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L1/11

26 September 2003

The Chief Executive
West Coast Regional Council
PO Box 66
GREYMOUTH

Dear David

PUNAKAIKI ROCKFALL STUDY

Attached for your information is a copy of a recently completed study of the Punakaiki Rockfall Zone carried out by URS New Zealand Limited.

Council considered the URS report at their meeting on 25 September 2003 and passed the following resolutions in this regard:

1. *That Council extends the outer limits of the rockfall hazard area in Punakaiki, to that shown in red of figure 8 of the URS Punakaiki Rockfall Study 2003 and shown as the URS Maximum Rockfall Hazard Zone.*

2. *The current procedure of building inspectors evaluating the hazard risk and consulting with the Manager Regulatory Services when building proposals are considered to be prone to life threatening hazards should continue. If the risk is considered to be so great, staff may refuse to issue such consents and refer such matters to Council for a final decision or alternately owners may obtain a determination from the Building Industry Authority.*

3. *Landowners within the Scenically Sensitive Residential Zone of Punakaiki be advised of Council's decision in regard to the report and a copy of the full report be provided to the Punakaiki Information Centre for public scrutiny.*

Yours faithfully

Terry Archer
MANAGER REGULATORY SERVICES

Encl.

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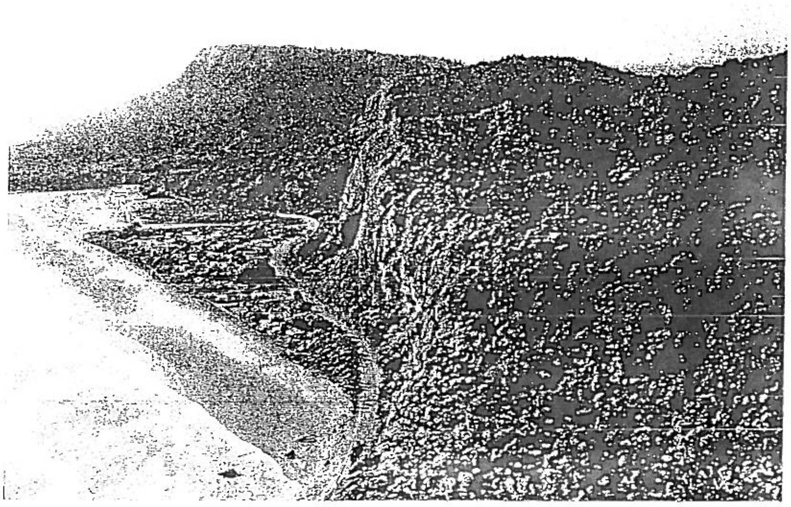
CI - DH.

Copy To David

FINAL REPORT

Punakaiki Rockfall Study

(Contract 02/03/30)



Prepared for

Buller District Council

P.O. Box 21
Westport

3 September 2003

52944-001/R001D

URS

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Date: 3 September 2003
Reference: 52944-001/R001D
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Executive Summary

URS New Zealand Limited has conducted a study of rockfall hazard associated with limestone cliffs above Punakaiki Village. The study incorporated review of previous studies, geological mapping, helicopter inspection of the cliff, excavation of test pits, review of anecdotal rockfall data and earthquake records, and analysis of rockfall trajectories.

Punakaiki Village is built on a 3000 to 6000 year old uplifted marine terrace mainly composed of beach sand. Blocks of limestone have accumulated in an apron of debris along the toe of the limestone cliff. Many of these blocks are in excess of 5 m across and the largest block is approximately 30 m in the largest dimension.

Geological evidence collected from the site (principally the presence or absence of limestone blocks within the strata or on the ground surface) indicates that rockfalls have affected an area that extends 20 to 80 m from the toe of the debris slope. We refer to this as the "Maximum Rockfall Hazard Zone" however most rockfall events are inferred to be much smaller and to accumulate within the debris apron. We infer that this zone includes the largest rockfalls that have occurred during the last 3000 to 6000 years and that rockfalls affecting a larger area have a very low probability of occurrence.

We consider that the seaward side of the highway corridor defines an appropriate 1% Annual Exceedence Probability (AEP) hazard zone[1]. Some debris from large rockfall events could travel beyond this zone, but on average debris would not exceed the zone more than once every one hundred years.

We suggest that the Maximum Rockfall Hazard Zone line defined in this report could be used to replace the "Rockfall and Rapid Debris Flow Hazard Area defined by Nathan that is currently contained within the BDC's District Plan. The 1% AEP hazard zone could also be used within the District Plan, but this study has not addressed the appropriateness of using this information for planning purposes.

[1] The 1% Annual Exceedence Probability zone defines an area which would only be exceeded by a rockfall once every hundred years on average.

1.1 General

Buller District Council engaged URS New Zealand Limited (URS) to undertake a rockfall study in the town of Punakaiki, which is located on the west coast of the South Island, approximately 55 km south of Westport. Previous workers identified the source of rock as the steep limestone cliffs (Te Ruahuanui) immediately east of the township. The Buller District Council wish to know the 1% AEP (annual exceedence probability) for the rock and debris runout.

1.2 Previous Studies

Nathan (1984) concluded that small rockfalls occur regularly during heavy rain and fall mostly on the talus apron at the slope base. While noting the presence of large blocks on the talus apron, he suggested that the three large limestone blocks west of SH6 were the result of rockfall from the cliff. He suggested a hazard zone that was up to 100 m west of SH6 in which no building should occur.

Cooper (2000) also noted evidence of previous instability and modelled rock trajectories using the program CRSP. For the purposes of the computer simulation, rocks were made spherical and 'released' from the very top of the rock face. The resulting run out distances reached were up to 100 m beyond the hazard margin established by Nathan (1984) and probably represent the maximum possible range of falling rock.

Yetton (2001) reviewed the work of Cooper (2000) regarding hazard at Punakaiki and suggested a more detailed investigation of the rockfall hazard. His recommendations form the basis of the scope of work in this report.

1.3 Scope of Work

The scope of work for the rockfall assessment carried out for this study comprises:

- A review of background information including aerial photographs, regional geology, topographical data, as well as archived and anecdotal information on historical slope activity;
- An engineering geological assessment of the limestone face and talus apron, with particular attention paid to past and present instability. This included the collection of rock defect data, assessment of groundwater influence and the recording other geotechnical information that will help assess the 1% AEP rockfall hazard. A helicopter flight enabled the limestone face to be viewed and photographed from different angles and enabled inspection of the top of the slope, which cannot be easily reached on land;
- Subsurface investigations involving the excavation of six test pits in order to better constrain the boundary of past rockfall and debris flow;

- The use of rockfall trajectory modelling to assess the likely 1% AEP runout zone. The program RocFall by RocScience was used for this purpose;

- The collection of recorded seismicity from the Institute of Geological and Nuclear Sciences (IGNS). This is used to determine earthquake shaking at Punakaiki and to assess its relevance to slope stability.

- The production of a Hazard Map indicating the 1% AEP.

2.1 Regional Geology

The location of New Zealand across the major tectonic boundary of the Pacific and Australian Plates results in the generation of seismic events in the South Island. The Alpine Fault forms the acknowledged plate boundary and is the site of a large proportion of tectonic movement. It passes from Milford Sound in the south, along the West Coast in a line towards Springs Junction and passes 65 km east of Punakaiki. In addition to the Alpine Fault, there are numerous other less active structures that contribute to the seismic activity in the Buller region.

