significant seismotectonic hazards to the dam associated with the active Dunstan Fault, and a fault trace passes through the dam itself. This has been taken into account in the design of the dam **(see Sketch 4 – principal features in the Clyde Dam foundations).**

EARNSCLEUGH FLATS, a horticultural area, is underlain by gravel and silt from the Clutha and Fraser rivers. A proposal for opencast gold mining over 560 ha of the flats is well advanced, but has attracted substantial local opposition. Mining of old Clutha River channels about 10 km downstream of Alexandra, in a similar setting, has been followed by effective rehabilitation of pastoral land. An older set of dredge tailings, left unmodified, is now regarded as an historic site.

FLOODING AT ALEXANDRA (Appendix C).

10 BUTCHERS DAM (Appendix F)

Tor topography is well developed on an exhumed ancient erosion surface in schist. Between the Jurassic and Miocene epochs, central Otago may have looked somewhat as interior Australia looks today. A low-relief surface, sometimes called a peneplain, covered much of New Zealand, although there is debate over whether all areas were "planed" at the same time and by the same agencies – some think the whole surface is marine although no marine sediments remain in most of Central Otago. Tors perhaps formed by differential subsurface weathering along joints; later stripping of softer weathered material has left resistant shafts and blocks of schist upstanding. Most Central Otago ranges have tors where they have not been glaciated – good examples are the Old Man and Dunstan Ranges (visible from this stop), the Old Woman (seen earlier) and the Pisa (seen later in the tour). Ranges that have been uplifted further so that the 'pepeplain' erosion surface has been destroyed, occur west of the Nevis-Cardrona Fault System and include the Remarkables (seen earlier).

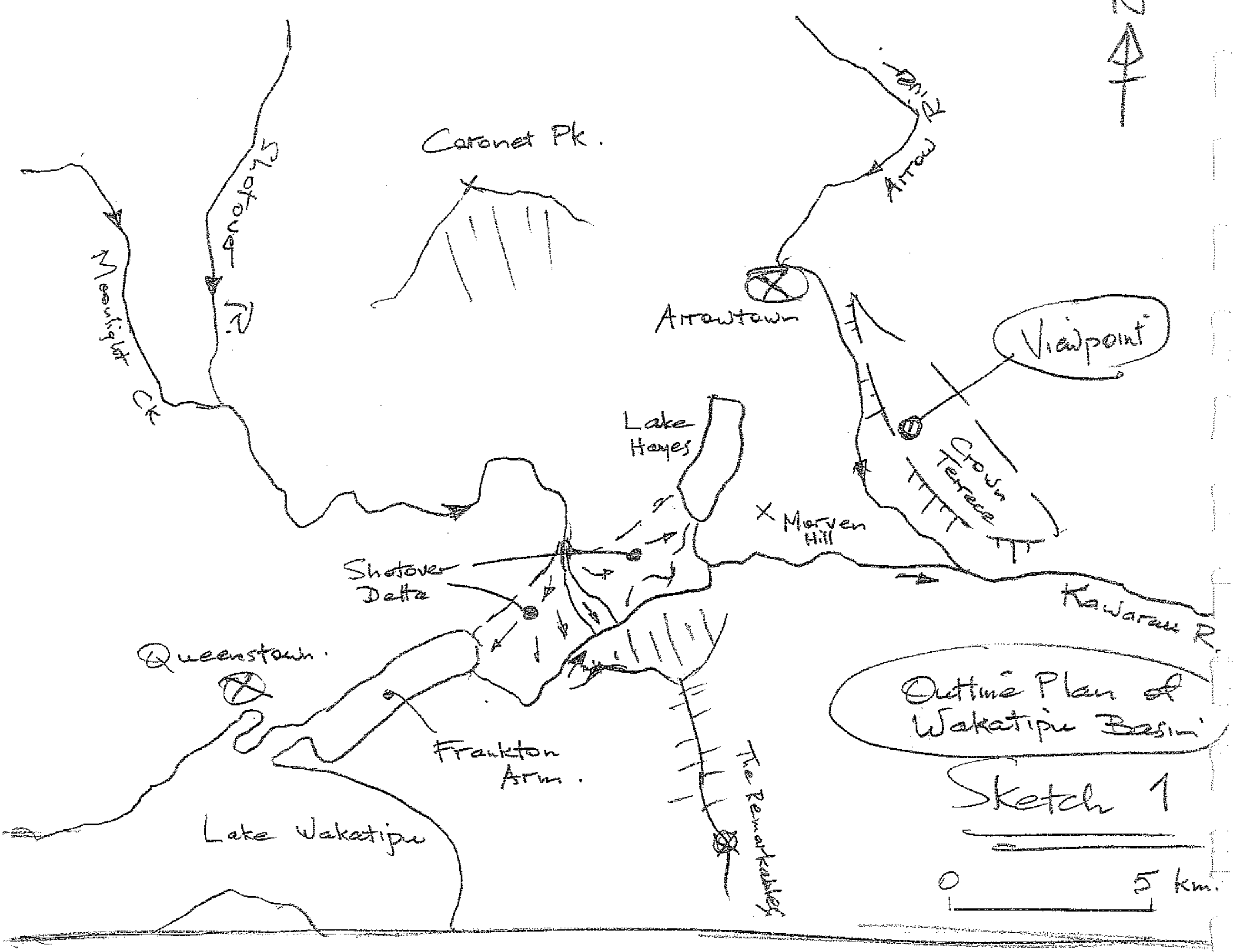
11 SANDY POINT

The Upper Clutha Valley is underlain by a major fault system – the Grandview Fault – linking the Pisa and Nevis-Cardrona systems; deformed glacial lake sediments in drillholes show its Quaternary activity. The ranges to the south (Pisa) and north (Grandview) are quite different in lithological and metamorphic terms, and a Cretaceous history of movement on the Grandview Fault may be inferred.

Continuing with the Upper Clutha fluvioglacial sequence, from this site the ice limits of the younger glacial advances, and some of their associated washout plains, can be seen. On the northern Pisa Range, scattered lateral deposits of the older ice advances are preserved. Large fans are built up off the Grandview Range to the east.

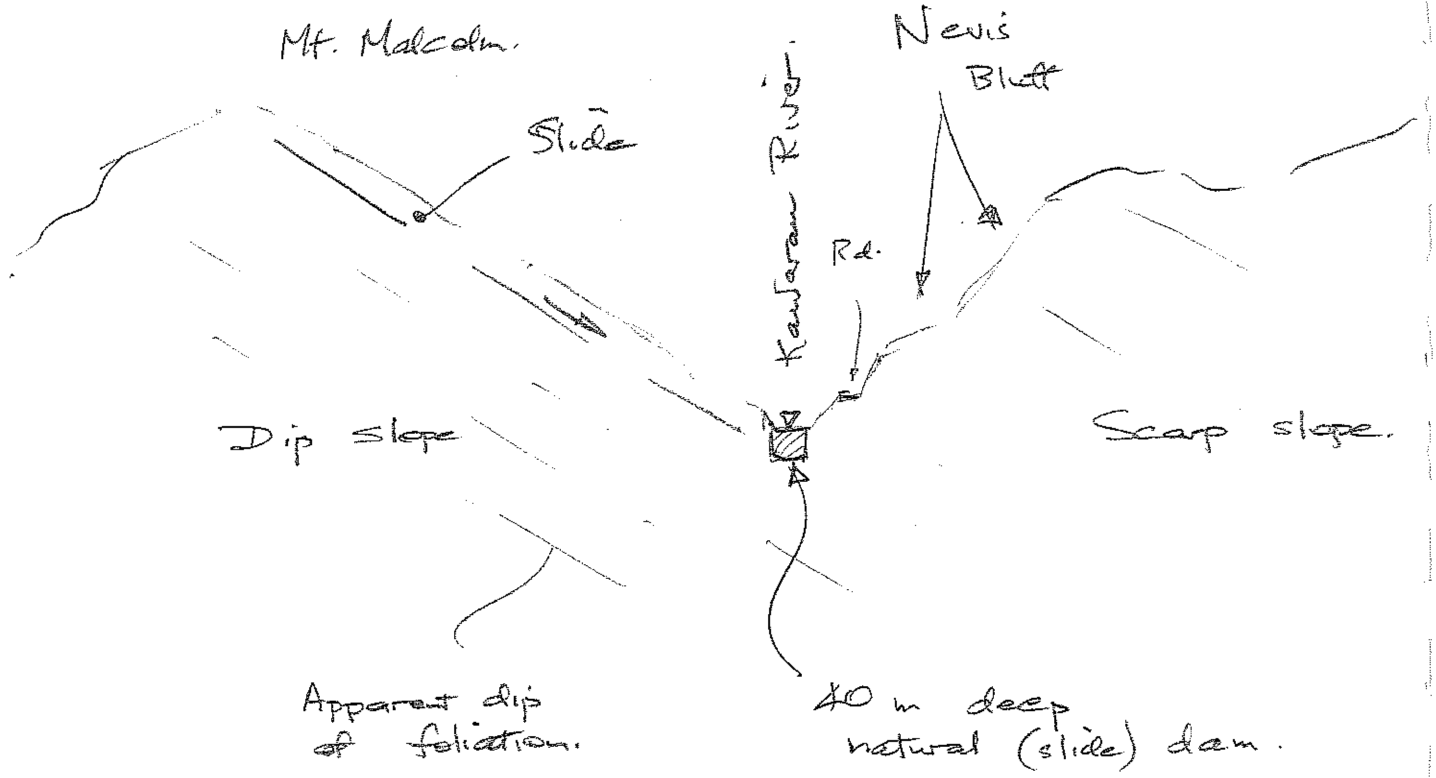
12 LAKE HAWEA

The Hawea/Mt Iron moraines, a couplet of Late Otiran age, impound both Lake Hawea and Lake Wanaka. Till textures are seen in road cuts around Lake Hawea township. At the east end of the moraines, an old overflow channel has been blocked off but is still able to be used as an emergency spillway. At the west end, a dam controls the outflow to the Hawea River, so that Lake Hawea forms a storage lake for the Clutha hydroelectricity generation scheme. The lake level was raised by some 20 m in 1958. This is in contrast to Lake Wanaka, which is uncontrolled.



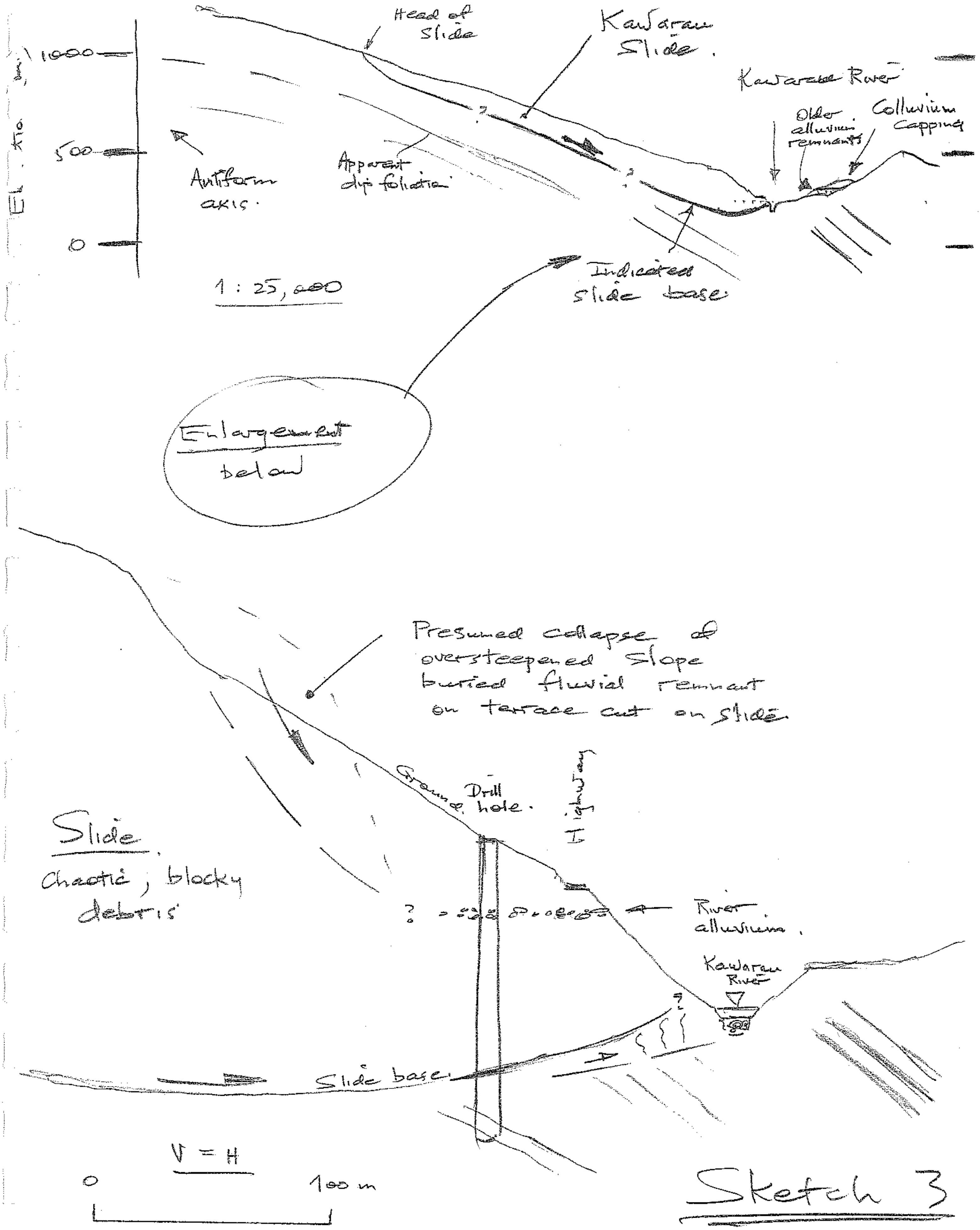
Outline Plan of Wakatipu Basin

Sketch 1



Section Through Nevis Bluff

Sketch 2



Sketch 3

Cross Section Through the Kawarau Slide as Viewed from The Roaring Meg Stop.

