Rock fall at the Takiroa rock art site, May 2010, Duntroon, North Otago, New Zealand

Simon C. Cox

GNS Science Report 2010/31
June 2010

GNS SCIENCE
TE PŪ AO

BIBLIOGRAPHIC REFERENCE

Cox, S. C. 2010. Rock fall at the Takiroa rock art site, May 2010, Duntroon, North Otago, New Zealand. *GNS Science Report* 2010/31, 20 p.

S. C. Cox, GNS Science, Private Bag 1930, Dunedin.
s.cox@gns.cri.nz

ISSN 1177-2425
ISBN 978-0-478-19774-7

CONTENTS

ABSTRACT .... **III**

KEYWORDS .... **III**

1.0 BACKGROUND **4**

2.0 STORM RAINFALL **6**

3.0 SITE GEOLOGY **7**

4.0 ROCK FALL **10**

Observations 10
Volume and mass calculations 13
Contributing factors 13

5.0 REMARKS **16**

6.0 CONCLUSIONS **19**

ACKNOWLEDGEMENTS **20**

REFERENCES **20**

FIGURES

Figure 1 Location diagram. (A) Map of New Zealand and excerpt of the NZMS 262 map showing the location of Takiroa relative to Duntroon. (B) Google Earth image of the Takiroa area (taken 12 April 2003), annotated with features of relevance to this report. The cliff is located at 170.644º E 44.8435º S. 5

Figure 2 Graph showing hourly rainfall (mm) at the Sunny Peaks rain gauge. Data supplied by Environment Canterbury. (http://ecan.govt.nz/services/online-services/monitoring/rainfall/)........ 6

Figure 3 Views of the cliff at Takiroa, looking south from the road. (A) Image from Google Earth “Street View” taken around 2006, prior to the rock fall (people provide scale). (B) Closer, annotated, image of the rock fall, taken by Geoff and Jan Keeling, 26 May 2010. The dashed red line shows the area and shape of the rock that fell. (C) Cartoon illustrating the descriptors undercut and overhung as used in this report to describe the cliff shape. Grey area represents the rock of the cliff. 8

Figure 4 Close up photographs of the failure area. (A&B) Photographs taken on the box thorn covered ledge above the scar, showing a steeply dipping fracture which has developed in the rock above the failure area (see also Figure 3). The incipient fracture can be seen in the back of solution holes beside the ledge at Y, and appears to link to the fracture at Z. While not a gaping, wide-open feature, it could in future give rise to a similar rock fall. (C) View along the failure area, highlighting the overhung nature of the cliff, variations in water content, and the presence of roots and soil on the face left behind after the failure. All photographs S Cox/GNS Science 31 May 2010. 11

Figure 5 Views west along the outcrop from beside the eastern rock art. (A) “Before” photograph by Augustus Hamilton in 1896 (supplied by Ngāi Tahu Māori Rock Art Charitable Trust) and (B) “After” photograph taken by S. Cox/GNS Science on 31 May 2010. Annotated yellow lines highlight the position of a prominent change in orientation of the cliff; the red line shows the failure scar. Note the undercut, unsupported pillar can be seen in A, and the encrusted, planar, 60-65° overhanging cliff face behind the cage. The new face formed by the failure very close to the orientation of the face with the art suggesting this older face may also have formed by a similar collapse prior to 1896. 12

Figure 6 A thin layer of roots and soil covers part of the upper side of this block. It matches the upper right-hand (western) edge of the scar on the cliff (see Fig.3B) and corresponds to part of the failure crack. Note the prominent change in colour in the surface beneath the helmet – the upper half of the block (that was once beside the failure crack) is wet (dark) whereas the lower half is dry (light). Water has penetrated the block to a depth of ~25 cm from the failure crack. A similar phenomenon can be seen in the block behind – in this instance the left hand steep side of the block has roots and the wet/dry transition is near-vertical. 14

Figure 7 Unsupported parts of the cliff. (A) View of the under side of the rock fall area, prior to the failure in May 2010 (Photo supplied by Ngāi Tahu Māori Rock Art Charitable Trust). The failed area is annotated with a red dashed line. No fracture is visible beneath the overhang. (B) An area of focus for geotechnical assessment of safety is behind the cage protecting the western rock art (see also right hand side Fig.3B). This area of the cliff is deeply undercut and unsupported. Variations in moisture content (seen in this photograph) may reflect seepage behind the cliff. Photograph S Cox/GNS Science 31 May 2010. 15

Figure 8 Hypothetical scenarios of rock fall at Takiroa in the future, include collapse of the cliff above the western rock art (green), a smaller collapse of the overhung cliff linking back to the open fracture observed near the ledge covered with box thorn (pink), or collapse of the overhanging nose (blue). Rock falls are a natural process at cliffs, but they can be highly infrequent and difficult to quantify. Cobble and some boulder-sized rocks perched on ledges or exfoliating along the cliff top could be relatively easily removed (rock-scaling) to improve public safety. It may be possible to rebuild damaged access paths in a position further out from the cliff face, thereby decreasing average time visitors are exposed to rock fall hazard. 18