Tectonic processes greatly influence the distribution of the geology in the Buller Region. Reference to geological maps by Bowen (1964) and Laird (1988) indicates that basement rocks are those greater than Cretaceous age (135 Ma – million years old) and in the general study area consist of Greenland Group sandstone and mudstone, gneiss belonging to the Charleston Metamorphic Group and Karamea Batholith granite. Mostly sedimentary rocks overlie the basement and include mudstone, sandstone, limestone and coal measures of between 2 and 135. There are also dykes, and some basalt and tuff associated with small-scale, localised volcanism. Quaternary age (less than 2 Ma) river gravels and swamp deposits rest unconformably over the older geology.

2.2 Earthquake Records

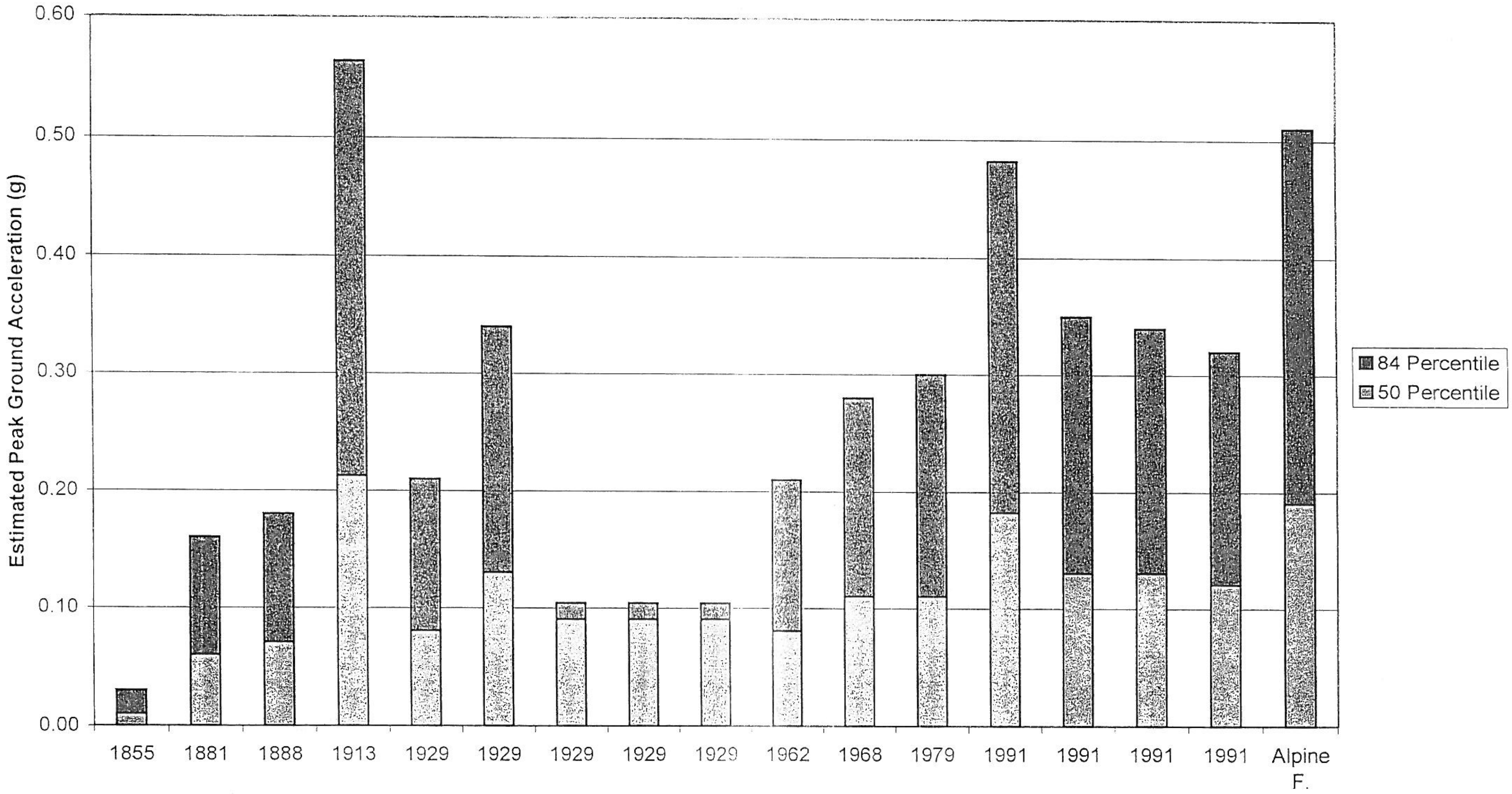
The proximity of Punakaiki to potential sources of large earthquakes has significant implications for the stability of the Te Ruahuanui limestone cliff. Lateral acceleration caused by ground shaking can loosen rock material and may be the predominant rockfall triggering mechanism. The frequency of earthquakes may therefore be significant in estimating the rock and debris runout 1% AEP.

Historical seismic data was obtained from IGNS dating back to 1826 (see Appendix A for table of data) and lists the earthquake date and epicentre location, magnitude, distance from Punakaiki and the shaking intensity felt at Punakaiki (using the MMI, or Modified Mercalli Intensity scale) for MMI>V. For data older than 50 years anecdotal information has been compiled by IGNS to best determine source location and magnitude.

The peak ground acceleration (pga) for MMI>V has been calculated using the earthquake attenuation model of Stirling et al. (2000). As Figure 1 shows, the historical earthquake that has resulted in the greatest amount of shaking at Punakaiki occurred in 1913 and was sourced only 19 km away. The fiftieth percentile (50^{th} %) pga is calculated at 0.21 g, with the eighty-fourth percentile (84^{th} %) estimated to be 0.35 g.

Cooper (2000) mentions the high probability of an Alpine Fault rupture occurring in the next 50 years, suggesting that this is a likely driver of slope instability in the study area. Figure 1 shows that the Alpine Fault, which is approximately 65 km away and has an estimated past magnitude of M8.0, has a 50^{th} % pga of 0.19 g and an 84^{th} % of 0.32 g. Based on this it may be concluded that the Alpine Fault does not produce local pga exceeding that of at least one historical earthquake.

Figure 1: Largest Historical Earthquakes Felt in Punakaiki



3.1 Site Geology

The geology of Punakaiki is described by Laird (1988) and is summarised in this report in Figure 2. The main structural feature is the Punakaiki Anticline, a gently deformed feature that is oriented NNE/SSW. In the core of the anticline is the Greenland Group sandstone basement, which is inferred to underlie the area, although there is no exposed rock of this type within 8 km of the township. The next successive layer is the Island Sandstone, a much younger Tertiary lithology composed of light brown, slightly calcareous muddy sandstone. Above this is the Potikohua Limestone, which can be described as a yellow, slightly weathered, massively bedded, very strong limestone, with very wide defect spacing up to 5 m. This is capped by light brown mudstone belonging to the Welsh Formation. Coastal erosion has removed the western limb of the anticline in this area, exposing the near-vertical limestone cliff immediately east of Punakaiki township. Over steepening of the cliff has resulted in instability and an apron of talus rockfall debris has accumulated at the slope base, mostly obscuring the Island Sandstone. As a result the exposed rock on the cliff is mostly Potikohua Limestone. The heavily vegetated Welsh Formation appears to be readily eroded and may represent a source of debris flow material.