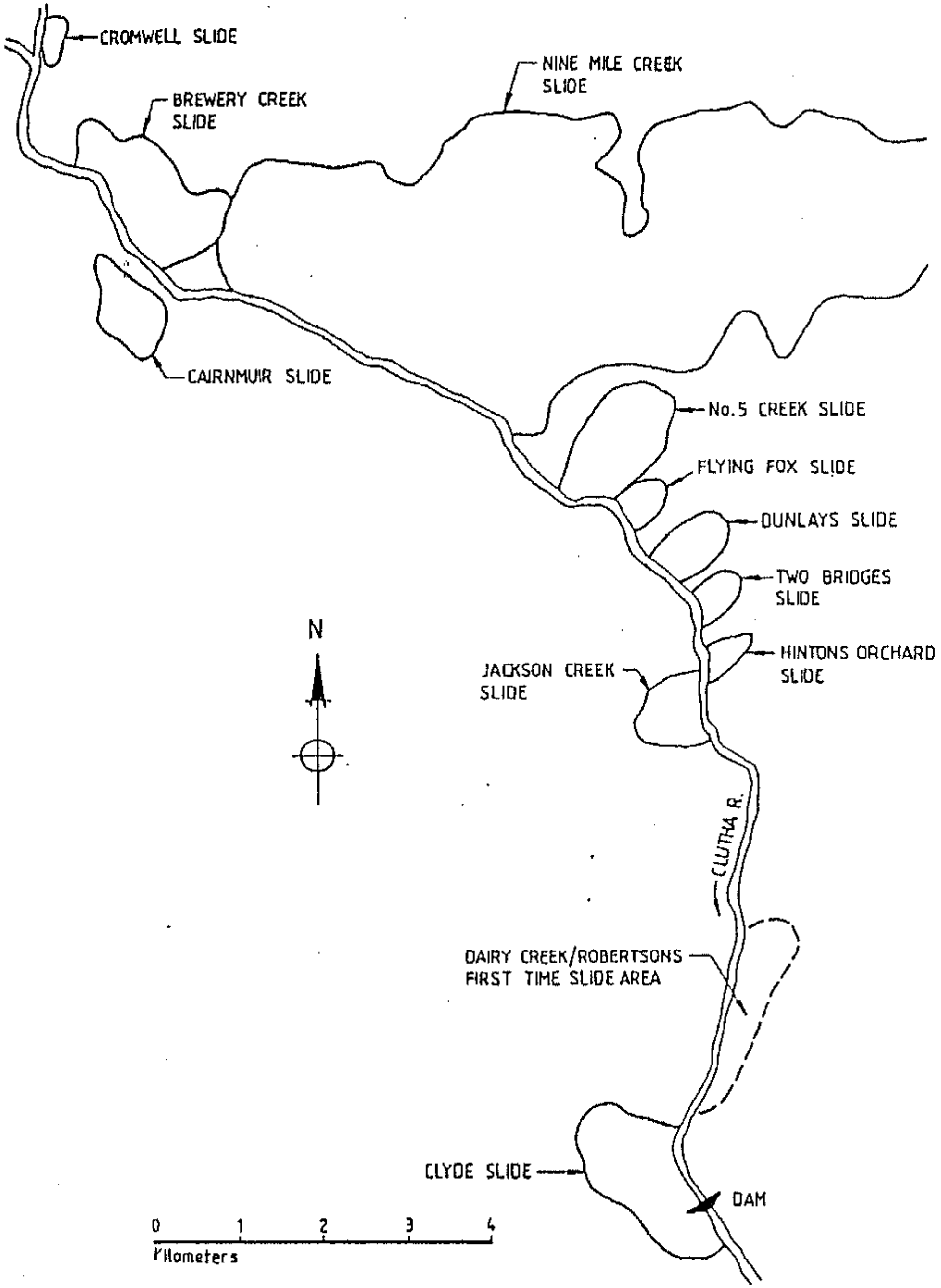


Figure 3. MAJOR LANDSLIDES IN THE CROMWELL GORGE

Sketch 4 and Notes

How is a hydro lake filled when there are landslides?

The filling of a hydro lake is a carefully engineered process. It is the time when the design of the dam and reservoir is tested and verified by careful observation and monitoring. In the event that unfavourable conditions develop, the lakefilling can be halted and if necessary even reversed.

Prior to lakefilling rigorous checks are carried out to ensure that all necessary work has been completed and that monitoring procedures are in place. Following the investigation, each landslide has been assessed for stability during and following lakefilling. Where necessary preventive works have been constructed. In all cases, the monitoring which is to be carried out during lakefilling and the anticipated responses of the instruments are specified.

Monitoring of the landslides is a large task. All major landslides have surface survey points, inclinometer holes and observation wells for measuring groundwater levels. These are read at specified intervals and the results carefully analysed. In addition there are schedules for visual inspection. If the monitoring reveals movement or groundwater trends which are not in accordance with those expected, appropriate actions are initiated. This may be to verify readings, take additional measurements, notify senior staff or to modify the lakefilling programme.

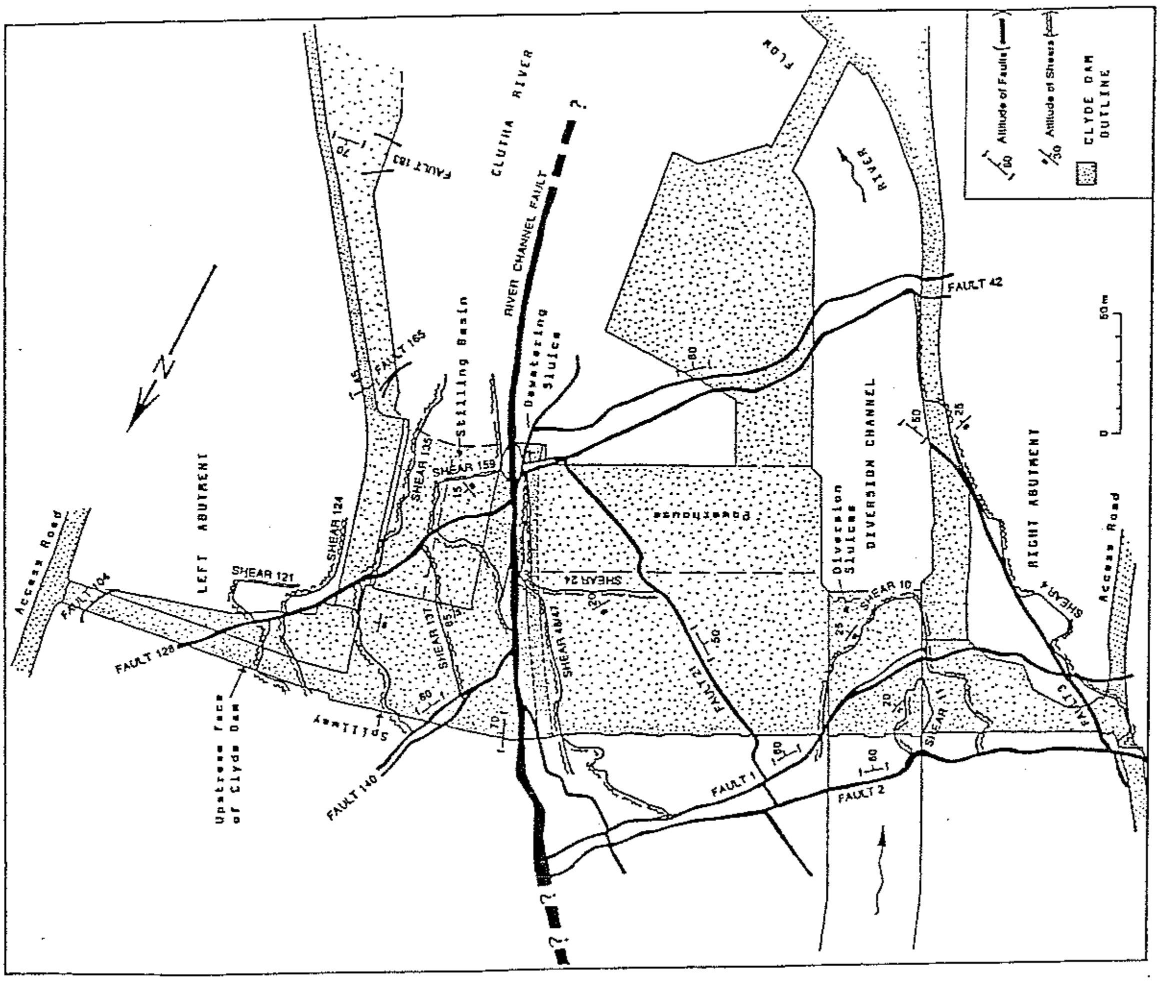
Following lakefilling, monitoring of the dam and reservoir performance will continue throughout their life. The results will be subject to close scrutiny, evaluation and revision by experienced staff. This is an accepted part of the safe operation of this type of facility.

Landslide:	Area (hectares)	Volume (10^6 cubic metres)	Length (metres)
Clyde	120	50	1200
Jackson Creek	30	10	600
Hintons Orchard	9	2	300
Two Bridges	17	1	600
Dunlays Orchard	74	30	650
Flying Fox	11	2	300
No.5 Creek	126	100	950
Nine Mile Creek	700	1000	4000
Cairnmuir	56	20	450
Cromwell	12	3	300

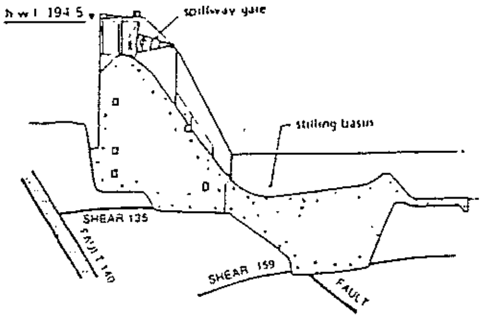
TABLE 1 — SIZE OF CROMWELL GORGE LANDSLIDES

From: New Zealand Geological Survey and Works Consultancy Services 1989: Cromwell Gorge landslides. Electricity Corporation of New Zealand report.

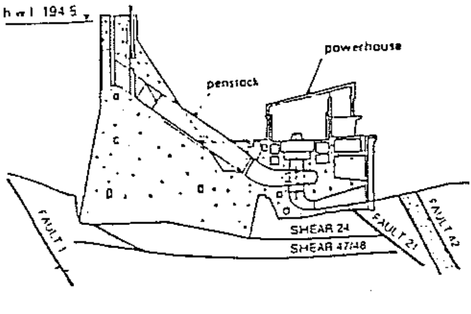
From: New Zealand Geological Survey and Works Consultancy Services 1990: Clyde Dam earthquake investigations. Electricity Corporation of New Zealand report.



Map showing principal geological features in the Clyde Dam Foundations.



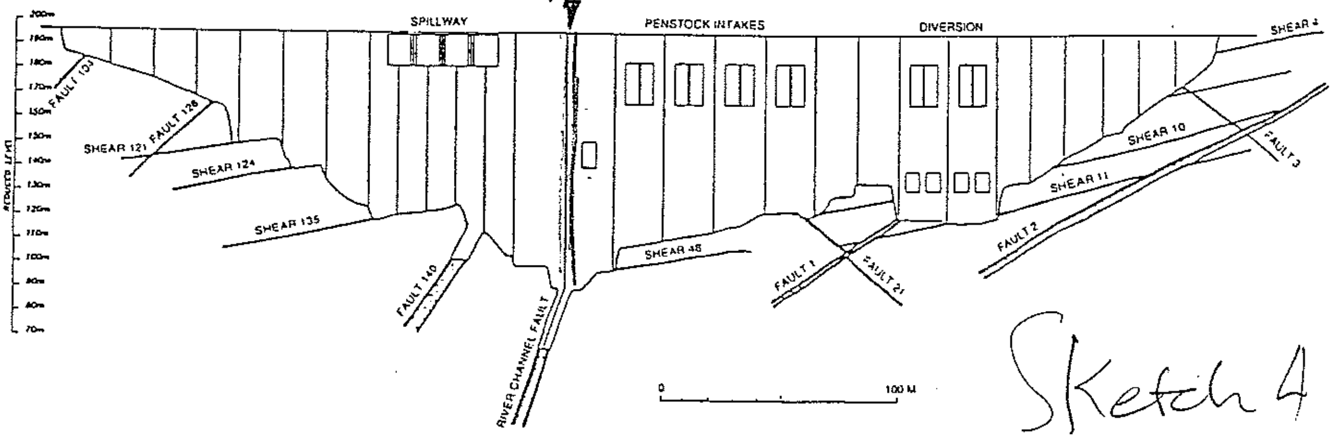
SECTION THROUGH THE SPILLWAY AND STILLING BASIN



SECTION THROUGH A PENSTOCK AND POWERHOUSE

0 50 100 M

Separation gap ?



ALONG DAM AXIS LOOKING DOWNSTREAM

Sketch 4

Cross sections through the Clyde Dam showing principal geological features.

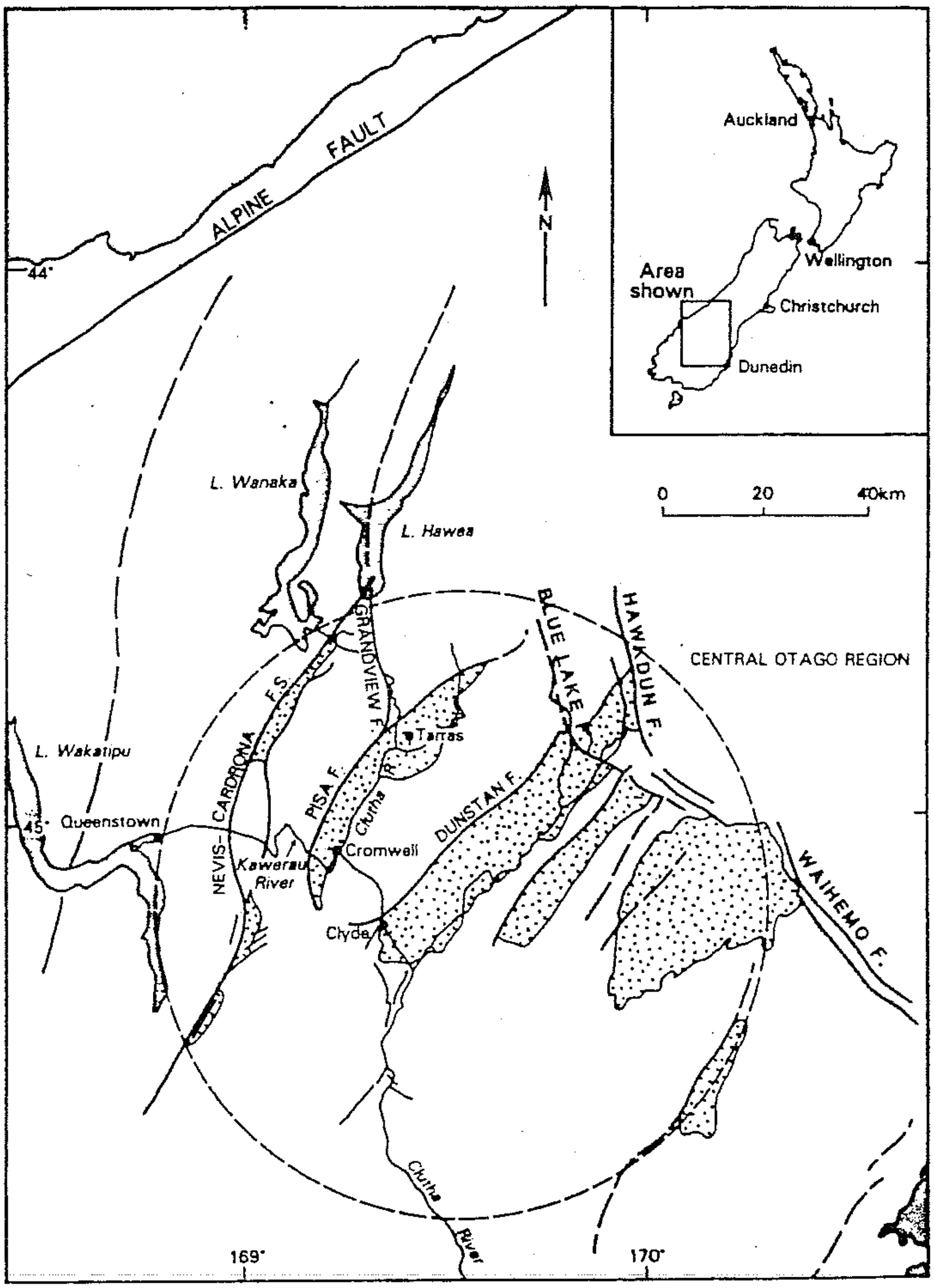


Figure 7-3 Map of Central Otago showing major faults, ranges, and basins.

From: Beanland, S. (compiler) 1987: Field guide to sites of active earth deformation: South Island, New Zealand. New Zealand Geological Survey record 19, Lower Hutt

APPENDIX A

Landslides, Bell (ed.) © 1991 Balkema, Rotterdam. ISBN 90 5410 032 X

Timing of relief and landslides in Central Otago, New Zealand

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ABSTRACT: Deformation of Central Otago in the Kaikoura Orogeny commenced about 5 Ma and climaxed in the last 2 Ma. Faulting and folding produced NE-SW-trending broad schist mountain ranges and sediment-filled valleys with relief of up to 2000 m. Principal rivers of the region flow along synclines and locally through antecedent gorges cut through anticlinal ranges. Deformation has been episodic and is on-going. Relationships between tectonic landforms and dated deposits indicate that most deformation is late Pliocene to mid-Pleistocene. About 15% of the vertical deformation occurred in the last 500 ka. Gorge erosion was controlled by uplift of mountain blocks, and uplift rates must have been similar to long-term average rates of river incision (0.27–0.29 m/ka). Mass movements are widespread on schist in Central Otago. They vary from thin, only slightly displaced regolith, to extensive sagging slopes and deep-seated landslides. The latter are strongly developed on the more steeply dipping foliation of the eastern flanks of mountain blocks, and on the sides of deeply incised gorges. In the Cromwell Gorge, landsliding began before 404 $(^{+150}/_{-60})$ ka. The Clyde Slide was active by 365 $(^{+160}/_{-60})$ ka, and many extant slides may have formed early in the onset of uplift and gorge development. Landslide movement is not constant and some landslides have been more active in the past. There is no evidence of landslide movement in phase with late Cenozoic climatic cycles, rather movement is linked to episodic tectonic uplift and fluvial and glacial erosion.