ABSTRACT

A rock fall of ~35 m^3 volume collapsed from limestone cliffs at Takiroa, Duntroon, North Otago overnight on 25-26 May 2010 during a severe and prolonged rain storm. Unwitnessed, the collapse occurred between two areas of historic and culturally important Māori rock art that receive ~20,000 visitors per year. Estimated to weigh between 40 and 77 tonnes, the debris damaged a path, garden and fences but the art was unaffected. Roots and soil on the failure surface indicate that the collapse occurred on a pre-existing fracture in the rock. The failed rock mass was deeply undercut and steeply overhung. The overhung nature of the cliff, low rock-mass strength and gravity, were main contributing factors with final failure interpreted to be triggered by water during heavy rainfall. The failure has highlighted that cliffs are naturally unstable. Earlier collapses have occurred at the site and future rock falls are inevitable, although the frequency is very difficult, if not impossible, to quantify. A full geotechnical review should consider improved signage and natural hazard warning; path design to minimise visitor exposure time to the hazard; rock-scaling; engineering support; and management of water/runoff. While issues of public safety are quite distinct from the protection and curation of cultural heritage, methods employed to achieve positive outcomes in both areas have some overlap.

KEYWORDS

rock fall, Māori, rock art, limestone, public safety, cultural heritage, Takiroa, Duntroon, North Otago

1.0 BACKGROUND

On the morning of Wednesday 26 May, 2010, local farmers Geoff and Jan Keeling noticed a major rock fall had occurred at the Takiroa rock art site, 3 km west of Duntroon, North Otago (Fig.1). Large blocks had fallen from the limestone cliffs during heavy rainfall the previous night (May 25-26). Unwitnessed, the fall destroyed part of a path, garden and fences installed by the Ngāi Tahu Māori Rock Art Charitable Trust. The collapse occurred in an area between two areas of historic and culturally important rock art, but the main works of art were unaffected.

The cliff and immediately adjacent land are part of a treaty settlement area owned by Te Rūnanga o Ngāi Tahu. The area has recently been upgraded for the public to view, appreciate and enjoy the art and now receives around 20,000 visitors per year[1]. Given the high number of visitors and the cultural heritage value of the site, GNS Science undertook a geological investigation under its Immediate Landslide Response facility through GeoNet.

This report is based on site observations made on 31 May 2010 after the storm had passed. While touching on issues of importance for public safety and curation of the rock art, this report focuses on description of the rock fall from a geological perspective. Although the report comments on possible actions to improve safety, it should encourage the seeking of and not be considered as a replacement for, a full geotechnical review and hazard assessment.

[1] Visitor numbers supplied by the Ngāi Tahu Māori Rock Art Charitable Trust.