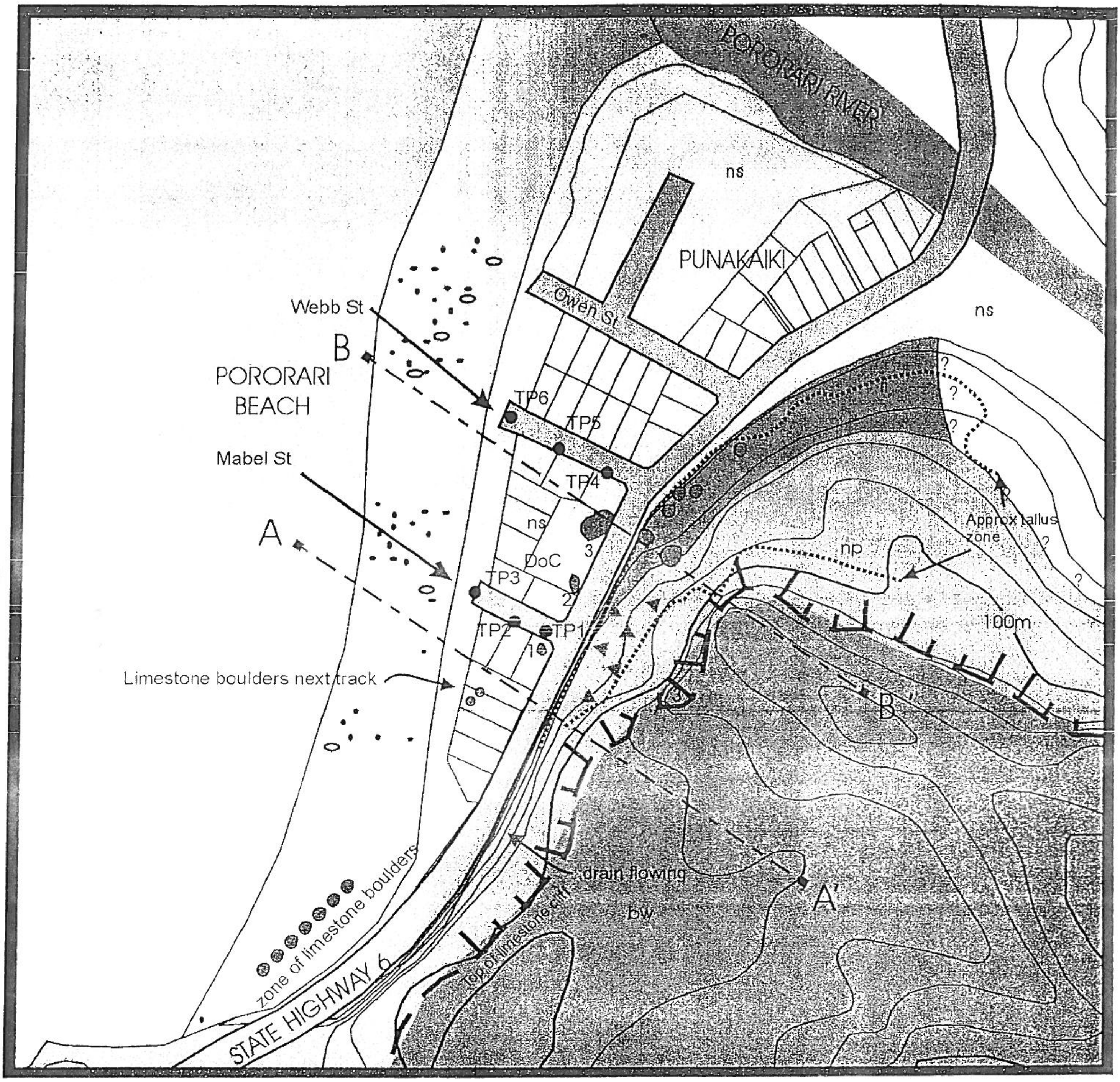
Between the slope base and the coast is the Nine Mile Formation, which is a term used to describe Holocene aged (less than 14,000 years old) fluvial, coastal or estuarine sedimentary deposits. At Punakaiki the Nine Mile Formation is a relatively flat surface that is less than 10 m above sea level. Six test pits excavated as part of this study indicate a marine origin and is described as a laminated and cross-bedded fine to medium sand. The precise age of the deposition of this material is uncertain, although a range of between 5000 years old (Laird, 1988) and 6500 years old (Suggate and Waight, 1999) is assumed.

Figure 3 shows the Potikohua Limestone cliff, which is near vertical with a slope angle/slope direction of approximately 75/308°. Bedding dips gently (9°) towards the southwest. Fifty-five joint sets were recorded and are presented in Figure 4, which shows the presence of one joint set oriented sub parallel to the rock face (dip/dip direction 77°/222°) and one normal to the face (83°/228°), creating an orthogonal geometry with bedding. The face normal joint set is parallel to the same limestone cliff southwest of the Pororari River and controls the orientation of the slope in this locality.

3.2 Evidence for Slope Instability / Field observation

Rock and soil debris has accumulated at the base of the limestone cliff east of SH6, forming an apron of talus debris. Thick vegetation has established on this debris, which consists of strong, angular limestone blocks ranging from 0.1 to 5 m in diameter within a matrix of sandy soil.

Investigation of the rock face indicates numerous areas of past block release. Bedding and joint orientation appear to be the main factors controlling the nature of slope instability with large overhanging rock and areas of fresh rock oriented parallel to discontinuities and bedding. Figure 5 shows that the spacing of defects appears to control the size of material released. Above the limestone face the Welsh



Basemap modified after Cooper (2000)

Geological Legend

Youngest	*Name of Deposit*	*Geological Description*	*Epoch*
ns		Wave sorted mixed sands and gravels	Recent
ns	Nine Mile Formation	Marine sand and gravel	Holocene
bw	Welsh Formation	Light brown calcareous mudstone	Miocene
np	Potikohua Limestone	Flaggy white polyzoan and foraminiferal limestone	Oligocene
	Island Sandstone	Light brown slightly calcareous muddy sandstone	Eocene