INTRODUCTION

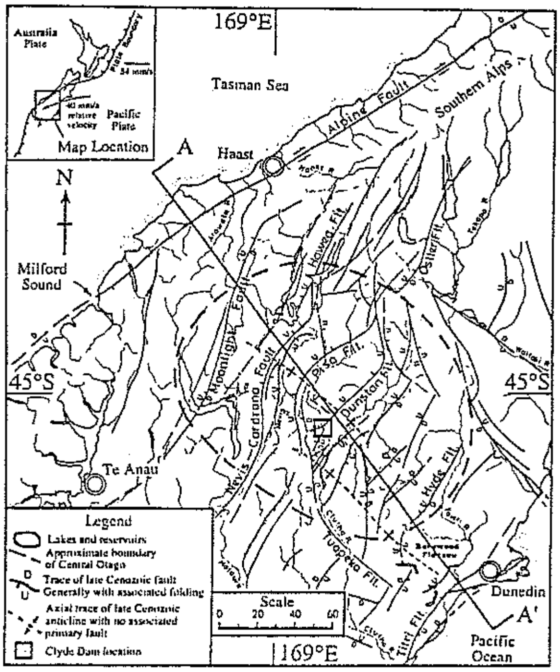
Central Otago is the inland southern region of South Island, New Zealand (Fig 1). In the lee of mountains from all quarters of the wind, it is the driest part of New Zealand, with a semi-arid climate. The region is one of broad-crested anticlinal ranges between wide synclinal basins, with relief of up to 2000 m (Fig 2). The deeply incised Clutha River and its tributaries drain obliquely across the area's structural grain. The mountains have low denudation rates and are dissected by sparse drainage networks. Steeper flanks of schist ranges, and the more deeply incised gorges often are mantled by slowly creeping landslides ranging in thickness up to 300 m. (Fig 3). This paper discusses relationships between the landslides and development of the basin-and-range landscape.

GEOLOGICAL SETTING

Basement schists of Central Otago were metamorphosed largely from quartzofeldspathic sediments about 200–150 Ma. Folding and faulting accompanying the metamorphism is known as the *Rangitata Orogeny*; many rock-mass defects now exploited in landsliding originated in this orogeny.

By 25 Ma, a formerly mountain land had eroded to rolling hills (Stirling 1990), the *Otago Peneplain* of Cotton (1917). The peneplain cut across deeply weathered (10–20 m) schist without regard to structure or lithology.

About 20 Ma, river and lake basins merged into one lake covering most of Central Otago (Douglas 1985). Manuherikia Group sediments deposited in and around it subsequently were overwhelmed with greywacke-derived gravel from the north (Maori Bottom Fm), and schist gravel from the south (Schoolhouse Fm). These units mark a slow beginning at ca. 5 Ma of the Kaikoura Orogeny, which has proceeded at a faster pace in the last 2 Ma. The peneplain now



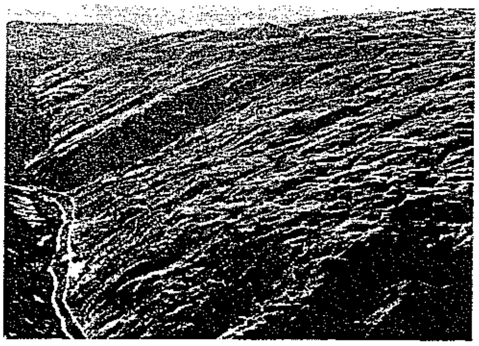


Fig. 3 Kawarau Slide, on left bank of antecedent Kawarau Gorge, 10 km from Cromwell. Toe is at-or-beneath river. Slide mantles schist antiform. Foliation dips toward river in lower slopes, and to right beneath displaced schist (upper right). Valley floor is buckled along toe. Slide thickness locally >350 m ; volume, about 1.5 x 10^9 m^3 (photo: D. L. Homer).

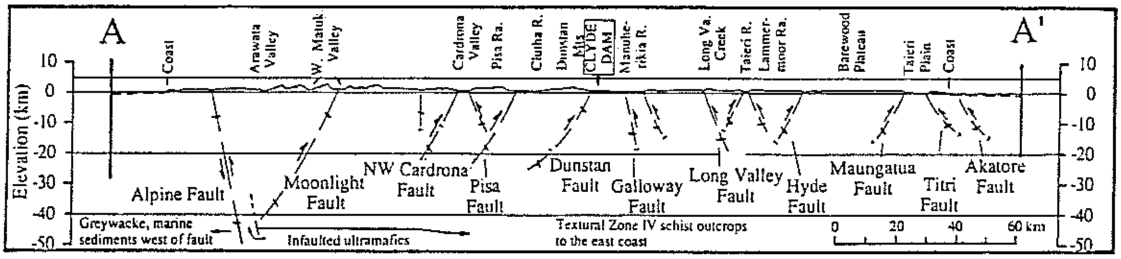


Fig. 1 Principal late Cenozoic fault/fold and fold complexes in Otago (modified after Thomson 1987). Faults commonly flank mountain ranges. First-order folds (not shown for diagrammatic simplicity) parallel major faults.

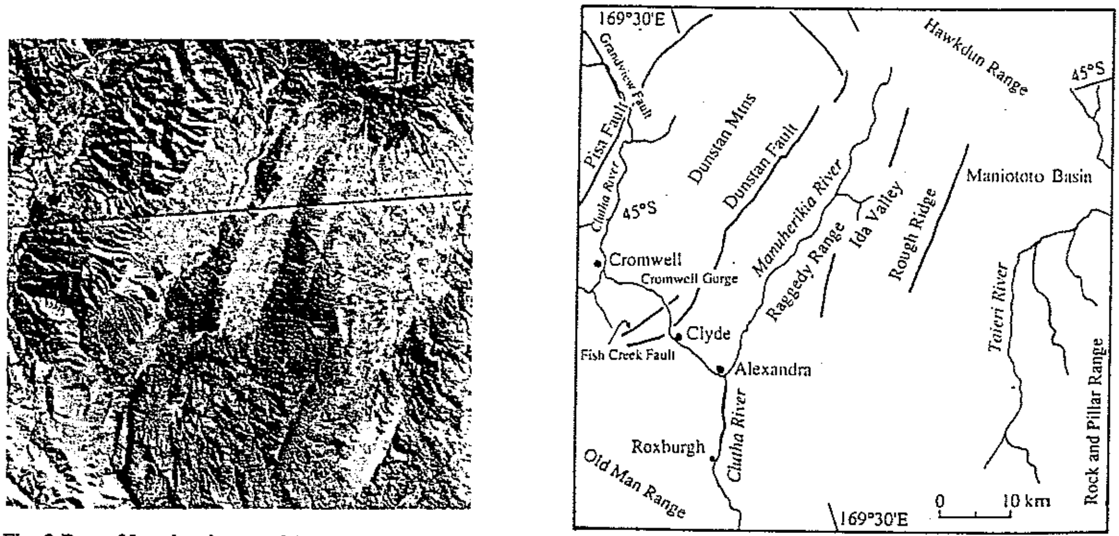
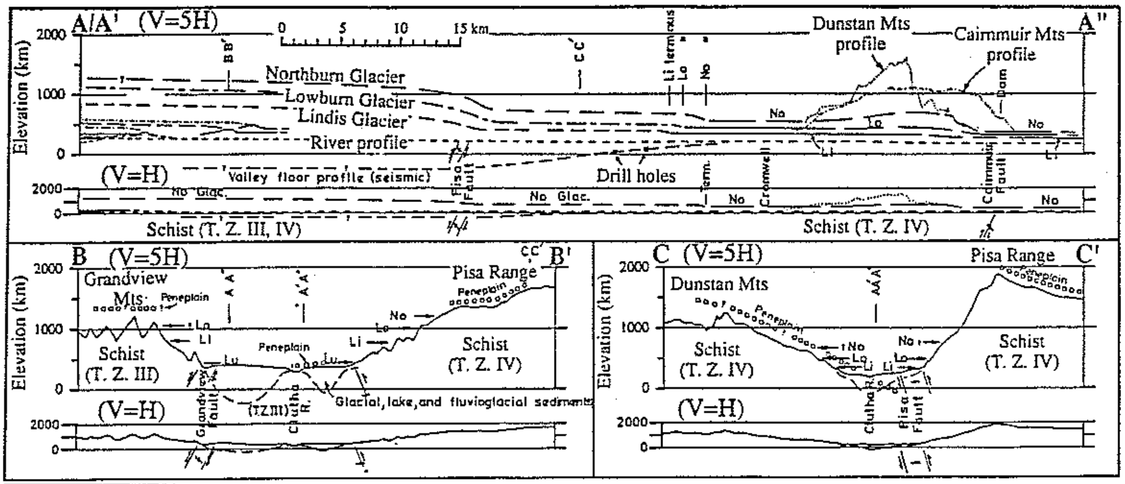


Fig. 2 Part of Landsat images 2805-21163-7 (upper) and 21165-4 (lower) showing warped and faulted peneplain surface on uplands, and basins filled with Cenozoic sediments. Clutha River cuts through southern end of Dunstan mountains to form Cromwell Gorge.



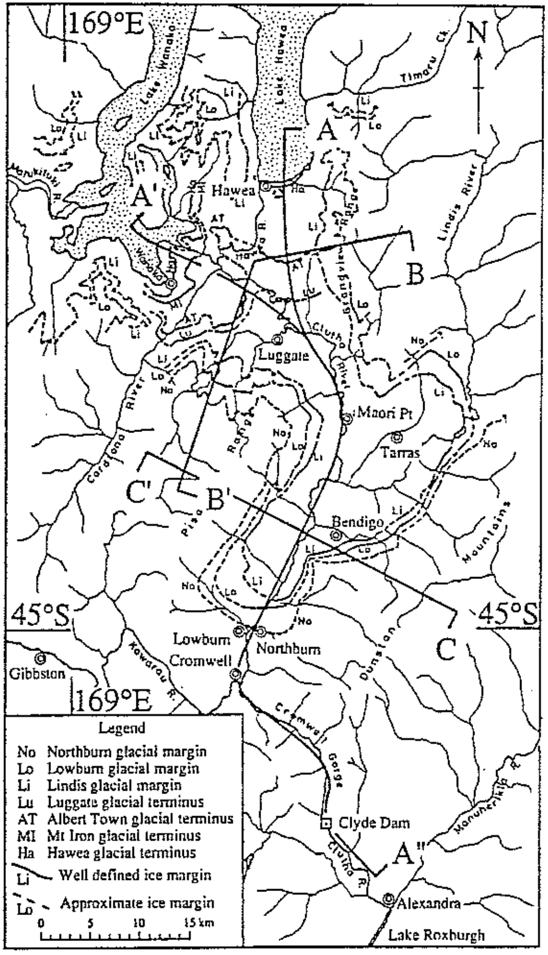


Fig. 4 Ice margins and glacier termini of mid and late Pleistocene age, Upper Clutha Valley. Moraine and terrace profiles of older, higher events through Cromwell Gorge are shown in Sections A/A'-A" (see Table 1 for ages). Two thirds of the relative displacement of crustal blocks (defined from known and inferred peneplain remnants) preceded the known glacial advances which have estimated ages up to ca. 1 Ma.

Table 1 Ages and deformation of glacial deposits and outwash terraces of Clutha River. Age correlation still is in state of flux. All age estimates suggest steady slow uplift in Cromwell Gorge over last 500 ka (Fig 5). See Fig 6 for steepening of modern river profile.

Glacial advance and terrace	Currently accepted age (ka BP)	Possible alternative age* (ka BP)	Isotope Stage	Height above river (m) Cromwell Gorge	Deformation in Upper Clutha Valley	Deformation in Cromwell Gorge
						Modern river locally steepened (Fig 5)
Hawea	18–16	18–16	2	25	None known	
Mt Iron	23	30–23		30	None known	
Albert Town	50–35	70–60	4	35–40	Faulted at Maori Pt and Albert Town**	?
Luggate	70	190–130	6	50–55	Folded and faulted along Grandview Fault**	?
Post-Lindis	250–140	280–245	8	75–120	?	?
Lindis	380–250	360–335 or 475–420 (>413††)	10 or 12	140–150	Inferred deformation of lateral moraines	Warped
Lowburn	ca. 500+	475–420, 565–525, 650–620 or older (>404†)	12, 14 or 16	180	Tilted at up to 60° in Pisa Fault zone	More warped than Lindis, local dips up to 3.5°
Northburn	ca. 1 Ma	650–620 or older	16 or earlier		Inferred deformation of lateral moraines	local 15° dip

* Isotope stage ages from Imbrie et al 1984

** Halliday 1986

†,†† U-Th dates from Central Otago, see text for locations and error limits.

†† May be contaminated by Th from sediment, but Isotope Stage 10 is within lower age limit of 328 ka at 1 standard error.

is widely exhumed. Upland erosion has removed only covering sediments and a 0–20-m thick weathered schist zone (Stirling 1991). It provides a crude datum for inferring deformation (Fig 4). Folding of the peneplain and Cenozoic sediments, and broad folds in the schist (Turnbull 1987) show anticlinal ranges and synclinal basins. Tectonic relief exceeds

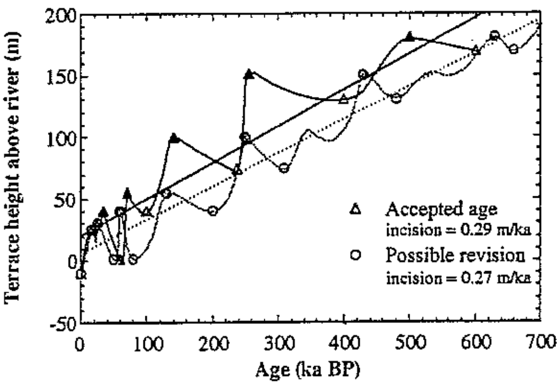


Fig. 5 Terrace height vs age in Cromwell Gorge for two age interpretations (Table 1), showing insensitivity of incision-rate estimates to exact chronology. Filled symbols - glacial aggradation terraces. Open symbols - interglacial strath terraces beneath alluvium. Curves show river aggradation and degradation. Data suggest long-term down-cutting of 0.27–0.29 m/ka.

2000 m, with smaller anticlinal hills with relief as little as 100 m within some basins. Second-order cross-folds make ranges and basins smoothly undulating (Stirling 1990).

Elements of drainage predate the present structural landscape: the Clutha, Kawarau and Manuherikia Rivers cross rising structures in gorges. Some trends may have been inherited from rivers around the Miocene lake. Rivers east of the Manuherikia, however, are accordant with, or rearranged by surrounding structures. Incision there has not kept pace with uplift, reflecting lower gradients and stream power, and not more rapid deformation.