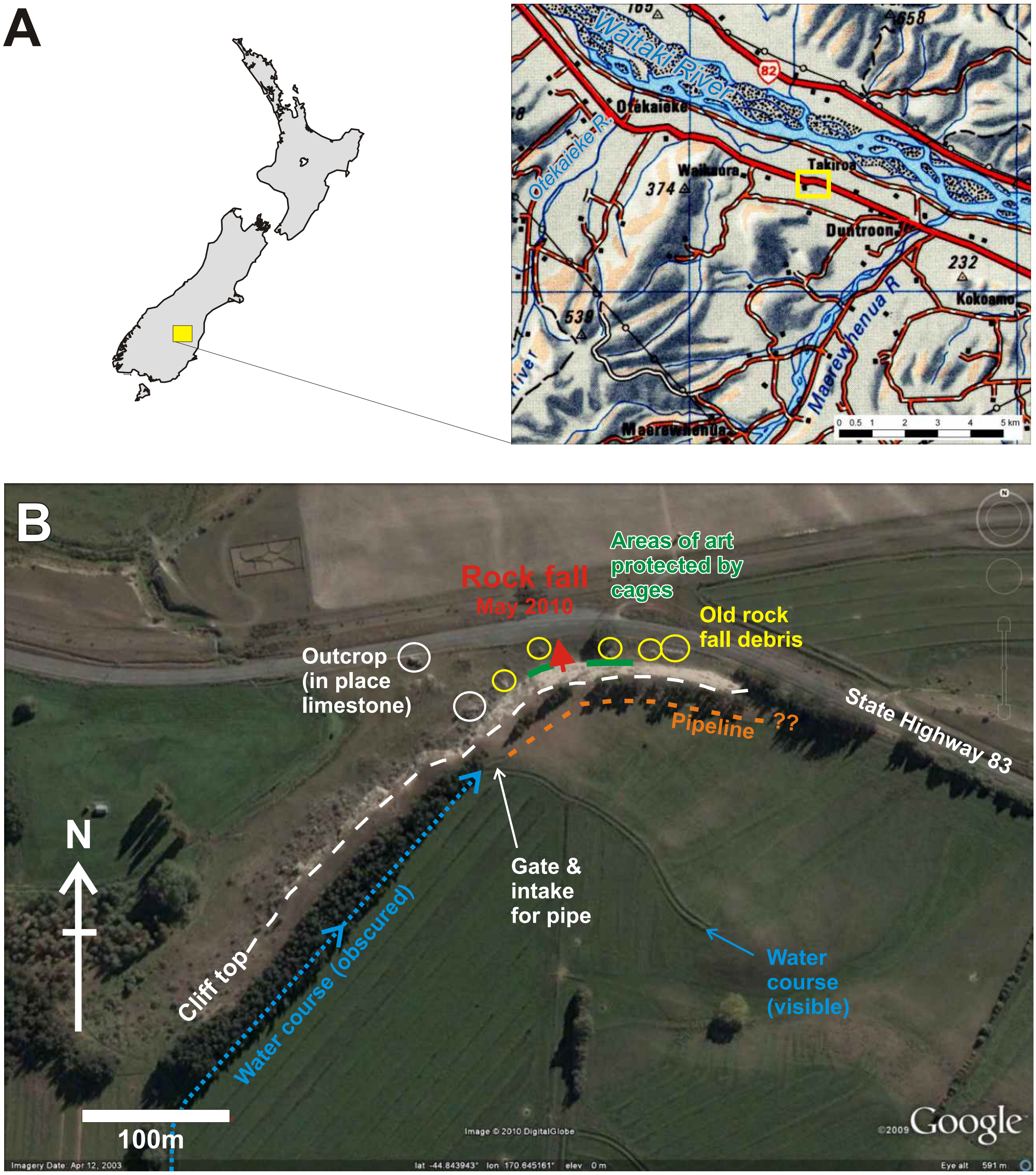


Figure 1 Location diagram. (A) Map of New Zealand and excerpt of the NZMS 262 map showing the location of Takiroa relative to Duntroon. (B) Google Earth image of the Takiroa area (taken 12 April 2003), annotated with features of relevance to this report. The cliff is located at 170.644º E 44.8435º S.

2.0 STORM RAINFALL

A slow-moving, deep, low-pressure centre crossed the South Island of New Zealand during the period 19-30 May 2010 and brought record rainfalls to Otago. The rain was particularly intense from Monday 24th –Tuesday 25th, locally reaching 10 mm/hour in some rain gauges. Daily rainfall records also came close to being broken, such as 260.5mm of rain recorded at the Dasher in North Otago, just short of the 265mm that fell in January 2002 (Otago Daily Times 2/6/2010 quoting Otago Regional Council data). Oamaru received 203 mm of rain during the month of May, which was 411% of normal rainfall and exceeded the previous record of 155 mm set in 1917 (Otago Daily Times 2/6/2010 quoting NIWA data). The storm resulted in widespread flooding, road and school closures, and many landslides and rock falls.

The Sunny Peaks rain gauge, about 20 km west of Takiroa, is the closest rainfall station to the rock art with publicly available hourly rainfall data (www.ecan.govt.nz). Total rainfall of 105 mm was recorded for the storm from 0900 on the 24th May to 0600 on 26th May, with the most intense rainfalls of 6.5mm/hour occurring between 1500 and 1700 hrs on 25th May (Fig.2).