Contours at 20 m intervals

TP1 = Investigation test pit location

A - - A' Line of Cross Section

Boulders or tallus

URS

Figure 2: Punakaiki Geology Map

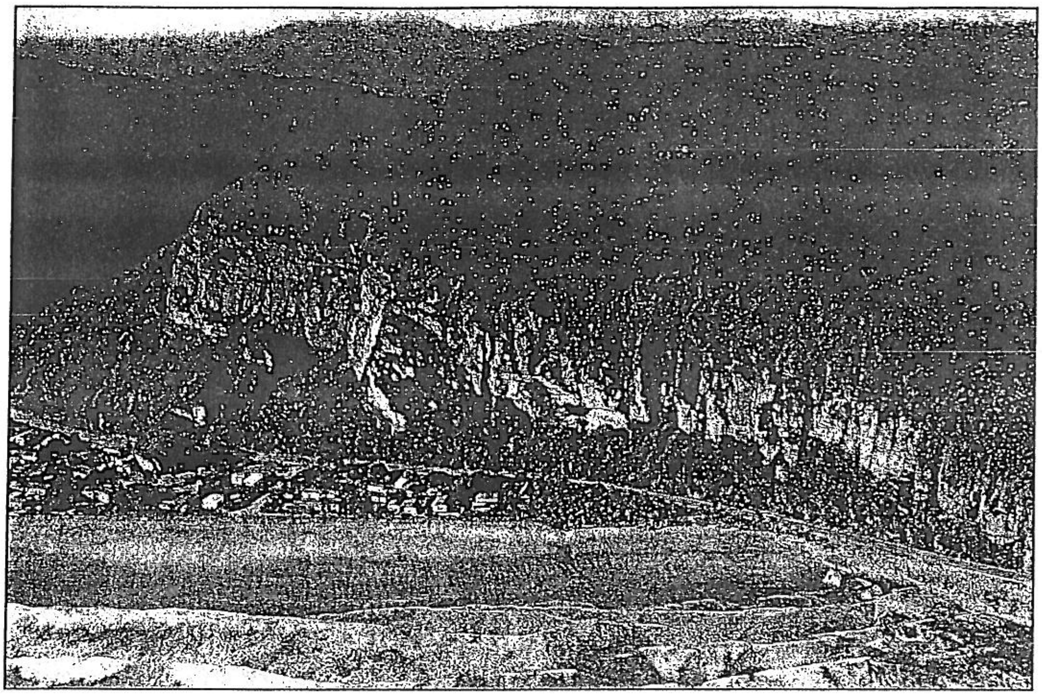


Figure 3: Potikohua Limestone rock face at Punakaiki

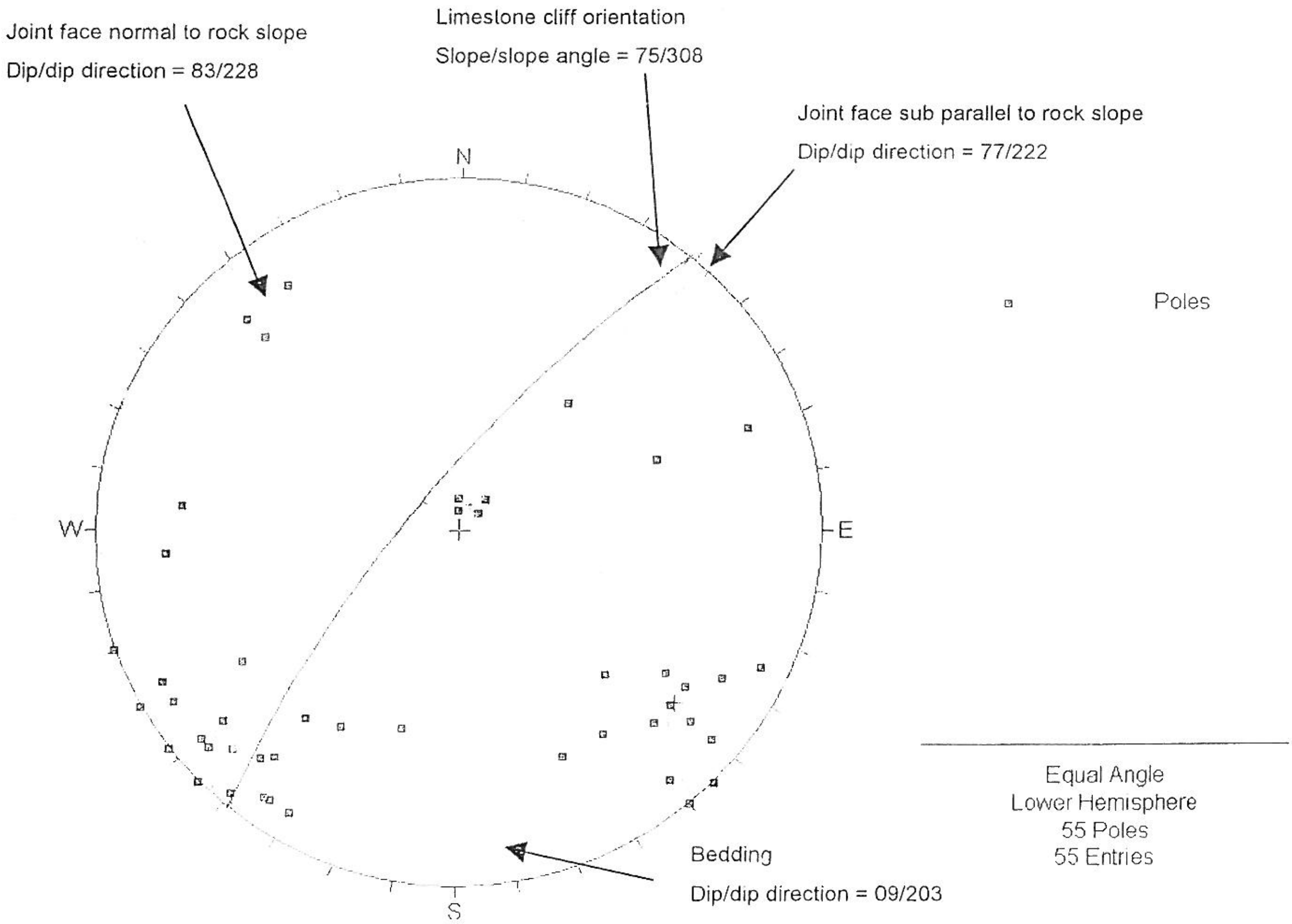


Figure 4: Stereonet plot of bedding and discontinuity data

Formation has eroded to a low angle. This is a likely contributor to debris flows, particularly during heavy rainfall events. A large amount of this material appears to have failed southwest of the Pororari River.

Three large limestone blocks provide evidence for rocks bouncing and rolling to the west of SH6. Block number 1 and 2 (see Figure 2) are up to 8 m in diameter appear to rest upon the surface of the approximately 5000 year old Nine Mile Formation. Block 3 is much larger – up to 30 m across – and seems to protrude above the Nine Mile sediment, suggesting that it fell prior to the deposition of the beach sand (see Figure 6 for photo of this block). All of these blocks have dips that are steeper and differently oriented[2] than the joints measured in the rock face and support the conclusion of Nathan (1988) that these are ex-situ and originate from the cliff face. If one accepts that the age of the Nine Mile Formation is 5000 years, then it can be said that at least two large blocks (number 1 and 2) have been released and crossed SH6 at a frequency of 1 in 2500 years.

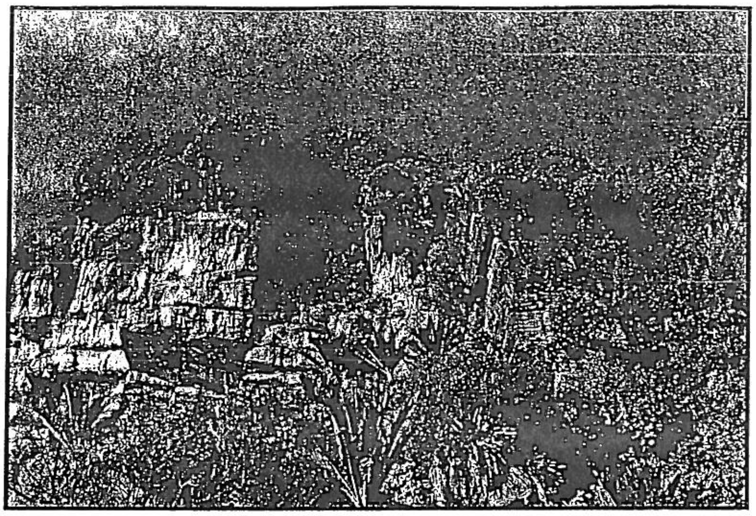
3.3 Anecdotal Evidence

Anecdotal evidence was collected by interviewing people with local knowledge, including Robin Reid of the Punakaiki Department of Conservation and Les Wright of the Historic Places Trust. In addition searches were made of the Christchurch Press archives and the Christchurch library. From this information it is apparent that in the early 1980s soil was saturated by 160 mm of rain, was mobilised and crossed SH6, entering the DoC workshop (see Figure 2 for location of workshop). The absence of large rock material meant that less damage was caused.

3.4 Subsurface Investigations

In order to better constrain the runout distance of past rock and debris flows six test pits were excavated between SH 6 and the beach (see Figure 2 for locations). Three pits up to 2.3 m deep were excavated and logged in Webb St and three in Mabel St. Appendix B shows the logged results of each pit and these can be summarised as containing cross bedded beach sands and gravels of the Nine Mile Formation. No limestone clasts were identified and there was no evidence of past debris flow in any of the pits. Radiocarbon dating of buried organic material was planned had boulders or debris flows been identified, but this was not necessary.