The Otago glacial sequence (Table 1, Fig 4) is described by McKellar, 1960, Officers of the N Z G. S. (1984), Thomson1987, Turnbull (1987). Ages, currently under revision, are constrained by the oxygen-isotope curve (Imbrie et al. 1984) and a few dates from Clutha Valley deposits. Hawea deposits are older than 15.1±0.2 ka (^{14}C, NZ88A, McKellar 1960). A concretion from Lindis-age lake silt at G41:162755 is dated (by U-Th) at 413 ($^{+\infty}/_{85}$) ka, but may be contaminated by Th from the silt. Massive travertine, well dated at 404 ($^{+150}/_{60}$) ka, is from isotope stage 11 and cements Lowburn gravel at G42:188593 (430 $^{+\infty}/_{108}$ ka), G42:196558 (400 $^{+170}/_{-60}$ ka) and G42:196560 (380 $^{+150}/_{-70}$ ka). Northburn deposits are considered to be ca. 1 Ma, but could be as young as oxygen-isotope stage 16 (650–620 ka BP). The chronology provides age control for inferring rates of tectonic deformation and possible uplift (Figs 4, 5).

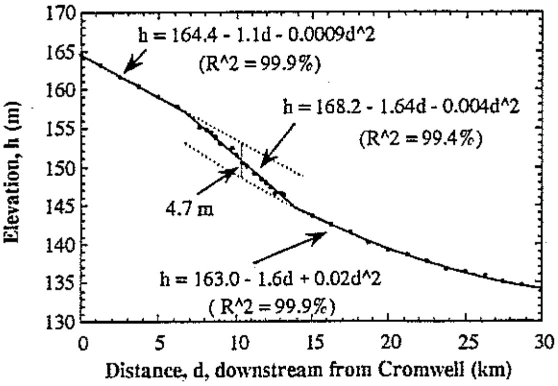


Fig. 6 River profile through Cromwell Gorge showing anomalous steepening amounting to drop of 4.7 m in 7 km. Data within anomaly by survey, otherwise by photogrammetry.

NEOTECTONICS

Central Otago is a block-faulted basin-and-range province (Cotton 1917), with a strong element of folding (Cotton 1919,1941). Some range fronts are monoclinal scarps. Most modern neotectonic studies concentrate on major faults (Fig. 1; see Yeats 1987). Many faults probably are Rangitata Orogeny features reactivated in Kaikoura time. Many are zones of intense fracturing and shearing, tens to hundreds of metres wide.

Timing and amounts of movement on major faults are difficult to evaluate because much displacement occurred long ago, or does not displace anything of known age. Amounts of displacement of mid and late Pleistocene moraines and outwash terraces in the Upper Clutha Valley indicate that most faulting and folding had occurred before 0.5–1 Ma (Fig 4). In the Cromwell Gorge, about 15% of the uplift of the Dunstan Range occurred after ca. 500 ka as recorded by uplift of the Lowburn terrace (Fig 4). Gorge erosion mostly has been controlled by uplift, and uplift rates must have been similar to rates of river incision, about 0.27–0.29 m/ka over the last 0.5 Ma (Fig 5).

Although ranges and basins are folded, it is not known whether folding still dominates. There are few areas where dated surfaces or sediment allow inferences of foldng or uplift rates. Sediment is folded in the vicinity of the Pisa and Grandview Faults, Upper Clutha Valley (Fig 1). The youngest deposits are of Luggate age (Table 1). Lowburn moraine is warped across the north flank of the Pisa Range (Fig 4), but the original profile is known only poorly from theory. The modern river profile in the Cromwell Gorge is anomalously steep upstream of the Fish Creek Fault (Fig 2, Fig 3 in Gillon and Hancox 1992). The river drops an extra 4.7 m in 7 km, in excess of that inferred from gradients up and downstream of the anomaly (Fig 6). Deformation is not apparent in terraces of the last 100 ka, indicating no discrete fault dislocation. A fold of less than 10 m amplitude probably could not be seen in these terraces. The Lindis terrace appears to be be warped by 50 m across the same zone (Fig 4), suggesting that the steepening of the river is not due to river constriction by movement or valley-floor bulging associated with the Nine Mile Creek Slide (see Gillon and Hancox 1992; Beetham et al. 1992a; b). If folding is occurring, it likely is episodic. If it occurred in steps of 4–5 m, a recurrence interval of ca. 75 ka would be indicated, consistent with the lack of visibly warped younger terraces.

Repeated geodetic surveys show continuing deformation in Central Otago (summarised in Pearson 1990). The Central Otago region of about 15 000 km^2 is being shortened along an axis of 50° to 90°. The angular strain is about 0.4 μradians per year west of the Manuherikia Basin (Pearson 1990), similar to rates for the San Andreas Fault in California, and the West Coast of South Island, New Zealand.

LANDSLIDES AND SAGGING METAMORPHIC TERRAIN

Mass movement occurs widely on schist slopes in Otago, forming a stepped and rippled landscape (Figs 3, 7), underlain by deep-seated rock-mass creep (*sagging*, Hutchinson 1988) and thick landslides (>100 m). Hutchinson defines *saggings* as "deep-seated deformations ... which .. do not justify classification as landslides," but admits the features would be "confined slides" if they were smaller and in compressible soil or rock. The inconsistency reflects lack of, and difficulty in obtaining adequate information from depths >300 m. Close association of sagging and landslides in Central Otago is evidence of a genetic continuum, collectively described as *sagging metamorphic terrain* (McSaveney and Stirling in press).

Fig. 7 Landsliding on schist slopes of tectonically elevated Pisa Range at Cromwell (bottom). Pisa Fault (zone) traverses photo below centre, while foreground terraces comprise fluvioglacial sediments of the last 350 ka. Prominent landslide to left of centre probably is actively creeping. Movement rates of displaced schist indicated by discontinuous transverse ridges are unknown, but on-going creep is likely. Foliation dips towards Cromwell as a result of late Cenozoic folding (photo: G. Randall).

Sagging terrain develops on rock masses weak in the presence of water because of structural defects and susceptibility to chemical weathering. It forms by deep-seated creep over tens of thousands of years. It occurs widely on steeper slopes (usually 20° or more) with high relief (usually 1000 m or more, and rarely as little as 300 m). Cromwell Gorge's left bank which averages 22.2±0.1°, is marginally less steep than the right bank at 23.4±0.1°, but is more widely covered in sagged terrain: differences in relief (1650 vs 1200 m), hydrology, and attitude of structural defects seem to account for the differences in slope stability, without leading to major differences in slope angle. Larger areas of sagging terrain occur where foliation inclines down slope, particularly on the steeper eastern flanks of ranges (Fig 7). Sagging terrain is not restricted to Central Otago, and occurs widely in all schist regions of South Island (Whitehouse 1983). Its distribution relates to long-term uplift and dissection, and the *in-situ* mass strength of the rock with all its defects.

Creep during sagging is unmeasured. Landslide creep generally is 0–20 mm/a, reaching up to several metres a year. Rates within landslides depend on groundwater pressure and whether toe material is being removed (by streams or another landslide). Spatially variable, high-pressure water systems occur widely within and beneath Cromwell Gorge landslides, and must occur elsewhere. Precipitation at higher altitudes supplies water, which feeds through faults, crush zones, open joints and rock fractured by movement.

Impervious fault and landslide gouges impede flow, and cause high water pressure and slope instability.

Structural defects and water were present before uplift began, so sagging initiated as uplift and incision provided relief. Landsliding was present in the Cromwell Gorge at G42:188593 before slide debris was cemented at $430\ ^{+\infty}/_{-108}$ ka. The Clyde Slide was active by $365\ ^{+160}/_{-60}$ ka. There is little sagged schist where relief is less than 300 m, or on gentler slopes, so it is likely that sagging appeared first in the gorges, after about 300 m of gorge erosion into schist. The first landslides, however, probably appeared much earlier: soft Manuherikia rocks overlying the schist are very susceptible to landsliding, in small masses, and on low gradients. Landslides likely featured in the landscape from the onset of the Kaikoura Orogeny and the first 100 metres or so of river incision, 2–5 Ma.

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APPENDIX B

CLIMATE

From a 2-yr climatic record on the summit of the Old Man Range, Mark (1965) estimated the mean annual air temperature and precipitation to be 0.6°C and 2100 mm, respectively (Table 1), with a winter precipitation maximum. A mean temperature of near 0°C for the summit was subsequently confirmed following the analysis of a 5-yr climatic record (1963 to 1968) by Mark and Bliss (1970). They also estimated that, on the average, 180 freeze-thaw events can be expected each year, with the soil remaining frozen for up to 3 mo in the winter. From a 6-yr record at 1000 m on the Rock and Pillar Range, Mark and Rowley (1976) estimated the mean annual air temperature to be 5.3°C, and the mean annual precipitation at 1320 mm. Relative humidities seldom fell below 50%. Measurements made at nearby stations over the same period showed precipitation to reach 1800 mm at 1150 m elevation, and then decline to 1020 mm at 1360 m. No record exists for the highest site visited (1760 m on the Pisa Range). However, based on a lapse rate of 1°C per 100 m (Mark, 1965), the mean annual temperature can be estimated at around −1.0°C.

When the foregoing climatic figures are compared with those recorded in alpine tundra areas elsewhere (e.g., French, 1976: 7), the summit regions of the fault blocks at or above 1500 m can be regarded as truly periglacial, a conclusion supported by the widespread occurrence of active turf-banked lobes and terraces on north- and south-facing slopes.

In contrast to the mountains, the basins below 800 m are semiarid (Table 1). The Manorburn Dam climatic station, located 30 km east of the Old Man Range, exhibits a four-fold reduction in precipitation compared with the summit, and a mean annual air temperature of 6.6°C. However, evaporation rates on the summits during the summer can be high. Mark (1965) estimated the potential evapotranspiration for the period December to March on the summit of the Old Man Range to approach that of Alexandra for the same period.

TABLE 1
Climatic information from selected stations in the field area

Location[a]	Altitude (m)	Period of record	Mean ann. ppt (mm)	Mean ann. air temp. (°C)	Numbers of freeze-thaw days
Old Man Range[b]	1590	1959–1960	≅2000	0.6	180
Rock and Pillar Range[c]	1000	1966–1972	≅1300	5.3	
Manorburn Dam[d]	746	1920–1977	497	6.6	130
Waipiata[d]	472	1926–1966	444	8.9	94
Cromwell[d]	213	1949–1980	401	10.8	88
Alexandra[d]	141	1922–1980	343	10.6	86

[a] See Figure 1 for locations.
[b] Data from Mark (1965) and Mark and Bliss (1970).
[c] Data from Mark and Rowley (1976).
[d] Data from New Zealand Meteorological Service (1984).

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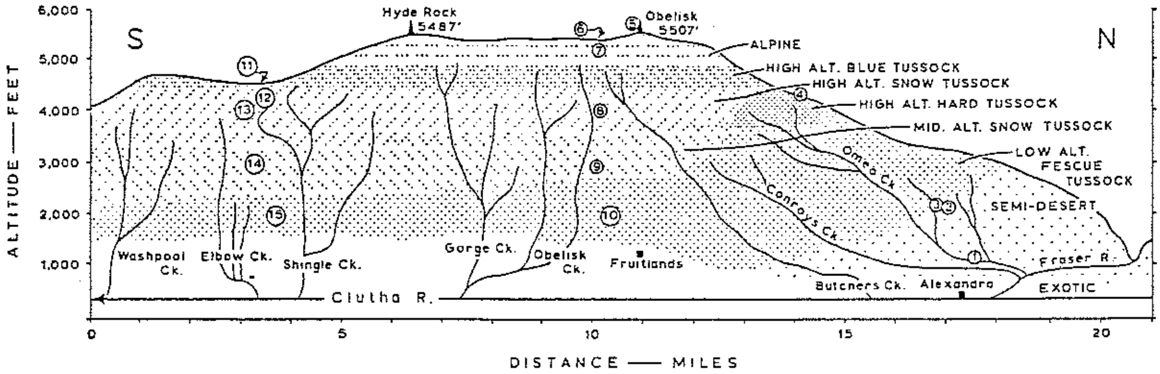


FIG. 12 Semi-diagrammatic sketch of the Old Man Range, as viewed from the east, showing the pattern of vegetation types and the approximate location of the climate stations.

From: Mark A.F., 1965. In: *Central Otago*, Lister R.G. & Hargreaves R.P. (eds), New Zealand Geographical Society.

EFFECT OF SCHEME F ON LOCAL CLIMATE

From analysis of the above measurements, from personal observation of the weather and climate of the region, and from a review of available literature, it is clear that overall, the effects of the hydro developments on climate will be small, and confined to a few hundred metres of the lake and dams. The main changes are discussed below.

1. *Destruction of the climatic resource presently occupied by the Cromwell Gorge orchards.*

This will be the major *'climatic'* effect of the Scheme, since the area is relatively frost free and favoured for apricot growing. For example, during September to the end of December 1974, Earnscleugh recorded 43 ground frosts, Cromwell 30 and the Cromwell Gorge at Annan's orchard but 6. Probine (1949) found temperatures to be on average 3.3°C, and occasionally up to 6°C warmer in the Cromwell Gorge at Annan's than on the Earnscleugh flats. There have been only 3 spring frosts to produce severe damage in the Cromwell Gorge in the last 75 years (Ray Annan, personal communication). All of these were advection frosts, and wiped out most of the fruit for the season in Central Otago.

Furthermore, the Gorge is favourable for fruit ripening, compared with other Central Otago orchard areas. Only Cromwell has similar warmth (Table I), but it suffers the hazard of early to late season frosts. The degree day heat units (base temperature 10°C) for the period November to April 1974-75 inclusive are as follows:

Cromwell Gorge	995
Cromwell	996
Earnscleugh	930
Roxburgh	887

This combination of summer warmth and lack of frost found within the Gorge is unique in the southern half of the South Island. These climatic facts, combined with suitable soils, allow the Cromwell Gorge to produce high quality, high yielding, early season apricots. The area is often described as the most suitable for apricot growing in New Zealand.

Thus the climate of the Gorge is of such high quality that it may be considered as a *first class climate,* and as such, should be husbanded in the same way we seek to conserve first class soils. Areas of first class climate may be considered as those with few climatic constraints, and suitable for intensive horticulture capable of growing a wide variety of crops. Clearly, the Cromwell Gorge is such an area, and with 13.5 percent of Central Otago's apricot trees, represents a resource which is not easily replaced. In the same way as we seek to prevent say, the spread of cities onto first class soils, so also we should give careful consideration before allowing areas of first class climate to be flooded for unrelated economic gain.

Economically Gorge orchardists can take advantage of this climatic resource in a number of practical ways:

(i) Because the risk of spring frosts is low, some orchardists elect not to use costly frost fighting equipment as is essential in most of Central Otago. Therefore, Gorge orchardists can make significant savings. For example, a gravity fed, frost sprinkler system costs about $3000/hectare to install, more if pumps are required. If an orchardist uses frost pots he may expect to burn on at least 5 nights/season (up to 28 nights at Earnscleugh), each burn using up to 4000 litres of oil;

(ii) Because air temperatures close to the ground are warmer than elsewhere in the district, Cromwell Gorge orchardists can prune so that more fruit is borne lower on the tree. This produces significant savings on labour costs for thinning and picking, in that less time is spent climbing up and down ladders. This special situation would lend itself better to highly intensive apricot production, as is being developed in Australia, where up to 90 tonnes/hectare can be expected;

(iii) The lack of spring frost, and high early summer heat units, usually mean the apricots from the Gorge mature one week earlier than those elsewhere in the district. To the Gorge grower this early fruit produces a price of $12/case, compared with a mid-season price of $6/case (1976–77 figures). Earlier harvesting enables him to acquire labour before the demand for pickers elsewhere becomes intense. There are also advantages for the whole district from these Cromwell Gorge Orchards, in that the early fruit lengthens the marketing and processing season.