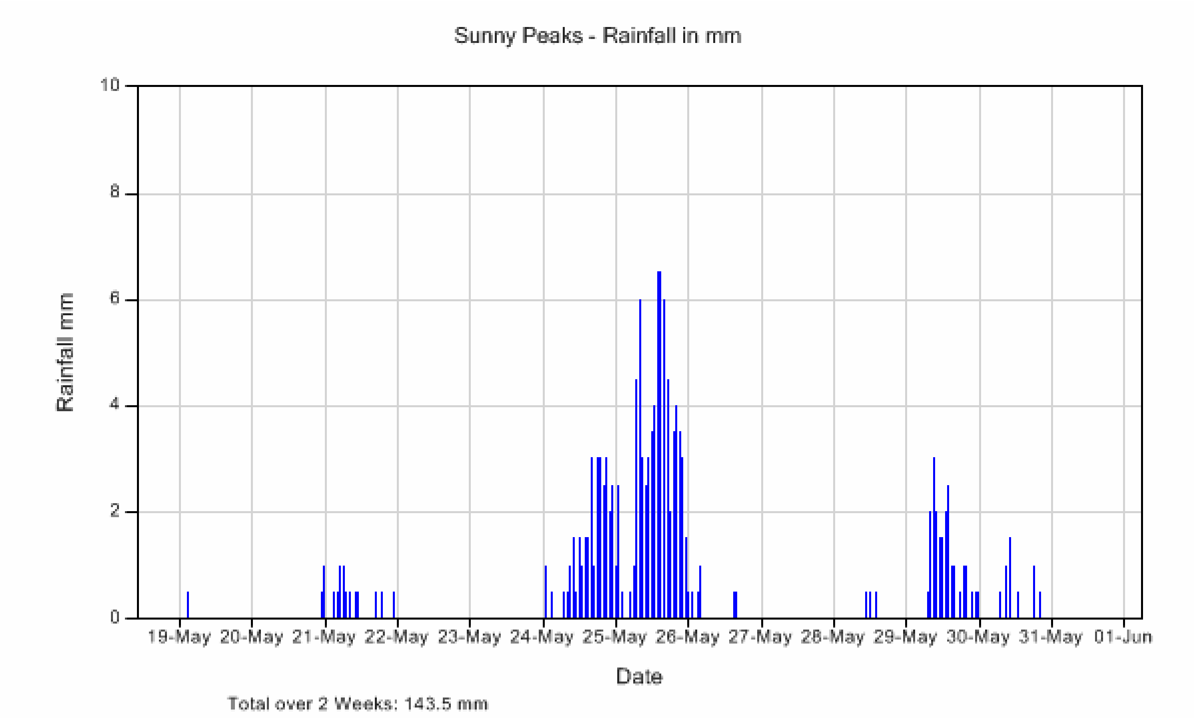


Figure 2 Graph showing hourly rainfall (mm) at the Sunny Peaks rain gauge. Data supplied by Environment Canterbury. (http://ecan.govt.nz/services/online-services/monitoring/rainfall/).

3.0 SITE GEOLOGY

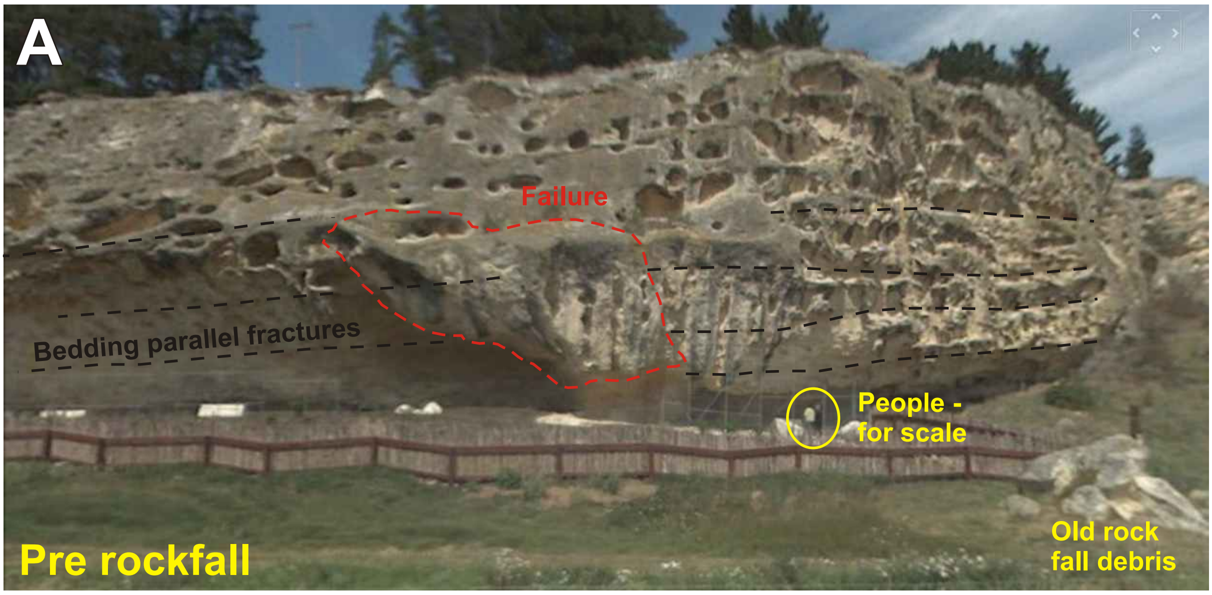
There is a limestone cliff beside State Highway 83 at Takiroa, 3 km west of Duntroon (Fig.1, 3). The rock is Otekaike[2] Limestone of the Kekenodon Group, a cemented fossiliferous limestone of Oligocene age (Forsyth 2001). Bedding in the limestone dips gently toward the northeast (055/12º)[3], delineated by subtle 1 to 5 m spaced variations in limestone hardness, cementation and concretions. The Waitaki River floodplain forms the main land surface at the base of the cliff (northern side), with at least two terrace levels with young Quaternary Gravels. Minor talus is also developed locally along the foot of the cliff. Above the cliff (south side) is terrace with a veneer of older (possibly middle) Quaternary Gravels that contain rounded pebbles and cobbles of weathered greywacke, schist and quartz. The cliff is up-to-20 m high, varying between steeply overhanging at the base, through vertical, to moderately sloping. In places the rock is deeply undercut into C-shaped caverns with adjacent unsupported, hanging pillars forming parts of the cliff (Fig.3C). The rock failure in May 2010 involved an area that was both overhung and undercut.