[2] Rock No., dip/dip direction: 1, 30°/045°; 3, 25°/135°.

a)


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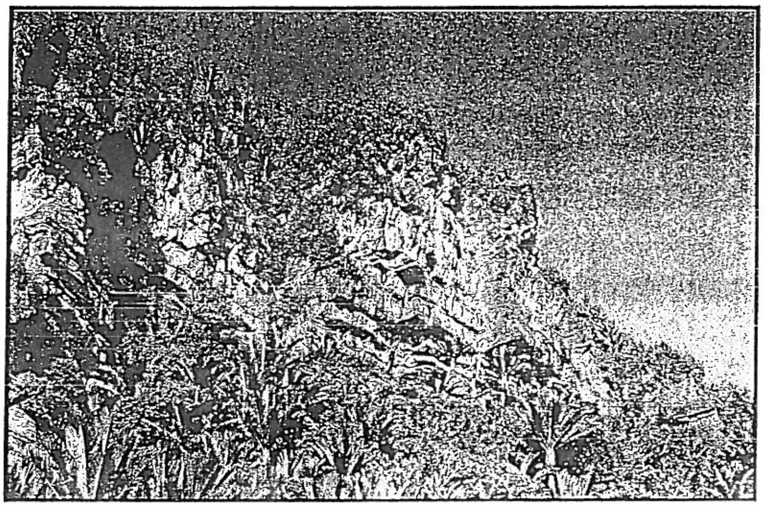

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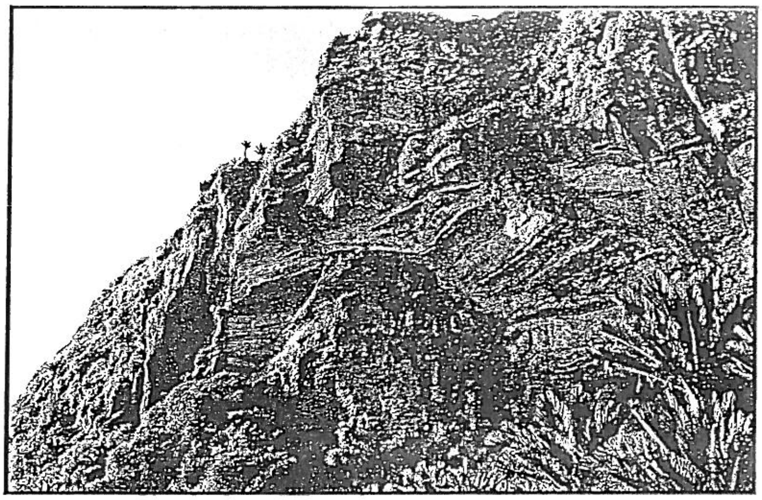

Factors suggesting slope instability include:

•Overhanging rock which shows where material has fallen.

•Yellow rock faces have been exposed more recently than those that are grey and lichen-covered.

• Blocky nature of face indicates shape of material that exits slope.

Figure 5: Evidence of past instability in the limestone rock face

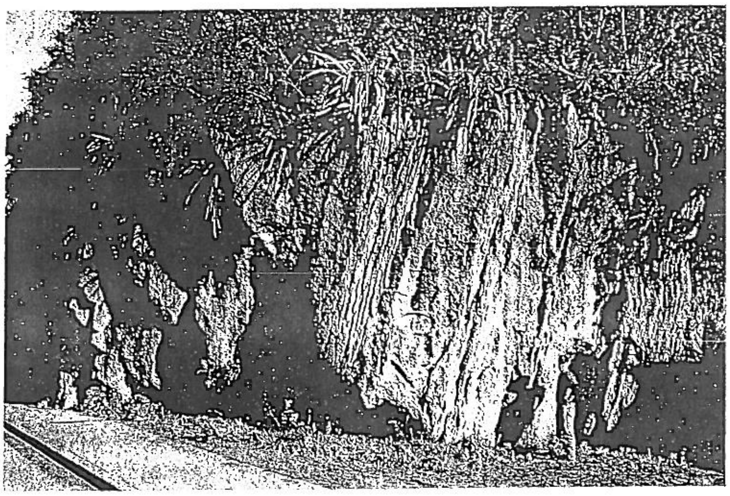

Figure 6: Block 3 rests to the west of SH6 and is approximately 8 m high

4.1 Evidence for Rockfall Mechanism

The accumulation of debris, largely comprising limestone blocks, between the base of the cliff and highway is interpreted to mainly represent debris from rockfall events. Analysis of the distribution of continuous joints collected along the limestone cliff indicates that these are mainly steeply dipping and strike parallel and normal to the cliff (see Figure 4). Bedding within the limestone dips gently (~5°) to the south, which results in a small component of dip into the face. The joint and bedding distribution is expected to give rise to rockfall with toppling failures being the principal failure mechanism[3]. Planar failure[4] could also give rise to rockfall if the material underlying a block fails under shear failure. This is considered to be possible given the relatively high clay content of the Island Sandstone, which underlies the limestone unit. Wedge failures within the limestone could also lead to rockfalls because rare joint combinations were observed that could allow a wedge failure to occur[5]. Wedge failures are considered to be the least likely mechanism for rock slope failure within the limestone at the site.

Typical joint spacing observed in the limestone cliff is in the order of 2 to 10 m, with an average estimated to be about 5 m. Much larger blocks have occurred within the rockfall debris as shown by Figure 7. The largest block is approximately 30 m in the longest dimension.

The volume of the largest rockfall could be up to approximately 20 000 m^3 if the large blocks (1, 2 and 3) all were part of a single event. We expect that most rockfall events are of much smaller volume, with many of the blocks being less than 10 m^3.

Geological evidence collected from the site (principally the presence or absence of limestone blocks within the strata or on the ground surface) indicates that rockfalls have affected an area that extends about 20 to 80 m from the toe of the debris slope. We refer to this as the "Maximum Rockfall Hazard Zone" on Figure 8. However, most rockfall events are inferred to be much smaller and to accumulate within the debris apron.

4.1.1 Rockfall Trajectory Modelling

We have undertaken computer modelling to investigate the "runout" or rockfall inundation zone using the computer program Rocfall developed by Rocscience Inc. The two test cross sections are the same that were analysed by Cooper (2000) using CRSP software.

[3] A toppling failure occurs when a relatively tall block rotates top first out of a slope.

[4] A planar failure occurs when a block slides along a principal joint, which is usually approximately parallel to the rock face.

[5] Wedge failure occurs when a block slides along two intersecting joints.