TABLE I

COMPARISON OF TEMPERATURES DURING A FRUIT RIPENING SEASON AT CENTRAL OTAGO ORCHARD AREAS, INCLUDING THE CROMWELL GORGE*

Month	*Location*	*Mean daily Maximum (C)*	*Mean daily Minimum (C)*	*Mean (C)*
November	Cromwell Gorge	23.1	8.4	15.8
	Cromwell	23.4	7.7	15.6
	Earnscleugh	22.4	6.7	14.6
	Roxburgh	21.4	7.9	14.7
December	Cromwell Gorge	25.7	11.4	18.6
	Cromwell	25.6	11.4	18.5
	Earnscleugh	25.0	10.5	17.8
	Roxburgh	23.4	10.5	17.0
January	Cromwell Gorge	24.4	9.0	16.7
	Cromwell	24.5	10.1	17.3
	Earnscleugh	24.3	8.0	16.2
	Roxburgh	23.1	8.3	15.7

*Data for 1974–75, when mean temperatures were close to 1°C warmer than normal.

Source: Meteorological Observations for 1974. *New Zealand Meteorologic Service,* Misc. Public. 109 (1974 and 1975).

2. Alteration of airflow

With any high dam across a valley, winds in the local area will be affected. Turbulence within a hundred metres or so may increase, or some shelter may be given, depending on direction of air flow.

With any northerly airflow at the DG3 damsite there is serious risk of dust from the site workings being blown down to the township of Clyde and nearby orchards. Such conditions exist for about one quarter of the time. Therefore, a vigorous programme of noise and dust control would seem essential at the dam site during construction.

Under calm, or near calm conditions and clear skies, frosts are a frequent feature of the Clyde area. The airflow and temperature conditions prevailing during frosty conditions close to the DG3 dam site have already been outlined (Fitzharris, 1976). Early in the night classical down valley katabatic air drainage occurs at speeds of 0.5–3.0m/sec in a layer below an inversion 30–40m above river level. This nocturnal air flow will continue with the creation of DG3 lake, but may decrease in strength because the present down valley gradient of 1:500 will be reduced to one of a level water surface.

As well, the possibility exists that some cold air in the northern part of the Gorge may then move toward Cromwell, rather than flow down valley toward Clyde, as at present. This could alter the frost regime of Cromwell.

Sometime in the morning hours (0000 to 0900 hours), the direction of airflow under spring frosty conditions often reverses at the DG3 dam site from down the Gorge, to up the Gorge. Cold air, often accompanied by fog, pushes up the Gorge from the Earnscleugh Basin in a layer about 40m deep. This intrusion of cold air steepens the up-Gorge temperature gradient (Fitzharris, 1976, 1977).

3. Alteration of temperature and frost incidence

A 65m high dam at Clyde would be as high, or higher, than the depth of fog and associated cold air intruding into the Gorge. Hence the DG3 dam will interrupt this process and impede the up-Gorge airflow on many Spring mornings. Consequently, cold air will pond below the dam, with a likely increase in the frost incidence and severity at Clyde. This cooling will be effective within about 1 km to the south and southeast of Clyde, and will increase the risk of frost damage to nearby orchards at the Gorge mouth.

The effect of the lake behind DG3 on temperature around Cromwell is uncertain. Several conflicting processes will be operating. Some, such as the presence of a water body, will act to moderate temperatures. Others, such as the previously mentioned cold air drainage toward Cromwell up the Gorge, will cool night time temperatures. Then too the urban heat island of the enlarged Cromwell will act to warm temperatures. Oke (1973) reports the maximum size of the urban heat island (found on clear, calm nights) is given by:

$$\Delta T = 2.96 \log P - 6.41, \text{ for North American towns} \qquad (1)$$

$$\text{or } \Delta T = 2.01 \log P - 4.06, \text{ for European towns} \qquad (2)$$

where ΔT = difference between background rural and highest urban temperatures (heat island intensity) in °C

P = population of town.

Cromwell's present population of 1500 is forecast to grow to perhaps 7000 at the height of hydro construction. Thus using equation (1), its heat island, presently predicted at 3.0°C will rise to 5.0°C. Alternatively, using equation (2), it will increase from 2.3°C to 3.7°C. The present urban heat island of Cromwell has been measured on two occasions, and ΔT found to be 2°–3°C, similar to that estimated by the equations. Thus an enlarged Cromwell may have an urban heat island up to 2°C warmer than present.

4. Increase in fog incidence

The increased water surface area in the Upper Clutha Valley is likely to increase the incidence of autumn and winter fog near Cromwell. A definite increase in fog occurrence is reported overseas in a number of studies on small man-made lakes (Nemec, 1973). The main mechanism is cold air advection over a warmer water surface. Such an increase in fog incidence at Cromwell could be investigated further by applying mathematical models for the numerical solution of the heat and moisture diffusion equations for the turbulent boundary layer above the lake. Such simulation methods are currently used to predict fog produced by cooling ponds of thermal power stations (Tsai and de Harpporte, 1973).

5. Effect on rainfall

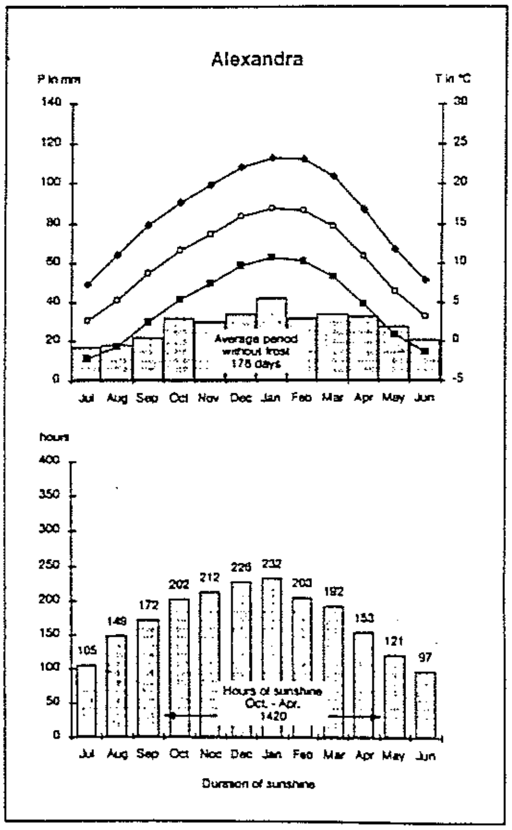
Central Otago has a well developed summer rainfall maximum, often ascribed to convectional thunderstorm activity produced by strong surface heating (Maunder, 1965). There is some overseas evidence that man-made lakes can suppress thunderstorm activity, and hence rainfall, by reducing surface heating (Nemec, 1973). The effect appears most pronounced with a large number of small reservoirs in the same region, but may be less important in mountainous areas such as Central Otago, where the hills themselves rather than the valleys, act as significant summer heat sources for the atmosphere.

From: Fitzharris B.B., 1979. *Climatic questions in the Upper Clutha Valley*, New Zealand Geographer 35(2): 64-70.

TABLE I
CLIMATE STATISTICS FOR NEW ZEALAND AND CENTRAL EUROPEAN WINE AREAS FOR THE GROWING SEASON

Climate Station	*Latitude (degrees)*	*Sunshine (hours)*	*Frost-free period (days)*	*Temperature of warmest month (°C)*	*Growing Degree Days (base T of 10°C)*
Auckland	37S	1388	309	19.7	1,626
Gisborne	39S	1479	294	18.8	1,377
Napier	40S	1490	306	18.9	1,440
Blenheim	42S	1601	233	17.4	1,170
Alexandra	45S	1420	176	17.0	979
Queenstown	45S	1389	227	15.8	775
Montpellier	44N	1929	244	22.3	1,760
Bordeaux	45N	1541	214	19.6	1,356
Freiburg	48N	1368	195	19.4	1,146
Bernkastle	50N	1138	190	18.7	1,026
Ahrweiuler	50N	1088	178	17.7	887
Wurzburg	50N	1302	168	18.2	957
Geisenheim	50N	1322	197	18.5	1,044

Data Sources: New Zealand National Institute of Water and Atmospheric Research and the German Weather Service.

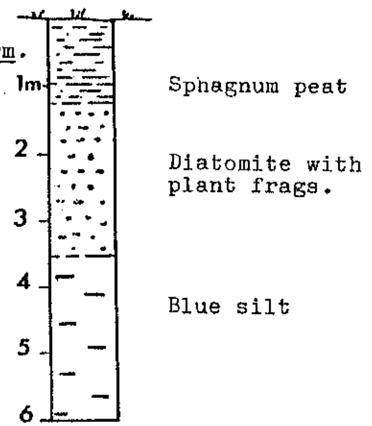


From: Fitzharris B.B. & W. Endlicher, 1996. *Climatic conditions for wine grape growing*, New Zealand Geographer: 1-11.

TWO POLLEN PROFILES ON THE OLD MAN RANGE

(M. McGlone)

These notes are preliminary only as full pollen diagrams have not yet been constructed. No radiocarbon dates are available, although a sample for dating has been submitted from the Waikaia Bush Road site. 2 sites have been examined on the Old Man Range:-



1. *Campbell Creek. Altitude 1,220m.*

This site lies in a small glacial valley. Peat, overlying silt, covers the valley floor to a depth of one to two metres. At the site sampled however, sediment depth is approximately 6 m.

Vegetation History

The vegetation changes deduced from the pollen curves are essentially similar to those already reported for the central South Island. At Campbell Creek the first plant cover after the glacier retreated was extremely sparse consisting of scattered herbs and low growing woody cushion plants.

Pollen production must have been extremely low at the site and the pollen of tree podocarps and *Nothofagus* which forms an appreciable proportion of the pollen spectrum must have arrived by long distance dispersal from distant areas.

As conditions ameliorated a continuous grassland was established probably with a sizable proportion of various shrub species. The pollen spectrum at this point is dominated by *Coprosma* and Graminae with only traces of tree pollen, so the regional vegetation must have been some shrubland - grassland combination.

At the same time as *Sphagnum* peat began to accumulate on the site the shrubland - grassland was replaced by podocarp forest, mainly *Podocarpus spicatus* but with significant proportions of *P. dacrydioides* and *P. ferrugineus*. Although the lowland forest was essentially made up of podocarps, the treeline, at least near the site, was probably *Nothofagus menziesii* and *Phyllocladus*. The actual site was, as today, subalpine grassland. Such taxa as Gentiana, Astelia, Myosotis, Euphrasia, Stylidiaceae and Caryophyllaceae which are prominent in such grasslands are present, occasionally in quantity, throughout the profile.

In turn, the podocarp forest was to a large extent replaced by *Nothofagus fusca* type forest in the region. *Nothofagus solandri* var *cliffortiodes* pollen was noted and that species probably replaced *Nothofagus menziesii* at the treeline.

Very shortly after the rise to dominance of the *Nothofagus fusca* type forest, fires swept the region. Tree pollen percentages were drastically reduced and grassland once again became a significant element in the regional vegetation. Fine charcoal fragments were noted in the profile at this level.

At 5 cm from the surface the first exotic pollen types, *Pinus* and *Salix* were noted indicating the beginning of European settlement in the area.

2. *Waikaia Bush Road. Altitude 1,400 m.*

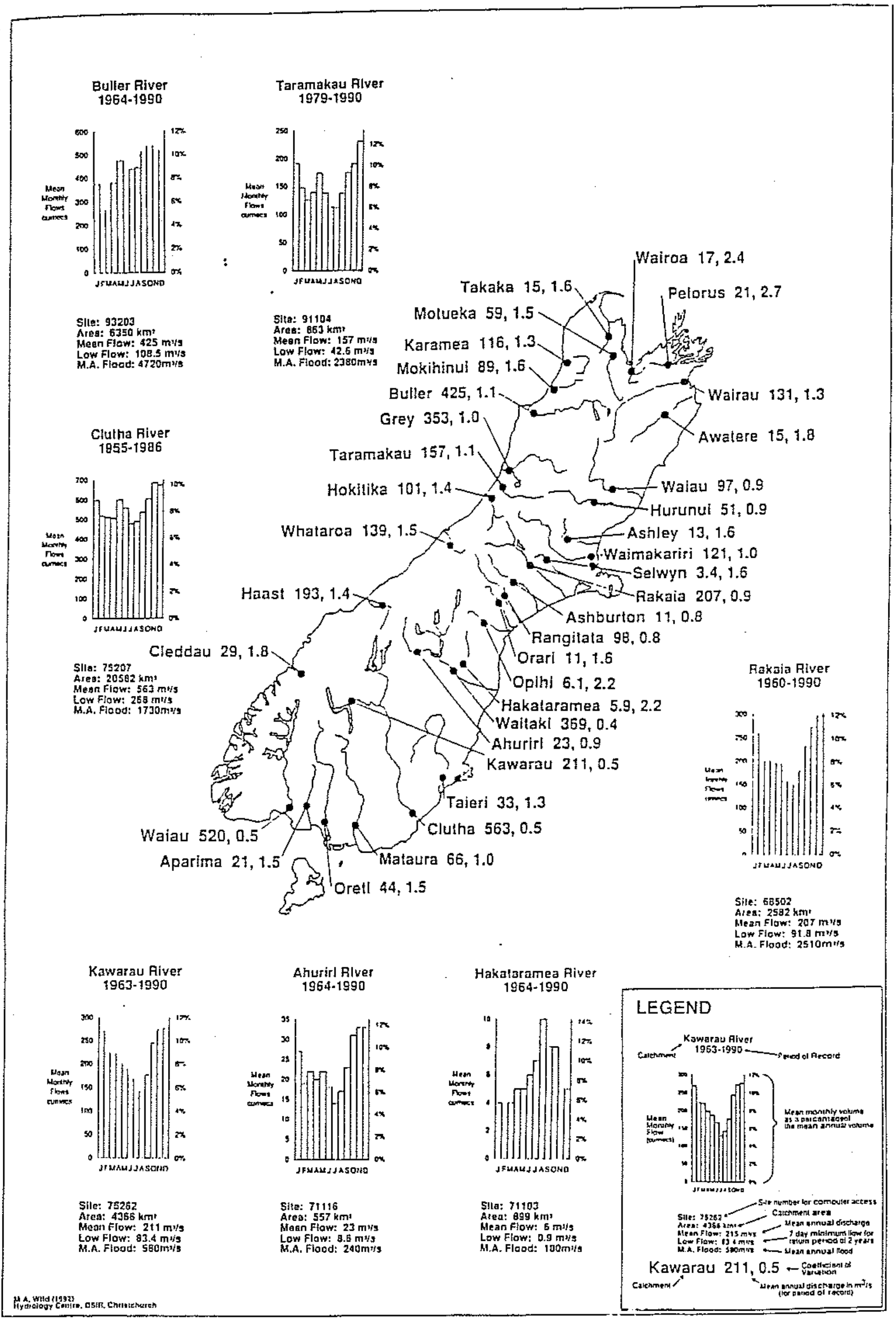
The samples for this site were taken from a road cutting through a sloping bog some 2 km from Campbell Creek. The peat surface has a cover of small rushes, herbs and cushion plants. The profile is approximately 70 cm deep and is a fairly uniform compact fibrous sedge peat throughout. The base of the profile consists of a gleyed silt with numerous rock fragments.

Vegetation History

This site differs from Campbell Creek in that it is more compressed and only includes the very top of the shrub-grassland zone. Otherwise the general pattern of events is essentially similar.

From: INQUA: Guidebook For Excursion 8. (1973).

APPENDIX C



M.A. Wild (1992)
Hydrology Centre, DSIR, Christchurch

Figure 2.3 Map of the mean flow and coefficient of variation of major rivers in the South Island, based on data held in National Institute of Water and Atmospheric Research or Regional Council archives.

From: Duncan M. J., 1992. In: *Waters of New Zealand*, Mosley M.P. (ed). New Zealand Hydrological Society

$13.6 million flood payout

By Regan Horrell

ALEXANDRA — A $13.6 million flood protection and compensation package for Alexandra was announced by the Government and Contact Energy yesterday.

A deed formalising a joint contribution of $6.8 million each was signed at the Beehive in Wellington by Contact Energy chief executive Paul Anthony and Acting Prime Minister Jim Anderton.

Mr Anderton and Civil Defence Minister George Hawkins are expected in Alexandra next Tuesday to announce details of further Government funding towards "some enhancement of community amenities."

The $13.6 million would provide for the construction of floodbanking, the purchase of about 30 flood-affected properties and easements over properties where flood protection work was not practical.