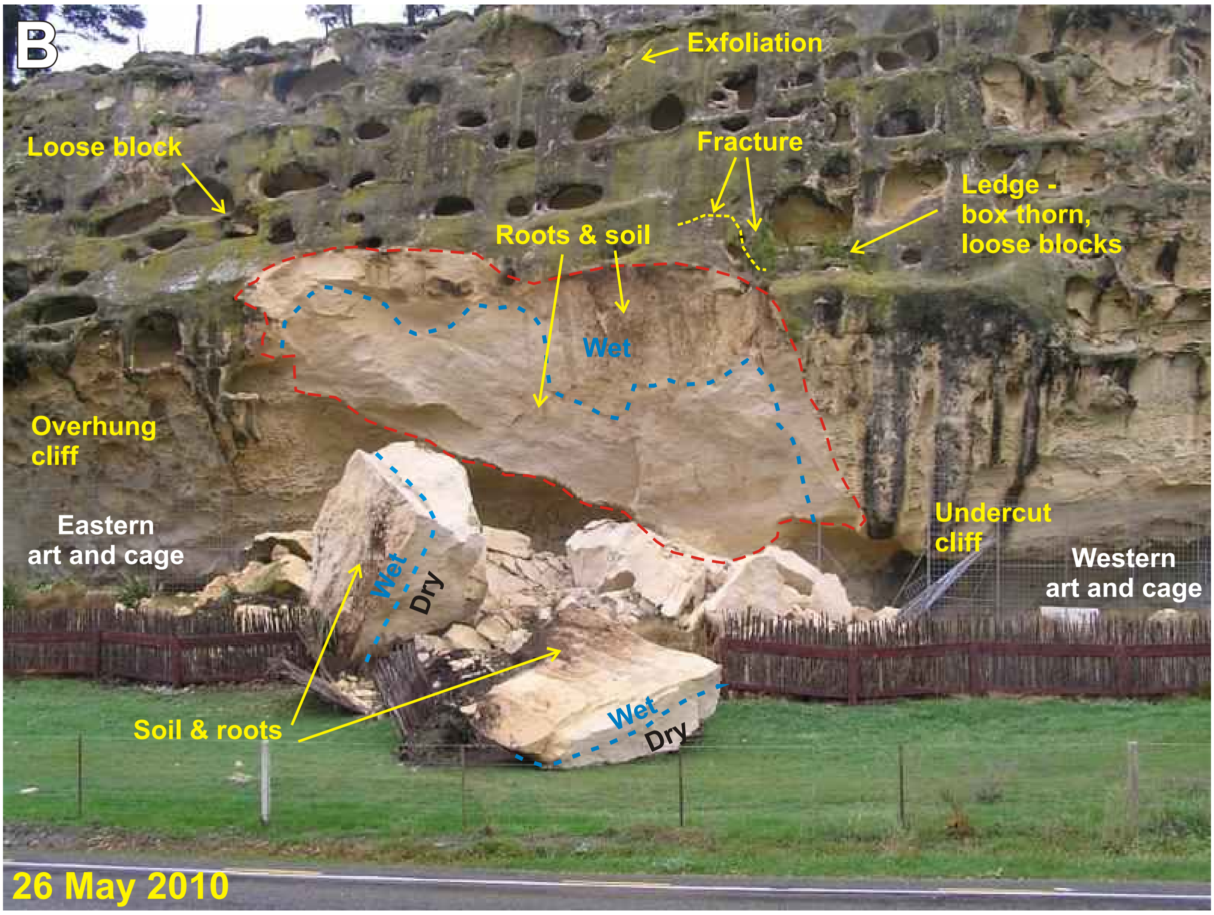
The limestone at Takiroa contains very few fractures. A set of low-angle fractures parallel to bedding is persistent throughout the rock mass, spaced at regular 1-2 m intervals (Fig.3A). These fractures are continuous across the outcrop, traceable for at least 70 m. Within bedding layers the limestone is massive. There are rare, steeply-dipping fractures up-to-3 m long. Minor exfoliation fractures of similar dimensions, but sub-parallel to the cliff surface, occur sporadically and almost invariably about the grey, upper parts of the cliffs.

Otekaike Limestone is a relatively soft rock, weakening considerably in the presence of water. It hardens on freshly exposed or cut surfaces over a period of 2-10 years, commonly developing a natural seal from moisture with time. Calcium hydroxide in freshly exposed rock reacts with atmospheric CO_2 to precipitate calcite, or very fine calcite or aragonite are dissolved in rainwater and re-precipitated in the near surface when it dries, thereby case hardening the rock. Fresh cream-coloured surfaces turn grey-green and grow a moss/mould cover, with microbial mats and mosses potentially aiding calcite growth reactions. Other minerals, such as gypsum, alum, or salts, are commonly precipitated on surfaces where water has been evaporated.

[2] Geological literature uses the spelling Otekaike Limestone whereas the official geographic place name is generally spelt Otekaieke.

[3] All orientations in this report are given as a dip direction (bearing with respect to true north) and dip angle (inclination of a surface with repect to horizontal), in the form dip dir/dip.





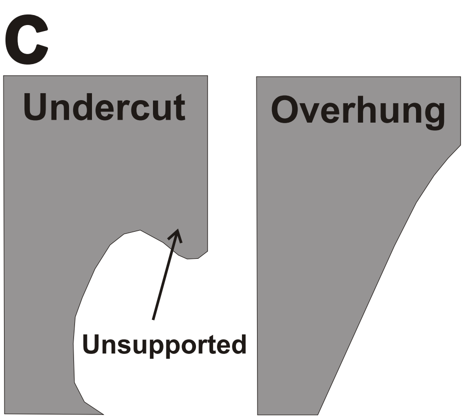


Figure 3

Views of the cliff at Takiroa, looking south from the road. (A) Image from Google Earth “Street View” taken around 2006, prior to the rock fall (people provide scale). (B) Closer, annotated, image of the rock fall, taken by Geoff and Jan Keeling, 26 May 2010. The dashed red line shows the area and shape of the rock that fell. (C) Cartoon illustrating the descriptors undercut and overhung as used in this report to describe the cliff shape. Grey area represents the rock of the cliff.