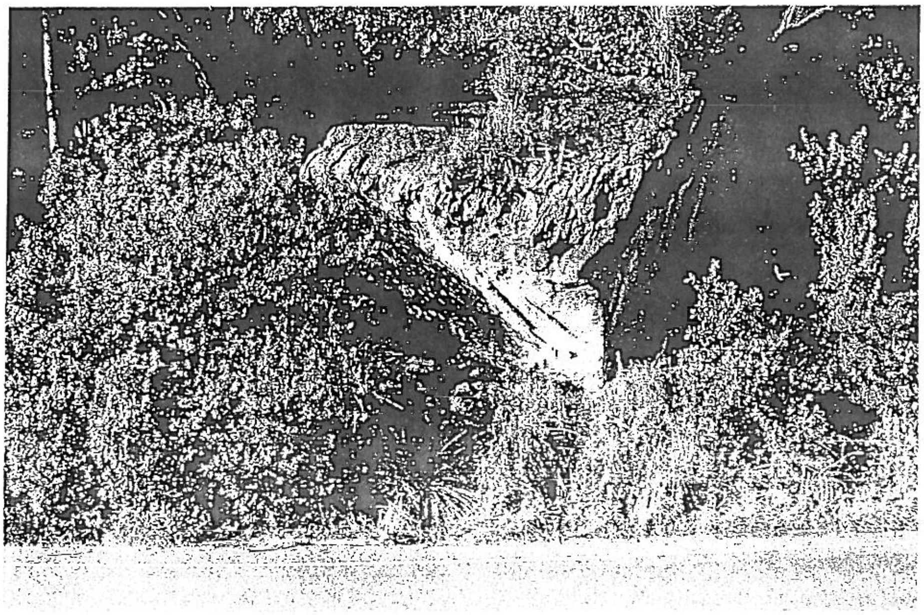

Figure 7: Photograph of a large block in the talus beneath the limestone cliff

The following assumptions were incorporated into the rockfall analysis for our "best guess" assessment:

- Rockfall blocks have dimensions of 5m × 5m × 5m, and a mass of 332 000 kg.
- The debris apron on which the block lands is an irregular surface with physical properties:

The results of this modelling (presented in Appendix C) indicate that rockfall blocks come to rest within 40 m of the toe of the debris slope. Many blocks are contained within the debris apron and do not reach the highway corridor.

Sensitivity analysis has been undertaken as part of the modelling and involves holding all but one variables constant, and varying this to evaluate the resulting rockfall distribution. This analysis indicates which parameters the modelling is most sensitive to. The sensitivity analysis indicates that the roughness of the debris apron is the parameter that most affects rockfall runout distance.

The results of rockfall trajectory modelling are consistent with the geological evidence collected from the site.

4.1.2 Earthquake Induced Rockfall

Strong earthquake shaking is a likely trigger for rockfalls. Section 2.2 discusses the historical seismicity data collected by IGNS, and the interpreted acceleration felt at the site during those events. The data indicates that the site has been exposed to moderately strong shaking on several occasions during the last 100 years. Although small rockfalls were likely to have been generated by these earthquakes, no anecdotal evidence for large rockfalls has been found.

The Alpine Fault is expected to generate strong shaking at the site and it is expected that significant rockfalls could be triggered by this event. Alpine Fault earthquakes of Magnitude 8 are thought to have a return period of 200 to 300 years. The maximum acceleration generated by such an earthquake is calculated to be similar to the largest shaking experienced during the last 100 years (as indicated by Figure 1), but may last much longer. The rockfall debris accumulated during the past 3000 to 6000 years includes debris from rockfalls that may have been generated during Alpine Fault earthquakes.

4.2 Evidence for Debris Flow

Debris flows are relatively rapid landslides that typically occur as a result of heavy or prolonged rainfall in steep terrain. Mr Robin Reid from DoC (Punakaiki office) described a debris flow that occurred in the early 1980s following very heavy rain. The source area for this event is believed to be the upper part of the slope above the limestone outcrop. The debris flow inundated the highway and crossed into the DoC workshop area. The debris mainly consisted of thick muddy sediment.

Potential source areas for debris flows include the debris apron at the base of the cliff and the Welsh Formation mudstone at the top of the cliff. The debris apron is capable of generating small debris flows, but these will be finite in volume and runout because of the limited source area. The upper slope above the cliff is a relatively small source area, but any debris that falls from the cliff will generate high velocities and have greater potential runout distances.

The lack of landslide-derived debris encountered by the test pits suggests that debris flows have not been frequent or large during the recent past.

4.3 Rockfall Hazard Zones

The Maximum Rockfall Hazard Zone defined in Figure 8 represents the area within which rockfall debris has been found. We infer that this zone includes the largest rockfalls that have occurred during the last 3000 to 6000 years (the age of the Nine Mile Formation sediments on which the village is built) and that rockfalls affecting a larger area have a very low probability of occurrence.

The majority of rockfall debris has accumulated within the debris apron at the toe of the cliff and we infer that most future rockfall events will be contained within this area. The rockfalls with the greatest runout distance (which may or may not be the largest rockfalls in terms of volume) are expected to pass beyond the toe of the debris apron, but are not expected to pass the "Maximum Rockfall Hazard Zone" limit.

We consider that the seaward side of the highway corridor defines an appropriate 1% Annual Exceedence Probability hazard zone[6]. Large rockfall events would travel further than this zone, but on average the zone would not be exceeded more than once every one hundred years.

[6] The 1% Annual Exceedence Probability zone defines an area which would only be exceeded by a rockfall once every hundred years on average.

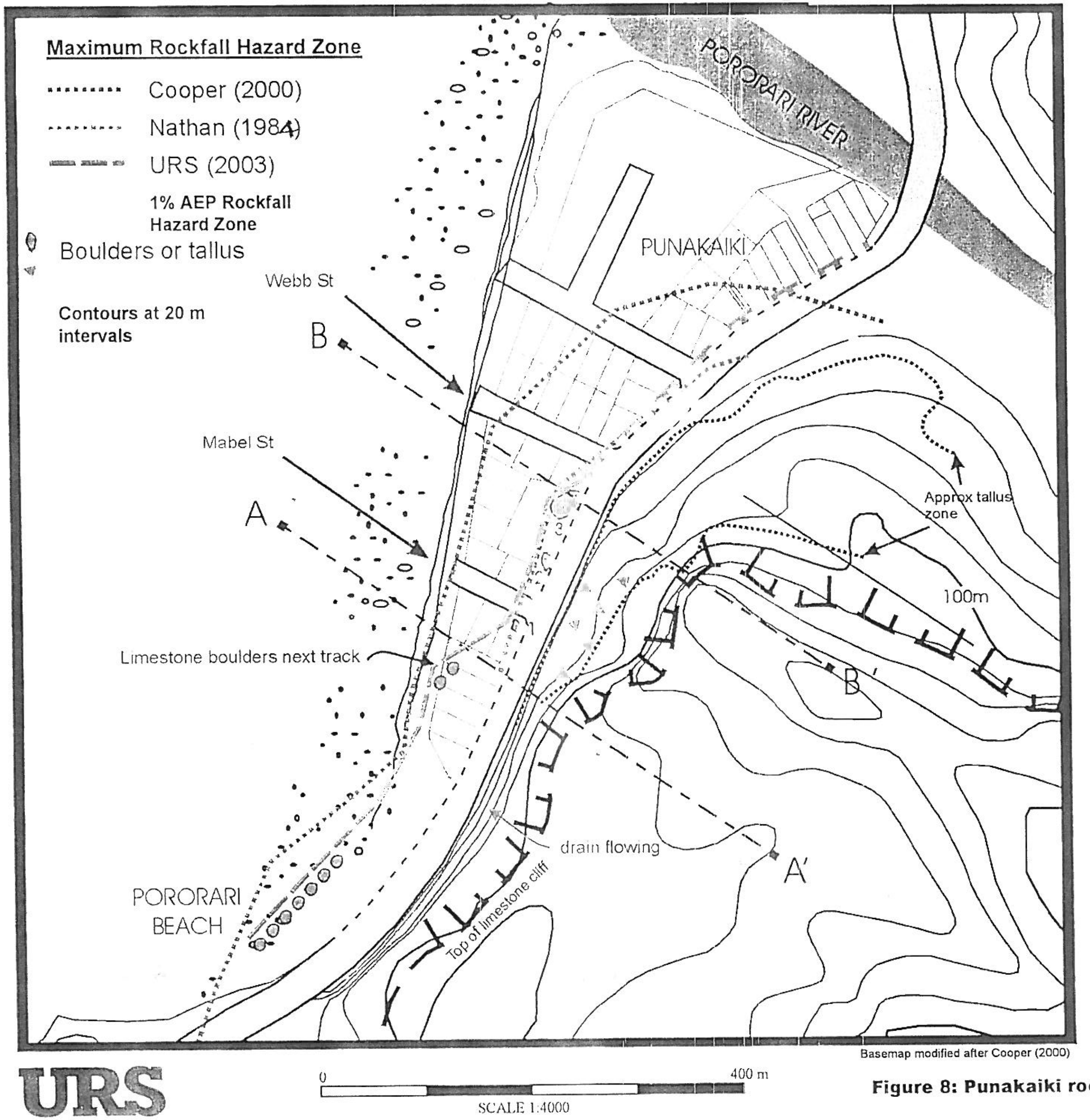

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Figure 8: Punakaiki rockfall hazard zone