An aerial photo with the proposed flood protection marked.

The package ended extensive consultation with the community, technical experts, government officials and Contact staff during the past six months.

The November 1999 flood was the third in five years to hit the town with residents blaming the Clyde and Roxburgh hydro-electric dams for the buildup of silt in the Clutha River.

"The package is designed to provide Alexandra with a high standard of flood protection for the future and will also offer help to those who were seriously affected by past flooding," Mr Anderton, Mr Anthony and Mr Hawkins said in a statement.

Mr Anderton, who pledged Government action during the election campaign in Alexandra last year, said it had been a major exercise in co-operation between central and local government and Contact.

"Contact could have taken a hard line approach, but it is making its contribution and I am delighted at the attitude it has taken."

Mr Anthony said yesterday Contact had no legal liability but accepted a community responsibility as the owner of the dams.

"We can't crystal-ball gaze about future flooding but the protection is substantial with all eventualities considered."

Mr Anderton said yesterday flood protection could take eight to 12 months to complete but negotiations for settlement with owners of flood-affected properties would start almost immediately.

■ Reaction, Page 3

Main points

- **A $13.6 million payout to fund floodbanking and the purchase of about 30 flood-prone properties.**
- **Contact Energy's $6.8 million contribution exclusive of GST would be equally matched by the Government.**
- **Location and design of the flood banks would be based on the recommendations of the Otago Regional Council's independent engineers report in August between Orchard Drive and the bridge, the central business district and the Linger and Die area.**
- **The Government would consider funding for some enhancement of community amenities at a Cabinet meeting on Monday, with details announced in Alexandra next Tuesday.**
- **Contact Energy and the Government have not accepted a legal liability for the silt buildup in Lake Roxburgh blamed for three floods in five years.**

The Southland Times 08.10.00

No answers over flood work

ODT 14-11-00

By Debbie Jamieson

Alexandra: A big question mark hovers over the issue of flood protection work in the Manuherikia Valley and Galloway, 7km east of Alexandra.

Frustrated residents yesterday asked a meeting of the Alexandra flood project sub-committee what action was being taken in the area and received few answers.

Some properties in the area have been flooded three times in the past five years and residents blame a build-up of silt in the Manuherikia River, caused by the Roxburgh Dam, for the damage.

No specific mention of the area has been made in relation to a government and Contact Energy-funded $20 million flood protection package for Alexandra.

However, the package was based on a report by the Clutha Solutions Co-ordinator Alex Adams that recommended $1 million be set aside for work on the Manuherikia River bed and surrounds and another $250,000 for investigation work into sediment location and characteristics in the river.

Steve Green

When questioned about the funds, Central Otago District Council chief executive Steve Green said the committee was not party to the details of the government-funded package.

"We have no other information other than it was part of his [Mr Adams'] recommendations," he said.

All residents of Alexandra and surrounding areas on "flood prone" properties that would not be protected by flood protection works or would need to build flood banks had received letters from a crown agent notifying them of the purchase of their properties.

However, some people in Galloway whose properties had been flooded many times had received no communication while others were surprised to receive some.

Galloway holiday home owner Helen Flockton said she received a letter requiring her property for easements "totally out of the blue".

The property had been flooded in the past but water had not entered the house. She was concerned a compulsory sale would be forced on the property for flood protection work.

Neighbour Robyn O'Brien had not received a letter even though his Galloway farm had been flooded three times in the past five years.

Other affected properties include the Alexandra Holiday Park, which is taking legal action against the Crown and Contact Energy, and the Ithiel farm owned by Bob Harrison-Lee.

Speaking after the meeting, sub-committee chairman Malcolm Macpherson said he did not believe flood protection work was to be funded in the area and properties contacted for purchase were being considered with unprotected properties in Alexandra.

He had attempted to find some answers from government departments to the residents' concerns.

"It's all a bit vague," he said.

A meeting of residents is being planned at the holiday park this week.

• **Flood bank application lodged — page 11**

Otago Daily Times 14.11.00

Flood bank application lodged

ODT 14-11-0

By Debbie Jamieson

A resource consent application for flood banks in Alexandra's Linger and Die area has been lodged with the Otago Regional Council and is open for submissions.

Submissions will close on December 1 and the application will be heard on December 15.

The work includes a 135m long flood bank with a 4m wide access way on top. Fifteen properties will be directly affected. Costs will be met by a $20 million government and Contact Energy funded flood protection package.

Regional council chief executive Graeme Martin told the Alexandra flood project subcommittee yesterday that an independent commissioner was being appointed to hear the consent, as the council was the applicant.

References to landscaping the area in front of the flood bank were to be removed from the application, to comply with an earlier decision made by the sub-committee, that the landscaping of that area be dealt with separately.

About 20 members of the public and the media were excluded from the subcommittee's discussions on the consultation process for building flood banks in Alexandra's central business area and the Clutha River left bank.

Land and Information New Zealand general manager, business support, Brian Usherwood, said all owners whose properties were required for purchase or easements for flood protection works in Alexandra had been sent letters by agents The Property Group.

People who felt they ought to have been contacted and had not been should talk to The Property Group at its office in the ACC building from next week or telephone 0800 579797.

Otago Daily Times 14.11.00

Plan to rebuild centre of Alexandra

By Debbie Jamieson

Alexandra: Two blocks of shops and offices in Alexandra's central business area will be demolished and redeveloped if a new flood plan goes ahead.

A new Warehouse building and about six other retail outlets will be developed under the proposal put forward by the Alexandra Flood Project subcommittee and the Alexandra Community Board.

All buildings on the blocks bordered by Tarbert, Limerick and Rivers Sts would be removed, excluding the historic Bodkins building, sub-committee chairman Malcolm Macpherson said yesterday.

The proposed design includes a 200m-long floodbank that would cut through the Bendigo Hotel, the former CRT site and behind Molyneux Motors. Off-street parking may be established in front of the bank.

Malcolm Macpherson

The purchase of about 12 properties not designated "flood prone" would be funded from a $3.55 million (excluding GST) Government-supplied amenity fund administered by the Alexandra Community Board.

Board chairwoman Daphne Hull said a meeting with directly affected property owners on Monday night resulted in near unanimous support for the proposal.

"A show of hands showed if not 100% support, then very close to it. A couple of people are still a little bit nervous about their futures," she said.

The proposal depended on willing-sell agreements with building owners.

About $1 million, or one-third, of the amenity fund would be spent purchasing properties not earmarked for Government purchase, at a similar rate to those being purchased by the Government.

Another third would fund the relocation of council-owned properties — the swimming pool, museum, senior citizens' rooms and the scout hall. The final third has not been allocated.

Mr Macpherson said a developer would need to be found before the project moved ahead, as funding for new buildings was not included in the total $20 million Government and Contact Energy funded flood protection package.

Depending on the design of the retail area, it could make about 5000sq m available for retail space.

Warehouse officials who approved the plan with the flood project committee and community board members last week told the *Otago Daily Times* they would prefer to build a new store with a floor space of about 3000sq m.

The store would be similar in both size and appearance to the new Warehouse in Frankton, near Queenstown. The company would not build a "big red shed" but something more sympathetic with the Alexandra environment.

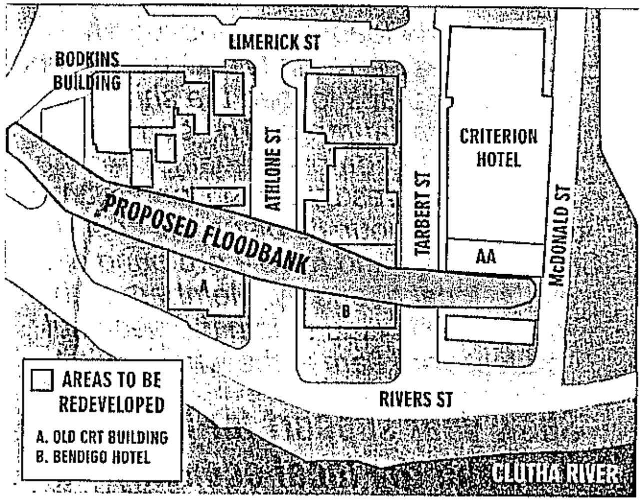
The proposed floodbanks would protect the area from the Clutha River during floods, Mr Macpherson said.

The design of the bank is the same as that preferred by the Otago Regional Council in an engineer's report released in August and involves removing the Bendigo Hotel, which has a historic facade.

A tentative timeframe has been set out for the development that depends on property purchase negotiations, finding a developer and final approval from the Warehouse to go ahead.

Mr Macpherson said planners hoped to complete the work before Christmas next year and that would necessitate a construction phase of 20 weeks. To enable this, the project would have to start "reasonably quickly", he said.

ALEXANDRA REDEVELOPMENT



ODT graphic

Resource consent is already being sought for flood protection work in Alexandra's Linger and Die area and floodbanks are also proposed along the left bank of the Clutha River, from the Alexandra bridge to Orchard Dr.

Otago Daily Times 22.11.00

APPENDIX D

From: Turner A., 1990. In: *Southern Landscapes*, Kearsley G. & Fitzharris B. (eds), Department of Geography, University of Otago.

The highest concentration of boulders occurs near the base of Mt Malcolm and it is conceivable that a debris flow could have transported some of the boulders to their current location. However although the general downstream fining of the boulders is consistent with this mechanism some of the landform features observed are clearly inconsistent. The boulder distribution pattern expected from a debris flow is not apparent. Although the boulders furthest downstream are located south of the road, the majority are strewn essentially straight down the valley and are confined to north of the road. Boulders would be strewn obliquely across the valley away from Mt Malcolm if transport was by a debris flow. Furthermore the boulders are concentrated in a central zone rather than in levees and a terminal lobe. It is likely that the matrix of a debris flow from Mt Malcolm would be coarse and a great range of material size would be transported by the flow. Although some of the finer material would be removed by subsequent erosion, most of the material would be expected to remain to form a tongue-like feature with an irregular surface; this is clearly not the case.

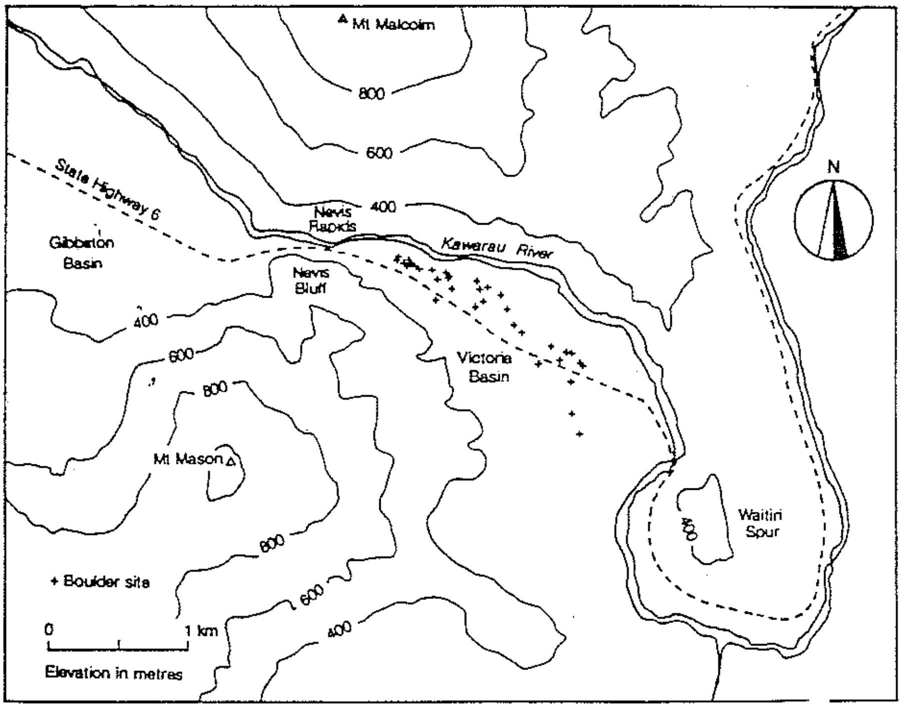


Figure 4: Location of the largest boulders on the Victoria Basin surface

Furthermore a rapid slope failure would have been needed for boulders to be transported any appreciable distance but this is not a feature of landslides in the area. Landslides in the Cromwell Gorge following flooding of the toe by Lake Dunstan and an earthquake would move at a rate of only about 1.5 m per day (D.S.I.R. 1990). Many of the boulders are hundreds of metres away from the slopes and a debris flow would not be capable of transporting boulders such distances across an essentially horizontal surface at such slow speeds. It appears, then, that a debris flow was not responsible for transporting the boulders.

The distribution of boulders across Victoria Basin is not inconsistent with transportation by a glacier and then ablation of stagnant ice. It is conceivable that massive boulders could have become quite evenly distributed across the ice as it flowed down valley and then be deposited across the valley as the ice ablated. However certain expected features associated with this mechanism are absent. The boulders are not associated with a hummocky surface as would be expected if all material being carried by a glacier was deposited. Meltwater features such as kames and eskers are also absent, as are terminal and lateral moraines. If such features had been deposited originally then their removal would require an extreme fluvial event; that is an outburst flood. More significantly, no boulders or even smaller rock debris occur upstream of Nevis Bluff in the Gibbston Basin yet ice transport would result in similar features on both sides of the Bluff. The absence of these features appears to rule out glacial activity as a possible transport mechanism for the boulders.

The distribution of the boulders is consistent with transport by an outburst flood, being strewn down the valley in the zone where the maximum flow velocities would occur. Also the boulder occurrence begins immediately downstream of Nevis Bluff and the concentration of boulders decreases with distance from the constriction, which suggests transportation from a local source. The general decrease in size is as expected and the size anomalies could be explained by ice-rafting in the turbulent waters, or boulders starting from different elevations on the slope, and sampling errors. The boulders rest on, or are partially buried in, a nearly horizontal surface and this suggests extreme fluvial activity resulting in an armouring of the surface. This is consistent with the interpretation of Macfarlane (1985) who describes the surface as heavily degraded. The virtual absence of scour holes around the boulders casts doubt on this mechanism, but subsequent deposition of fine material by the Kawarau River before it became entrenched in its present channel could be the reason for this situation. The absence of debris upstream of Nevis Bluff is unexpected as the constriction would cause deposition through the temporary damming of flood waters. One explanation is that the bursting dam was located some distance upstream of Nevis Bluff and the material was not transported as far as the constriction. Another possibility is that the dam was at Nevis Bluff and all material was transported downstream of that point.

The possibility of an outburst flood raises several questions including the nature and location of the initial lake and the existence of other landform features. The existence of a lake higher than the level of current Lake Wakatipu has been established by the occurrence of lake deposits at the south-east end of the Crown Range (Bell and Swanson, 1977) and in the Gibbston Basin (R. Thomson, pers. comm.). During glacial times, ice in the Arrowtown Basin could have blocked river drainage from the Arrow and Shotover valleys to form a lake. The Gibbston Basin deposits require a dam downstream; this would appear to rule out an ice dam since the glacier would have occupied the Basin and so possibly indicates an earth dam near Nevis Bluff. A connection between these deposits and the transportation of the boulders has not been established but it is apparent that water has been impounded to a high elevation upstream of the boulders and catastrophic dam failure is a possibility.

An outburst flood would result in the deposition of finer material downstream. Backflooding up tributary valleys such as the Nevis River would occur, resulting in an upstream fining of material and bedding which indicated up-valley currents. The existence of such features would confirm outburst flood occurrence, while their absence may simply be due to subsequent erosion. The "Kawarau Moraine" at the mouth of the Gorge near Cromwell contains exotic rocks and a glacial origin has been suggested (Park, 1908). Bell (1982) suggested the possibility of the flushing of debris by an extreme flood. Although this feature was formed well before the boulders in Victoria Basin were deposited (250,000 years ago compared to 70,000 years ago, R. Thomson pers. comm.), the boulder deposition supports Bell's suggestion. Channels have been formed on the Waitiri Spur and these may have been caused by outburst floods, but this is only speculative. The channelisation may instead be due to normal river erosion which occurred when the Kawarau and Nevis Rivers were aggraded above their current levels.