There are a wide variety of textures on the surface of the Takiroa cliffs. These include:

1. smooth, hard, grey, cemented surfaces; commonly lichen covered and pocketed with caverns; typically found near the top of the cliff.

2. thin encrusted surfaces, with softer rock behind, generally cream-coloured and found on planar faces beneath overhangs (e.g. left side, base of cliff Fig.3A or Fig.4);

3. highly irregular, soft or very-soft, commonly honey-combed surfaces; found in the back of cavernous weathering or on curved surfaces beneath overhangs.

These variations in the cliff surfaces reflect differences in the geological processes that formed the rock surfaces, such as fractures and rock collapse and subsequent protection from the elements, or long-term weathering in the rain. Cavernously weathered pockets are present throughout the cliffs, providing a window into the rock a depth within the cliff. For the most part the limestone beneath the outermost surfaces appears relatively homogeneous. While it contains variations in cementation and concretionary layering, which do cause some variations in rock strength, for the most part the strength variations occur at a different scale and are unrelated to changes in cliff surface texture.

4.0 ROCK FALL

Observations

The rock-failure area is marked by a prominent, light-coloured fresh scar between the two main areas of rock art (Fig.3B). By registering photographs to scale in a GIS (Geographic Information System), the scar was digitised and calculated to have an area of 45 m^2. The scar is relatively planar and overhanging, oriented between 150/60° and 130/65° at the base, and 145/80° at the top (Fig.4). Small variations in orientation occur, particularly a change in dip-direction to 120 at the eastern side of the scar.

Slight colour differences (visible on 31 May 2010) mark variations in moisture content between wet and dry rock (annotated in Fig.3B, shown also in Fig.4). The upper part and right hand (west) side of the scar were nearly saturated, whereas the lower part of the scar was drier. A mat of soil and roots plasters the upper part of the scar, but attached roots also occur on the lower third of the scar. The roots and soil indicate that the failure plane was present in the Takiroa cliff prior to the collapse.

Centimetre-scale orange-brown oxidation bands can be seen throughout the scar and fallen rock mass. These appear to be at a high angle to the scar, near-parallel to bedding. They are interpreted to reflect pre-existing oxidation and flow of fluid through the rock at times prior to the current geometry forming the cliff edge. They are not believed to be relevant to the failure of May 2010.

There are no wide-open (gaping) fractures immediately above the fallen rock mass[4]. A narrow, steep closed fracture is, however, present immediately above the failure scar, cutting through the rock immediately to the east (left) of the ledge where box thorn is growing (Fig.3B & 4). The box thorn may be exploiting part of this fracture, with root penetration to provide adequate moisture for plant growth. This fracture is steep, oriented at an angle with potential to aid further collapse. Although it appears to be discontinuous across the surface, it has possibly yet to propagate consistently through the harder grey cemented crust and may be more continuous through the deeper rock mass. It warrants further inspection and consideration in any future geotechnical appraisal.

Photographs of the cliff prior to the rock fall show that the failed rock mass was deeply undercut and steeply overhung (Fig.5, see also Figs. 3C and 7). A C-shaped cavern was present below the rock that fell, much of which was unsupported with an 80° overhanging face above. No indication of fractures, either below or above the rock that fell, is visible in photographs and images available for this report.

Rocks fell onto a landscaped path and garden, creating a pile of bouldery rubble reaching ~1.5 m high. Two larger rocks, with surfaces matching the fracture at the top of the cliff, fell and/or rolled into new orientations (Fig.3B). One slid through a fence and came to rest 15 m from the base of the cliff. The rock fall also damaged a cage fence erected to protect the western art works from visitors, but no art was damaged. The principal damage was to the garden and landscaping installed by the Ngāi Tahu Māori Rock Art Charitable Trust.

[4] Inspection by abseil was carried out on 31 May 2010.