The accumulation of debris, largely comprising limestone blocks, between the base of the cliff and highway is interpreted to mainly represent debris from rockfall events.

Analysis of the distribution of continuous joints and bedding surfaces indicates that rockfalls are likely to result mainly from toppling failures of the limestone.

Typical joint spacing observed in the limestone cliff is in the order of 2 to 10 m, with an average estimated to be about 5 m. Much larger blocks have occurred within the rockfall debris, the largest block is approximately 30 m in the longest dimension.

The volume of the largest rockfall could be up to approximately 20 000 m^3 if the large blocks were each part of single events. We expect that most rockfall events are of much smaller volume, with many of the blocks being less than 10 m^3.

Geological evidence collected from the site (principally the presence or absence of limestone blocks within the strata or on the ground surface) indicates that rockfalls have affected an area that extends about 20 to 80 m from the toe of the debris slope. We refer to this as the "Maximum Rockfall Hazard Zone", however, most rockfall events are inferred to be much smaller and to accumulate within the debris apron.

Rockfall trajectory modelling (presented in Appendix C) indicates that rockfall blocks generally come to rest within 40 m of the toe of the debris slope. Many blocks are contained within the debris apron and do not reach the highway corridor. The results of rockfall trajectory modelling are consistent with the geological evidence collected from the site.

Strong earthquake shaking is a likely trigger for rockfalls. Historical seismicity data indicate that the site has been exposed to moderately strong shaking on several occasions during the last 100 years.

The Alpine Fault is expected to generate strong shaking at the site and it is expected that significant rockfalls could be triggered by this event. The maximum acceleration generated by an Alpine Fault earthquake is calculated to be similar to the largest shaking experienced during the last 100 years but may last much longer.

Debris flows are relatively rapid landslides that typically occur as a result of heavy or prolonged rainfall in steep terrain. Anecdotal evidence indicates that a debris flow occurred in the early 1980s following very heavy rain. The lack of landslide-derived debris encountered by the test pits suggests that debris flows have not been frequent or large during the recent past.

We consider that the seaward side of the highway corridor defines an appropriate 1% Annual Exceedence Probability hazard zone[7]. Some debris from large rockfall events could travel beyond this zone, but on average debris would not exceed the zone more than once every one hundred years.

[7] The 1% Annual Exceedence Probability zone defines an area which would only be exceeded by a rockfall once every hundred years on average.

Recommendations

The Maximum Rockfall Hazard Zone defined in this report is equivalent to the "Rockfall and Rapid Debris Flow Hazard Area" recommended by Nathan that is currently contained within the Buller District Council District Plan and could replace it.

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Appendix A – Earthquake Magnitude Data

YEAR	DATE	LAT	LONG	MAGNITUDE	EPI-CENTRAL DISTANCE (km)	MMI*	Pga 50% (g)	pga 84% (g)	SOURCE
1460		-41.4	174.8	A F	299	V			
+									"Haowhenua"
1826		-45	167	A F	474	V			
1846	Jul-04	-42	172	C F	57	V			
1846	Nov-18	-41	172	6.5 F	136	V			
1848	Oct-15	-41.5	173.8	7.1 F	216	V			
+									"Marlborough (I)"|Location:
									Eiby (1980)
1855	Jan-23	-41.4	175	8.1 F	315	VI	0.01	0.02	
+									"Wairarapa"|Location: Eiby
									-1989
1868	Oct-18	-40	173	7.0 F	274	V			
+									"Cape Farewell"|Location:
									Anderson et al. (1994)
1881	Dec-04	-42.6	172.3	6.8 F	96	VI	0.06	0.10	
1888	Aug-31	-42.6	172.3	7.0 F	96	VI	0.07	0.11	
+									"North Canterbury"|Location:
									McKay (1888), Cowan (1991)
1888	Oct-23	-41.5	172.5	7.0 F	119	V			
1901	Nov-15	-43	173	6.9 F	168	V			
+									"Cheviot"|Magnitude: Dowrick
									& Smith (1990)
1913	Feb-22	-42	171.5	6.0 F	19	VII	0.21	0.35	
+									"Westport"|Location: Hogben
									-1913
1914	Nov-22	-37.5	176.5	7.2 F	677	V			
+									"Bay of Plenty"|Magnitude:
									Gutenberg & Richter (1949)
1929	Mar-09	-42.79	171.93	7.1 F	89	VI	0.08	0.13	
+									"Arthur's Pass"|Location:
									Yang (1989)|Magnitude:
									Dowrick & Smith (1990)
1929	Jun-16	-41.7	172.2	7.8 F	86	VII	0.13	0.21	
+									"Buller"|Location: Bastings
									(1933, 1936, 1937), Dowrick
									(1994)|Magnitude: Dowrick &
									Smith (1990)
1929	Jun-18	-42	172	6 F	57	V			
1929	Jun-18	-42	172	6 F	57	V			
1929	Jun-19	-42	172	C F	57	V			
1929	Jun-20	-42	172	6.3 F	57	VI	0.09	0.01	
1929	Jun-22	-42	172	6.3 F	57	VI	0.09	0.01	
+									Magnitude: Dowrick & Smith
									-1990
1929	Jun-22	-42	172	6.3 F	57	VI	0.09	0.01	
1929	Jul-15	-42	172	5.8 F	57	V			
1934	Mar-05	-40.5	175.5	7.6 F	393	V			
+									"Pahiatua"|Location: Hayes
									(1937), Bullen
									(1938)|Magnitude: Dowrick &