The evidence presented here suggests that the large boulders on the surface of Victoria Basin were not transported by a glacier, while a debris flow could have transported some of the boulders. The preferred explanation is that a catastrophic dam failure caused an outburst flood to flow down the Kawarau Gorge. The outburst flood eroded material from the slopes of Mt Malcolm and deposited the debris immediately downstream.

This explanation is tentative and further study is needed to test its validity. Such work includes determining the nature and location of the dam, locating other erosional and depositional features further downstream, and establishing the lithology of the boulders to determine their origin. The presence of exotic debris would preclude a debris flow from being the only transport mechanism, while the absence of exotics would rule out glacial activity. Lithology would neither confirm nor deny the occurrence of an outburst flood directly, but may help in further refinement of the hypothesis.

APPENDIX E

ARCHAEOLOGICAL SITES - CENTRAL OTAGO

(J. Hamel)

While food resources were patchily distributed throughout the year, favoured stone resources were patchily distributed in space and their utilisation had to be coordinated with seasonal food gathering. Several types of stone such as silcrete, greenstone (nephrite) and vitrified mudstone occur inland well away from the richer food resource zones of the Otago coast. It has been argued that the Maoris went inland primarily to obtain stone for artifacts and had to carry supplies of preserved foods.

HAWKSBURN

Lockerbie has suggested from excavations at Hawksburn that exploitation of dwindling moa populations was also a reason for making the long trek into the harsher climate of Central Otago especially during the fifteenth and sixteenth centuries, when the moa populations on the coast had virtually died out. At Hawksburn there was evidence of moa hunting, blade making and hut building. Moa bone gave radiocarbon dates of AD 1550 ± 50 and AD 1500 ± 60 (Lockerbie 1959;86). The evidence suggests that people lived at Hawksburn in the same sense that they lived at Tuturau or any other exploitation site. There are traces of similar evidence from an eroded site at Millers Flat where large quantities of moa bone, charcoal and flake material have been found. (Bagley; pers. comm.).

OTUREHUA

The Oturehua site is a work-floor for the production of blades from the silcrete boulders which outcrop along the hillside. These boulders are the remnants of an extensive sheet of material variously known as orthoquartzite or silcrete since the nature of its origin is disputed. At the site a very skilful and controlled flaking process was used to take off long blades and the debris of this activity in the form of hammer stones, blades and nuclei is scattered over several acres. Soil build-up has been slow and the occupation layer consists of 20 cm of colluvium, stone material and a small amount of charcoal. This has given radiocarbon dates of AD 1053 ± 27 and AD 1023 ± 82 (R2054/2 and R2233/2, Leach 1969a;52), making this one of the earliest occupation sites in New Zealand with two well-provenanced dates. No midden material or living floors were located. (Leach 1969b; 69).

Other sites in Oturehua Valley are similar in surface appearance to the excavated site. Also a canoe was reported to have been found at the head of the valley. All the known occupation material lies on the valley sides along the 1500 foot contour.

In the eleventh century the hillsides may have carried an open podocarp forest with a considerable fauna of moas and smaller forest birds, under a milder climate than now prevails. Oturehua could well have been a site for the exploitation of food resources as well as of silcrete. (Leach, pers. comm.)

The distribution of silcrete blades in the coastal sites cannot be used with assurance to show that coastal peoples travelled inland mostly to get silcrete. Boulders of silcrete are found in many of the rivers leading out of Central Otago and waste flakes with chatter marks symptomatic of riverine transport are found in the coastal sites. There was no apparent need for coastal peoples to go inland for silcrete. The riverine material was also well cleaned of softer crystalline material in the process of transport.

The manufacture of long blades of the type found at Oturehua is almost confined to Otago and Southland and skill in blade manufacture declines after about 1600 AD. In the early period, the flaking of adze rough-outs was also more skilled throughout New Zealand than in the later period and a greater variety of adzes were made e.g. at Riverton and Tiwai. The origins of this stone technology are not well understood and the expected developmental sequences in the Pacific prior to 1000 AD are obscure. The decline in flaking techniques can be correlated with a rise in the use of greenstone and with the extinction of moa populations. The significance of these correlations have not been properly explored. (Leach, pers. comm.)

ARCHAEOLOGICAL SITES - CLUTHA VALLEY

(J. Hamel)

CLUTHA VALLEY

Hawksburn and Oturehua are the only sites in Central Otago which have been properly excavated and published. Other sites are known mostly from surface indications. A survey of known sites in the main Clutha Valley was carried out in January 1973 by Bagley for the New Zealand Historic Places Trust. Material found consisted mostly of single finds of artifacts, scattered ovens with little associated material and occasional cave finds such as the flax bag of 'household oddments' found near Middlemarch and on display in the Otago Museum. A total of 32 ovens and findspots were mapped by Bagley from Wanaka to the mouth of the Clutha River, about 200 miles of valley. Many of the ovens have been destroyed by ploughing and only some of those on spurs up from the valley floor have escaped the bulldozer. (Bagley, pers. comm.) The Taieri catchment seems to have a similar scatter of ovens as well as several silcrete working floors, but the deep middens characteristic of the coastal sites have not been found in Central Otago.

LAKE WAKATIPU

A few ovens have been recorded around the shores of the Frankton Arm of the lake and there is also a collection of early period adzes in the Smithsonian Institution collected by an American expedition which visited Queenstown to record the transit of Venus in 1874. Beattie gives traditional evidence of two 'villages' on either side of the Kawarau Falls another one at Frankton and another at Kingston and cites their Maori names. There are several legends linked to Lake Wakatipu and an historic account of survivors of a raid taking refuge at Queenstown Bay. (Beattie 1945).

At the head of Lake Wakatipu Simmons carried out some small excavations on a range of sites. About six miles up the Dart Valley from Kinloch he investigated a 'village' of small paved mounds with associated pits and paved pathways. Greenstone objects found previously suggest that the primary function of the site was for working greenstone from the source near the junction of the Routeburn and the Dart Rivers. Another site on a terrace above the Rees River immediately north of Glenorchy included a line of ovens, a scatter of flake material and quite a number of large adzes of the early period. Simmons found surface evidence of several other sites including single ovens and a complex of pits and ditches on Camp Hill. (Simmons 1957: 17). The radiocarbon dates have not yet been published.

From: INQUA: Guidebook For Excursion 8. (1973).

APPENDIX F

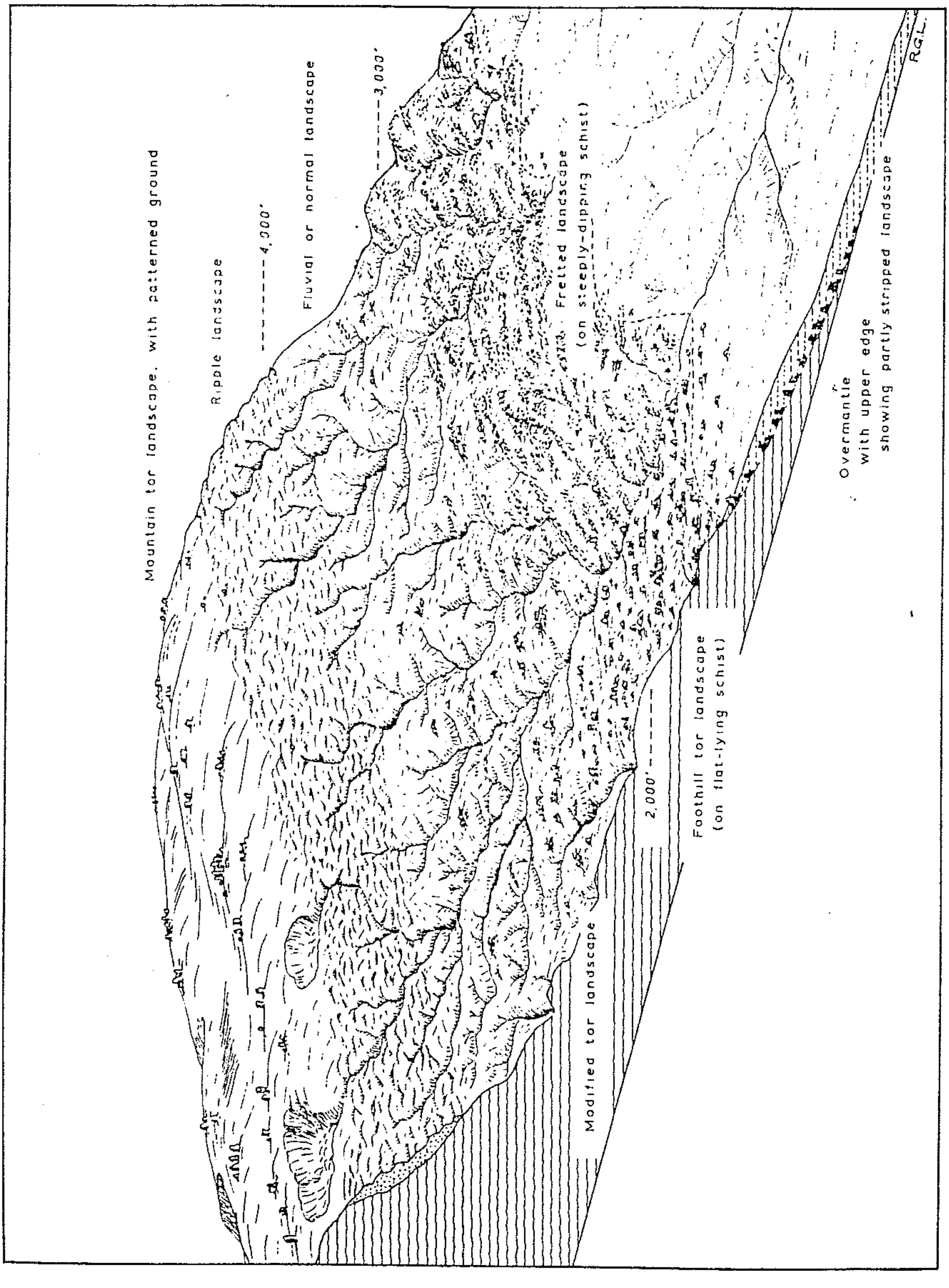


FIG. 3 Diagrammatic perspective sketch of a Central Otago block mountain, based on the Old Man Range, looking westward.

McCraw J.D., 1965. In: *Central Otago*, Lister R.G. & Hargreaves R.P. (eds), New Zealand Geographical Society.

THE OTAGO TORS - A REVIEW

(W. Brockie)

The landscapes of East and Central Otago are attributed to the deformation of an erosion surface by a suite of sub-parallel fault-folds into a series of tilted blocks. Above valley floors such landscapes exhibit many rough, craggy exposures of basement schist. These rocky outcrops have given rise to names like Rough Ridge, Raggedy Range, Rock and Pillar and are so numerous and extensive that the term 'tor landscape' has been used to describe the 7,500 km^2 of land over which they appear.

Although it frequently has a genetic connotation (Linton, 1955), the term 'tor' is here used in its original descriptive sense to denote an upward projecting residual of bedrock. (tor (Gaelic), a hill, rocky knob).

In one of the earliest attempts at presenting a rational origin for the Otago tors, they were thought to be roches moutonnées left by a retreating ice sheet. In the next 100 years studies progressively refined both observation and theory. Most have focussed on the role played by structure as a primary determinant of tor occurrence and form. General acceptance of the significance of variations in joint spacing has been supplemented by more detailed work on the schist lithologies. Typical of such research have been the attempts to resolve the conflicting opinions on the significance of metamorphic segregation and resistant large strata. It is now considered that the latter, bounded by bedding or shear planes, are responsible for the marked alignment of the tor outcrops.

Climatically directed processes, as the other major variable has been subject to more divergent opinions. Partly as a consequence of this, tor landscapes distinguished mainly on morphogenetic grounds have been recognised. Lowland tor forms have been attributed to a two-stage evolution in which late Cretaceous deep weathering etched out a subsurface pattern of rock salients, and subsequent erosion of the weathered mantle exposed the uneven weathering front as tors - a process which is still going on.

Tors of the unglaciated uplands have been considered as evolving in a different fashion. The present summit profiles of these ranges are regarded as an uplifted late Cretaceous erosion surface, subsequently degraded by cryoplanation during the Pleistocene. The associated tors are thus seen as residuals consequent upon the intense periglacial weathering experienced by the ranges. Studies suggest that frost shattered schist debris to a depth of over 40 m and locally as much as 160 m has been removed by solifluction and deflation.

Today these upland environments are near periglacial, and it would seem axiomatic that the more severe stadial climates of the Pleistocene would produce environments where cryergic processes would be more intense.

In any such scheme, the continued widespread occurrence of comparatively fragile, pedestal and shaft tors is something of an embarrassment. It has therefore been suggested that far from being an upland continuously subject to the extreme rigours of a periglacial climate, the plateau surfaces were mantled and insulated by permanent snowfields. Supporting this concept are the numerous nivation cirques, at least Otiran in age, that scallop the margins of several of the ranges. Under the 'nival protection' hypothesis, increased emphasis is placed on interglacial and interstadial weathering preparing the schist for frost shattering with the major cryergic activity reduced to comparatively short periods at the beginning and end of each stadial. In partial support of this, laboratory studies have emphasisted the resistance of unweathered schist to frost-shattering, but confirm the susceptibility of even slightly weathered rock to rapid breakdown.

In such a model, the upland tors are the present manifestation of a weathering-denudation system that extends back to the Cretaceous, the tors being time-independent within it.

Although highly deductive, this model appears to have some validity, though it has yet to receive critical field and laboratory testing. It may also serve to show that the

Otago tor landscapes offer a unique demonstration of convergent evolution - the concept that similar forms may result from the interaction of quite diverse processes.

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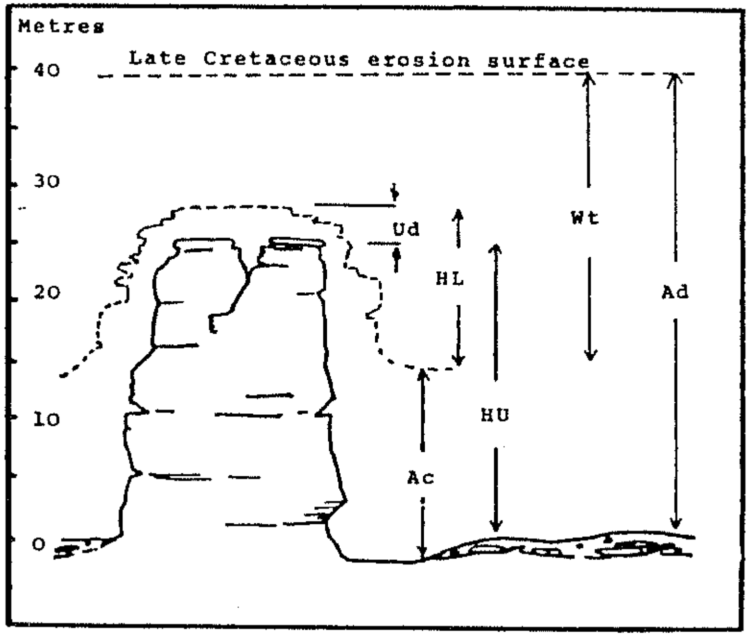


Estimated increments of degradation of upland surfaces

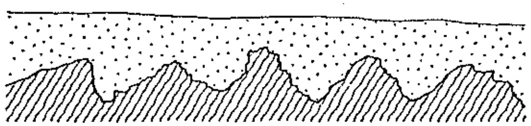
HU : height of upland tors
HL : height of lowland tors
Wt : observed thickness of deep weathered schist in lowlands
Ad : total amount of down-wearing between late Cretaceous erosion surface and cryoplanated tor-platform
Ud : unknown amount of earlier Pleistocene down-wearing of unweathered schist between upland and lowland tors
Ac : approximate amount of unweathered or partially weathered schist removed by cryergic processes

From: INQUA: Guidebook For Excursion 8. (1973).