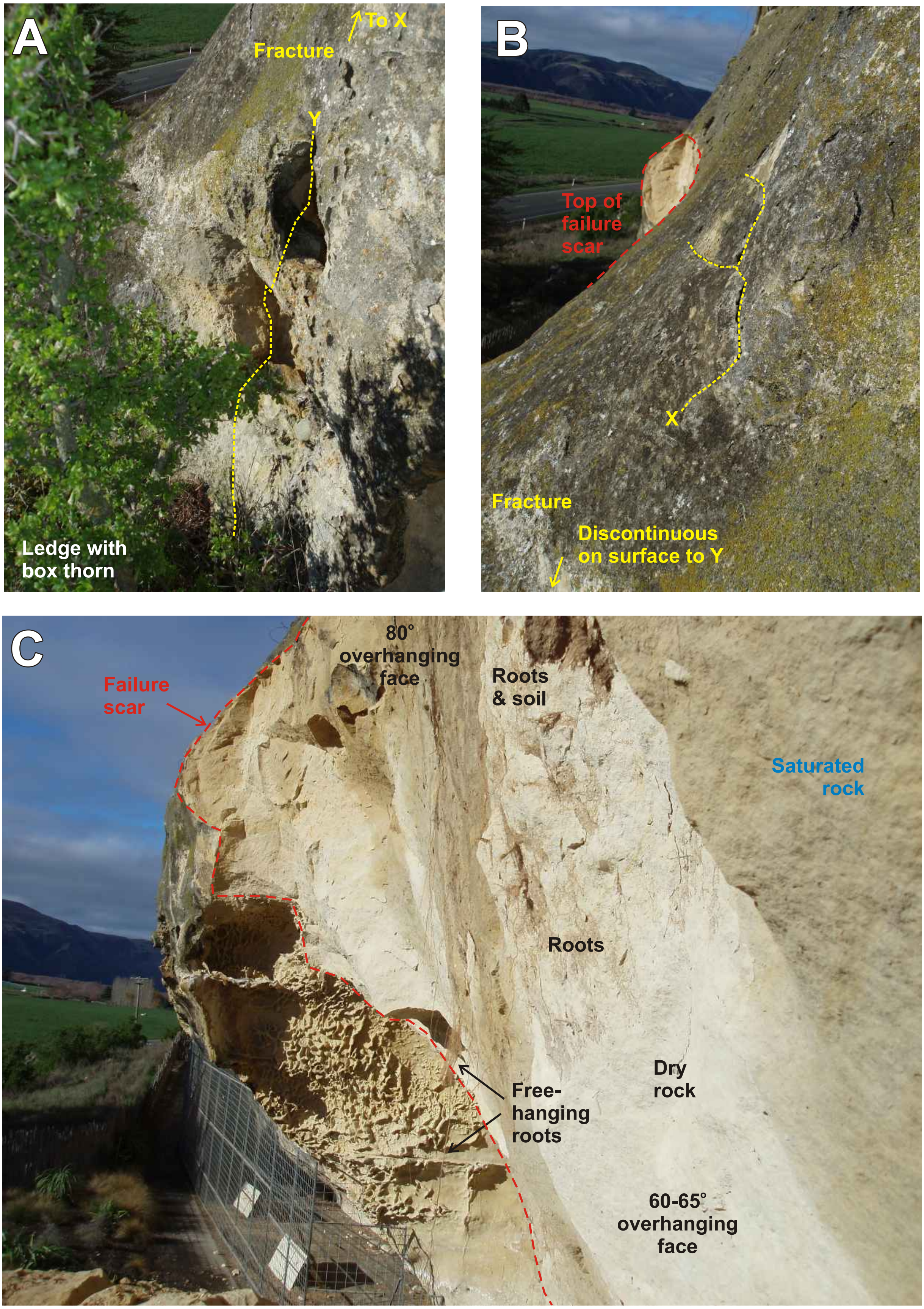


Figure 4 Close up photographs of the failure area. (A&B) Photographs taken on the box thorn covered ledge above the scar, showing a steeply dipping fracture which has developed in the rock above the failure area (see also Figure 3). The incipient fracture can be seen in the back of solution holes beside the ledge at Y, and appears to link to the fracture at Z. While not a gaping, wide-open feature, it could in future give rise to a similar rock fall. (C) View along the failure area, highlighting the overhung nature of the cliff, variations in water content, and the presence of roots and soil on the face left behind after the failure. All photographs S Cox/GNS Science 31 May 2010.