Appendix A – Earthquake Magnitude Data

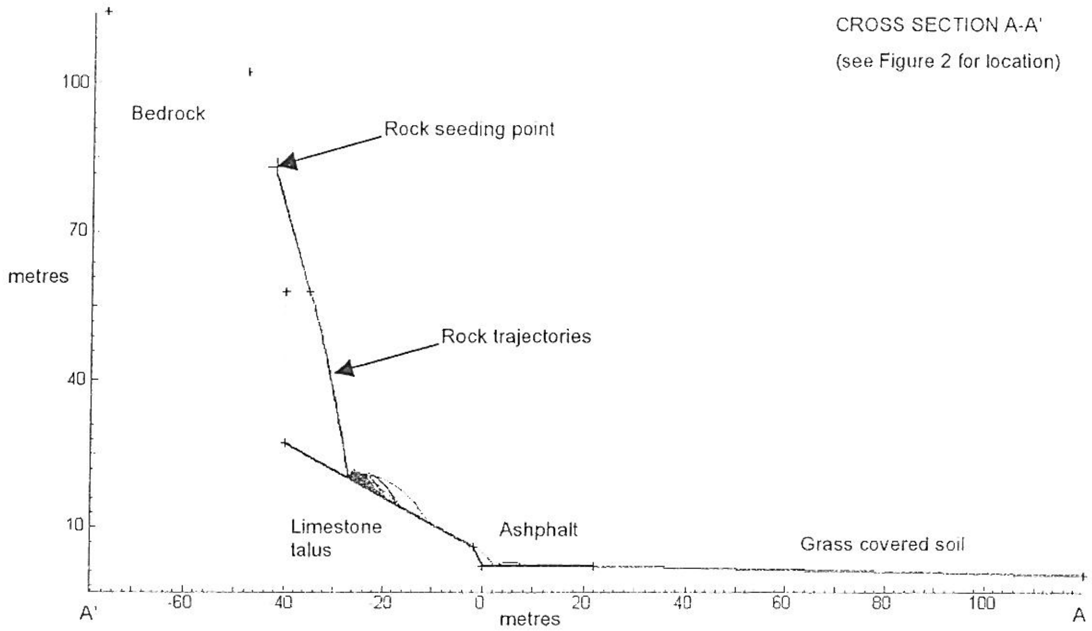
1946	Jun-26	-43.18	171.68	6.4 F	121	V			
+									"Lake Coleridge"|Numerous
									aftershocks. For isoseismal
									map, see Hayes, 1947. See
									also Eiby (1990).|Magnitude:
									Dowrick (pers. comm.)
1946	Jun-26	-42.12	171.09	4.3 F	20	V			
1953	Sep-29	-37.6	176.48	7.2 F	667	V			
+									"Bay of Plenty"
1955	Oct-02	-42.08	171.25	3.8 F	8	V			
1961	Jun-18	-32.41	179.39	6.9 F	1291	V			
1962	May-10	-41.67	171.44	5.9 F	51	VI	0.08	0.13	
+									"Westport"|Magnitude: Dowrick
									& Smith (1990)
1962	May-10	-41.75	171.42	4.9 F	42	V			
1962	May-17	-41.8	171.32	5.4 F	36	V			
+									"Westport (aftershock)"
1962	May-17	-41.6	171.43	5.4 F	58	V			
1968	May-23	-41.76	172.04	7.1 F	71	VII			
+									"Inangahua"
1968	May-23	-41.99	171.52	4.3	21	V	0.11	0.17	
									Location: Interpretation
									doubtful.
1968	May-24	-41.83	171.85	5.3 F	54	V			
1968	May-24	-41.95	171.78	5.7 F	42	V			
									"Inangahua (aftershock)"
1968	May-25	-41.87	171.77	5.3 F	46	V			
1968	May-30	-41.81	171.88	5.4 F	57	V			
1968	Jun-05	-41.81	171.88	5.2 F	57	V			
1968	Jun-14	-41.79	171.93	5.4 F	62	V			
1968	Jun-16	-41.99	171.69	4.8 F	33	V			
1968	Jun-23	-41.88	171.8	5.3 F	47	V			
1968	Nov-19	-42.15	171.46	4.0 F	11	V			
1969	Mar-13	-41.97	171.52	4.3	23	V			
1971	Aug-13	-42.08	172.15	5.7 F	68	V			
+									"Maruia Springs"
1973	Dec-22	-42	171.53	4.3 F	21	V			
1979	Mar-24	-41.94	171.63	5.6 F	32	VI	0.11	0.19	
1980	Nov-10	-42.01	171.43	3.9	15	V			
1983	Aug-22	-42.07	171.49	4.1 F	14	V			
1991	Jan-28	-41.89	171.61	6.1 F	35	VI	0.13	0.21	
+									"Hawks Crag I"
1991	Jan-28	-41.9	171.73	6.3 F	41	VI	0.12	0.20	
+									"Hawks Crag II"
1991	Feb-15	-42.04	171.59	6.0 F	23	VII			
1991	Feb-15	-42.05	171.56	4.6 F	21	V			
1991	Feb-24	-42.05	171.57	5.1 F	22	VI			
1992	May-27	-41.6	173.66	6.8 F	202	V			
+									"Marlborough"
1994	Jun-18	-43.01	171.48	6.7 F	99	V			
+									"Arthur's Pass"
	Jul-16	-42.03	171.64	4.6 F	28	V			
1995	Nov-24	-42.95	171.82	6.3 F	101	V			
+									"Cass"
1997	May-25	-32.31	-178.79	7.9 F	1395	V			
2000	Aug-15	-31.94	-178.55	7.6 F	1442	V			
1717				*8*	*65*		*0.19*	*0.32*	*Alpine Fault*

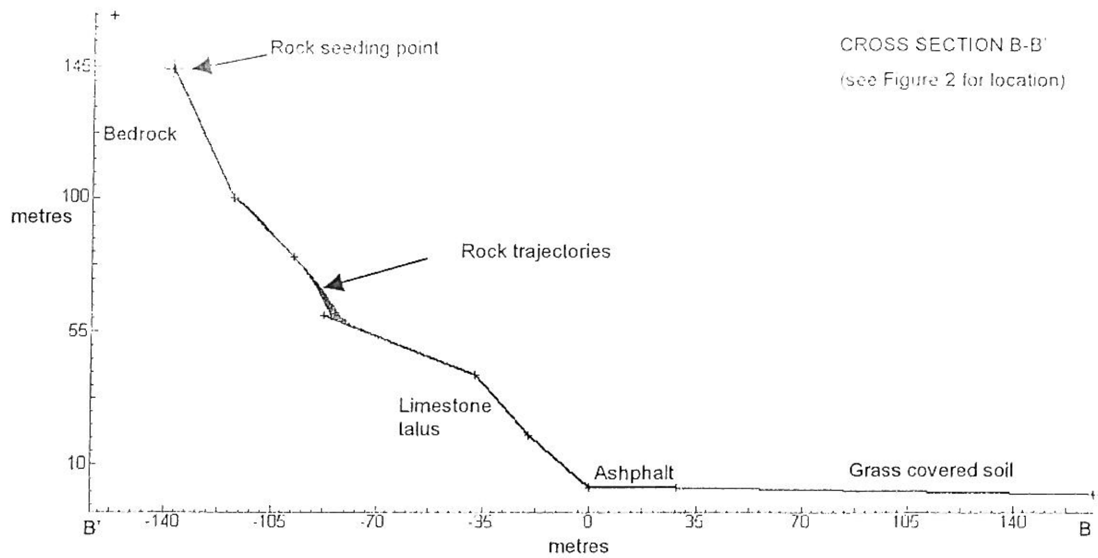
*MMI = Mercalli Modified Intensity

Appendix B – Test Pit Logs

Appendix C – Rockfall Trajectory Analysis Data

Appendix C – Rockfall Trajectory Analysis Data





RocFall by RocScience was used for trajectory analysis of falling limestone blocks from the limestone cliff at Punakaiki. The slope was divided into rock surface materials, which were chosen according to default parameters within the program. One hundred blocks were simulated falling from the seed point. The sensitivity analysis involved changing individual parameters before simulating the falling rocks.

Factors that do not significantly alter rock travel distance:

- Rock seeding point. This was conservatively placed at the top of the slope. Multiple seeding points were placed throughout the slope with negligible change in rockfall distance.
- Starting velocity. This was tested between 0.1 and 1.0 m/s.

- Mass of block. This was tested for blocks between 10 – 332000 kg and resulted in comparable travelling distance.

Factors that do alter rock travel distance:

- The properties of the surface were rocks fall. The ability of the limestone talus slope to absorb energy is critical to reducing the runout distance of falling rocks and boulders.