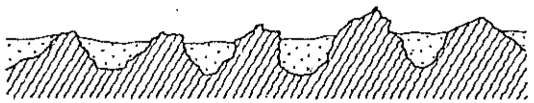
There is general agreement that the lowland tors of Central Otago are exhumed relics formed by the selective weathering of schist under semi-tropical conditions during the Late Cretaceous or Early Tertiary. The origin of the upland tors is not so clear. Implicit in earlier studies is the assumption that they also were initiated as lowland forms, but have managed to survive on the summits following the removal of weathered products as uplift took place during the Kaikoura Orogeny. By contrast, Wood (1969) concluded that the upland tors may have formed as recently as the last glaciation in response to periglacial activity. The credibility of the former hypothesis rests on the shaky premise that surviving lowland tors have been able to do so without serious modification during a million or so years of Pleistocene climatic oscillations. The other appeals to incompletely understood periglacial processes to accomplish differential weathering of a substantial volume of comparatively resistant bedrock, and its removal as weathered waste, all within the span of one glaciation.

Based on the field evidence and analytical results summarized above, and reported in detail elsewhere (Fahey, 1981 (in press)), it is proposed that the summit tors have evolved to their present state by differential weathering during interglacial periods of the Pleistocene, and sub-surface mechanical disintegration during intervening glacial episodes, with the weathered products being removed by solifluction and other mass wasting phenomena in transitional climatic phases. It is in a way a comprise, but it circumvents the major objections which can be levelled at the other two hypotheses. It neither requires all tors to have survived for an exceptionally long period, nor does it elevate frost action to a position out of keeping with its now-assessed geomorphic effectiveness. Some of the larger tors may indeed have originated as lowland forms, becoming enlarged and sharpened by frost action during subsequent glacial periods. This would not exclude the possibility that others may have been formed during colder periods of the Pleistocene. Thus, not only do the Otago tors illustrate the principle of convergent evolution, but also that individual tors may have had a composite evolution involving successive periods of diverse weathering processes.

From: Fahey B.D., 1981. In: *Man Environment and Planning*, Heenan L.D.B. & Kearsley G.W. (eds), Department of Geography, University of Otago.



a) Contact between weathered and unweathered schist



b) Weathered schist partly stripped—'pseudo-tor landscape'

c) Weathered schist completely stripped—'fretted landscape'

FIG. 6 Genesis of the fretted landscape.

FIG. 7 Genesis of the tor landscape.

a) Contact between weathered and unweathered flat-lying schist

b) Weathered schist completely stripped—'tor landscape'

McCraw J.D., 1965. In: *Central Otago*, Lister R.G. & Hargreaves R.P. (eds), New Zealand Geographical Society.

Given that rock type remains essentially constant across the field area, the virtual absence of pits at lower altitude strongly suggests that their altitudinal distribution is climatically controlled. Above 1500 m where their numbers are greatest, periglacial conditions prevail. Between 1000 and 1500 m, summers are milder and winters less severe; pits are still common but their frequency is reduced. Below 1000 m, precipitation falls off sharply, the number of freeze-thaw cycles declines, and pits are rare. The foregoing, coupled with the fresh appearance of many of the smaller pits on the high summits points to microgelivation as being the primary agent responsible for their origin and growth. Disaggregation through wetting and drying is believed to occur but to be of secondary importance. Detailed field evidence, augmented by precise chemical analyses support the contention that salt and chemical weathering play little if any role in pit development. Indeed, the increased potential for chemical weathering below 1000 m may well be a factor inhibiting pit development at lower elevations.

Frost weathering and hydration effects will be concentrated initially where water collects in pre-existing hollows on exposed rock surfaces. Pit growth takes place and schist detritus collects in the expanding hollow. Further comminution of this material into the sand and silt fractions is likely, some of which may be removed by wind when the material in the pits dries out. As pits approach their optimum size, activity becomes confined to a zone below the rim and a pronounced overhang develops. Pits then either begin to decay, or continue to expand but at a reduced rate. Coalescence of adjacent pits during the expansion phase may account for some of the larger ones observed, especially those that are irregularly shaped. However, those with a circular configuration are thought to have reached their present size independently.

Most of the larger pits were found on degraded tor surfaces. However, detached blocks occasionally displayed pits with diameters exceeding 50 cm. These blocks are thought to have become separated from the parent rock comprising the tors by frost wedging or macrogelivation. Although this process is still taking place today it is probably on a much reduced scale compared with that occurring during the last glaciation when periglacial conditions on the high summits were more severe. Thus the larger pits found on isolated blocks probably began forming during the Otiran Glacial Stage, under a climatic regime characterized by freeze-thaw events of greater magnitude than today. At the same time, however, the fact that individual blocks display pits ranging in size from a few to tens of centimeters across demonstrates that pit formation is an on-going process in the current periglacial climate. It is believed that the tor surfaces displaying the largest pits have been exposed to weathering at least since the beginning of the Otiran. Thus, 100,000 yr may well be required for pits in periglacial environments to reach a width of 1 m or more.

Mean values for major ion and SiO_2 concentrations, and for electrical conductivity (k) and pH, based on water samples taken from selected weathering pits

Location	Altitude (m)	Number of samples	Na^+	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Cl^-	SiO_2	k	pH
				(mg L^{-1})						(μmhos cm^{-1})	
Pisa Range	1760	8	0.70	0.64	0.49	0.18	0.13	0.42	<0.10	24	5.6
Old Man Range	1685										
December 1984		8	2.28	0.44	0.78	0.53	0.11	0.85	<0.10	35	5.1
February 1985		6	1.49	0.60	0.23	0.25	<0.10	1.64	<0.10	20	5.3
Dunstan Mountains	1630	4	0.32	0.53	<0.10	<0.10	0.08	0.35	<0.10	13	5.7
Rock and Pillar Range	1350	7	3.41	0.71	0.42	0.22	0.22	1.10	<0.10	35	5.5
Carrick Range	1300	4	0.73	0.79	0.54	<0.10	0.08	0.52	<0.10	30	5.5

TABLE 6

Mean values for water chemistry based on samples taken from melted snow, summit ponds, and subsummit streams on the Pisa, Old Man, Dunstan, and Rock and Pillar ranges. Comparative information from the relevant literature is included

Source	Number of samples	Na^+	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Cl^-	SiO_2	k	pH
					(mg L^{-1})				(μmhos cm^{-1})	
Snow	4	0.12	0.17	<0.10	<0.10	0.04	0.03	<0.10	5	5.0
Standing water	4	1.42	0.44	<0.10	0.56	0.09	0.15	0.25	36	5.4
Stream	4	1.37	0.31	0.16	<0.10	<0.10	0.06	1.04	25	5.7
Weathering pits	37	1.40	0.51	0.42	0.22	0.12	0.56	<0.10	24	5.6
Manuherikia River[a]	*	2.20	0.26	3.00	0.47	0.05	0.50	6.60	*	*
Lammerlaws[b]	*	2.20	0.26	0.89	0.52	0.33	3.17	*	*	*
Ellesmere Island[c]	4	28.5	9.9	5.5	4.0	22.0	46.3	0.68	232	*

[a] Data from Ahlers and Hunter (1984)—rock type, schist.

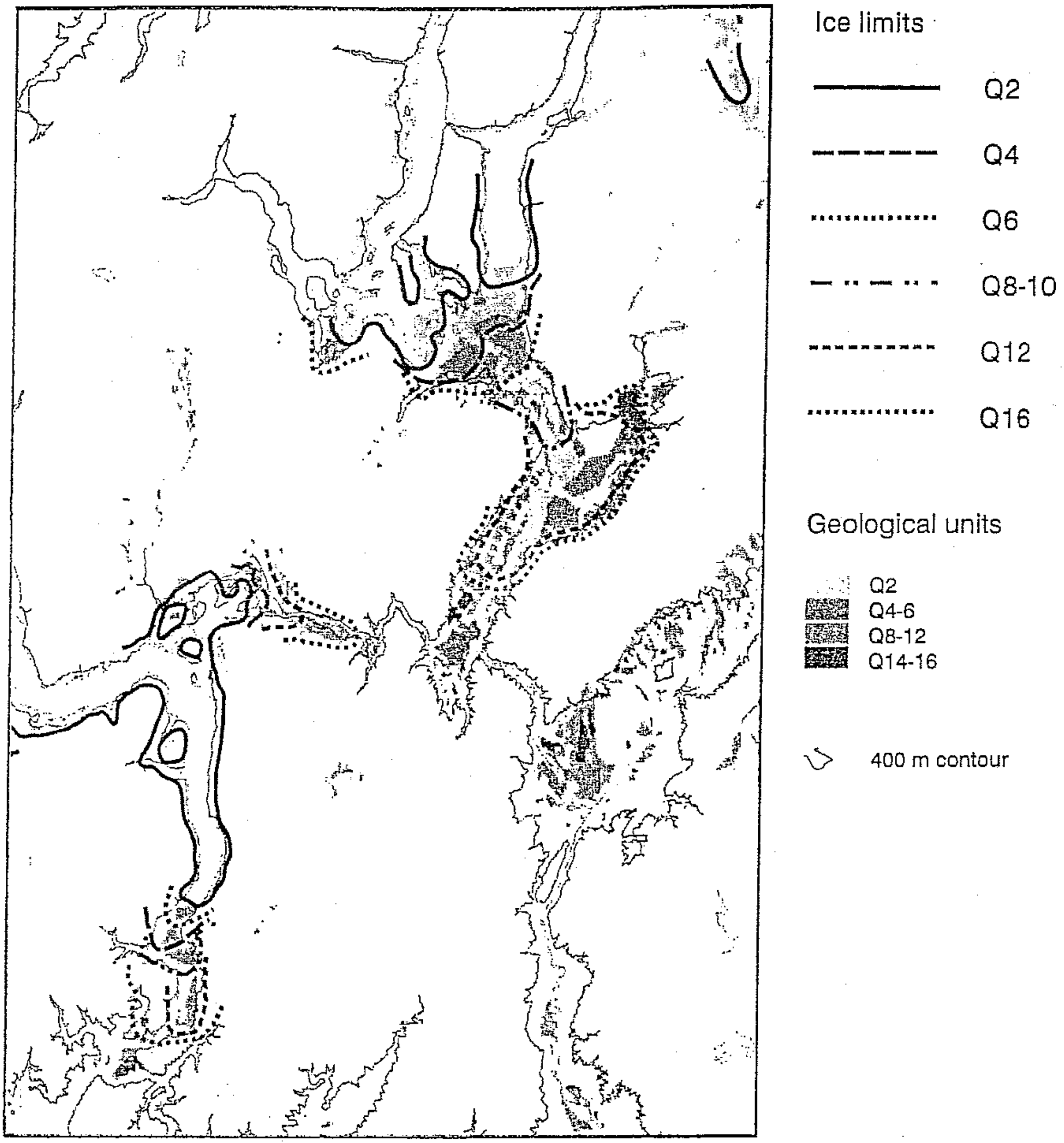
[b] Data from Holdsworth (1981)—rock type, schist.

[c] Data from Watts (1983)—rock type, granite.

*No data available.

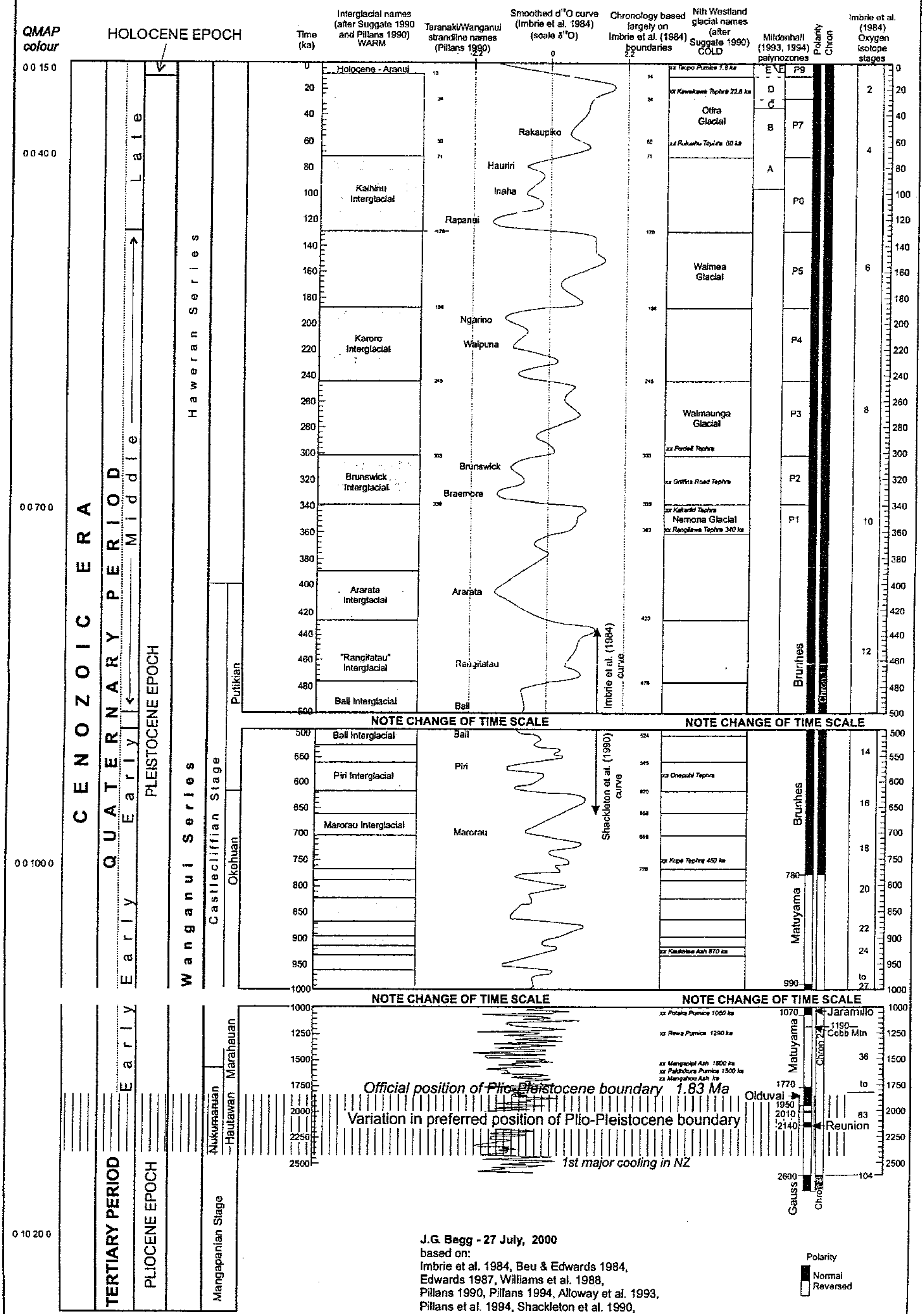
Fahey B.D., 1986. In: *Arctic and Alpine Research*, Vol. 18, No. 3, pp. 337-348.

APPENDIX G



Inferred down-valley limits of Wanaka, Hawea and Wakatipu glacial systems, and extent of main Quaternary deposits. Early Quaternary ice limits are not shown. Adapted from Geology of the Wakatipu Area 1:250 000 (I.M. Turnbull compiler, 2000), and based largely on work by R. Thomson.

A COMPOSITE QUATERNARY TIMESCALE FOR QMAP



J.G. Begg - 27 July, 2000
based on:
Imbrie et al. 1984, Beu & Edwards 1984,
Edwards 1987, Williams et al. 1988,
Pillans 1990, Pillans 1994, Alloway et al. 1993,
Pillans et al. 1994, Shackleton et al. 1990,
Shackleton 1997, Naish et al 1997,
Suggate 1990, Bassinot et al. 1994; Naish et al.
1999