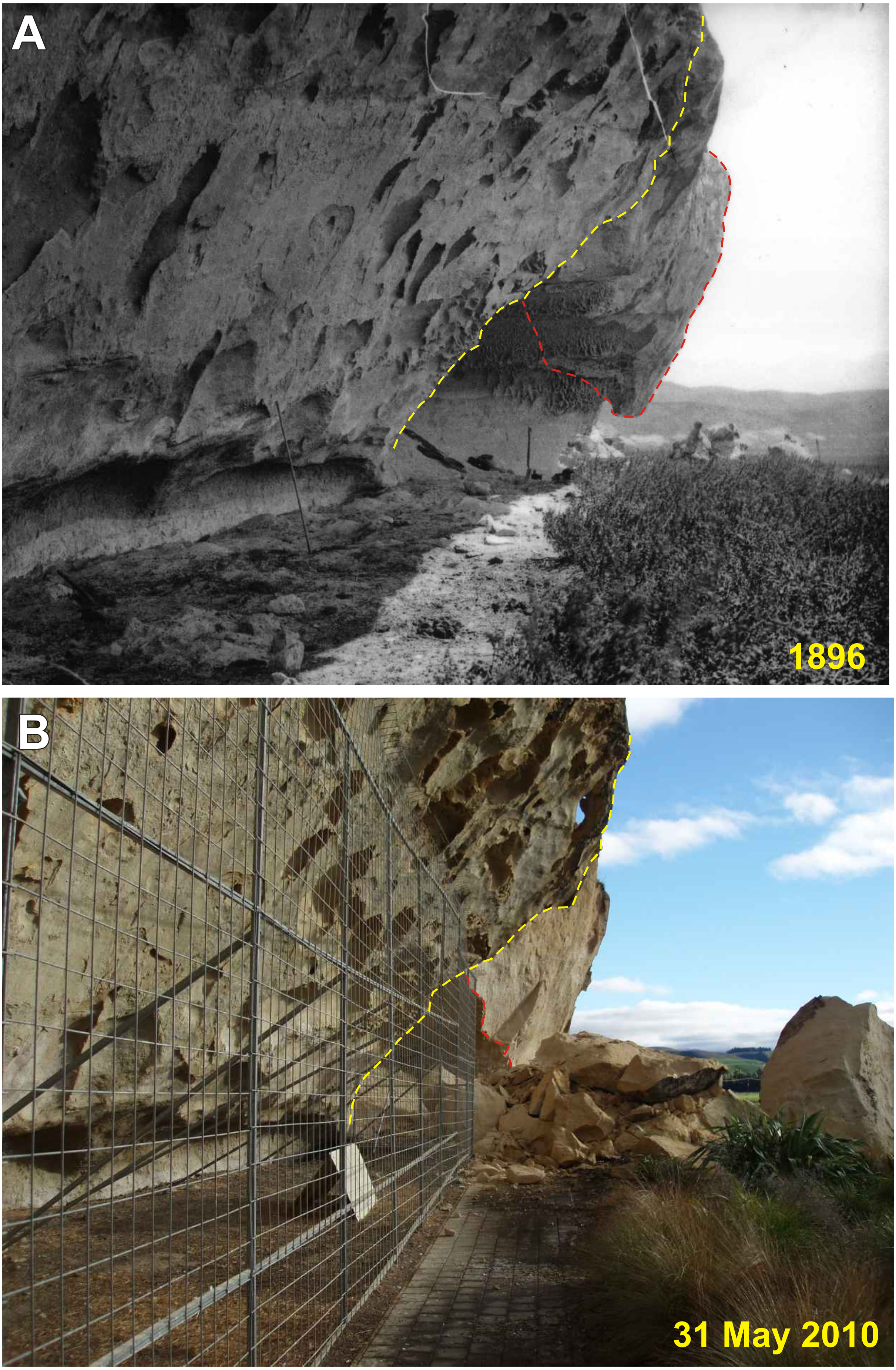


Figure 5 Views west along the outcrop from beside the eastern rock art. (A) “Before” photograph by Augustus Hamilton in 1896 (supplied by Ngāi Tahu Māori Rock Art Charitable Trust) and (B) “After” photograph taken by S. Cox/GNS Science on 31 May 2010. Annotated yellow lines highlight the position of a prominent change in orientation of the cliff; the red line shows the failure scar. Note the undercut, unsupported pillar can be seen in A, and the encrusted, planar, 60-65° overhanging cliff face behind the cage. The new face formed by the failure very close to the orientation of the face with the art suggesting this older face may also have formed by a similar collapse prior to 1896.

Volume and mass calculations

The area of the scar was measured to be 45 m^2 using a photograph scaled in a GIS. Calculating the mass of rock that collapsed entails a greater number of uncertainties because (i) the cliff and debris has a complicated geometry; (ii) the cliff shape before failure was not well known; (iii) debris is "bulked up" during fragmentation and contains void space between blocks; and (iv) the density has yet to be determined for conversion of volumes to mass. The volume of the limestone collapsed was estimated to be ~35 m^3 (resulting in ~40 m^3 of debris) based on comparison of before and after photographs in the GIS, and direct observations of the debris pile. Uncertainty in this volume is unquantified, but probably around ± 20%. Based on a dry density of between 1.4 and 1.8 tonnes/m^3 for limestone in North Otago[5], the failure mass (with uncertainty) is therefore thought to be between 40 and 75 tonnes (dry).

The discoloured, wet area of the failure scar is 20 m^2 (see Fig.3B). Observations of moisture in the fallen blocks indicated that water had penetrated the rock for distances of ~25 cm from the failure crack and cliff surface (Fig. 6). It is inferred that penetration of water occurred prior to failure, since the orientation of the wet-dry transition was observed to have variable orientation in fallen blocks, could not simply be related to wetting of the upper surface of blocks after they had fallen (see annotations Fig.3B). Assuming saturation occurred shortly preceding frailure to a 25 cm depth across the entire 20 m^2 wet area, ~2 tonnes of water could have been added to the mass that failed[6]. Accounting for uncertainties, this equates to as much as 5% additional weight from the water. The total weight of the fallen rock, including water, was somewhere between 40 and 77 tonnes.

Contributing factors

A search of data from the New Zealand seismic network showed there were no earthquakes that could have triggered a rock fall near Duntroon in the period 1200 hrs 25th May -0600 May 2010 (NZST) (Brian Ferris pers. comm.). There is also no disturbance at the base of the cliff, or modification of rock during construction of fences, which might indicate works had contributed to the instability. Triggering is herein attributed to the rain.

The main contributing factors in the collapse are the overhung nature of the cliff, low rock-mass strength and gravity. Rainfall exacerbated and triggered the collapse, presumably by locally increasing water content of the rock (making it heavier) and reducing its strength by increasing pore water pressure and/or lowering internal frictional strength. The failed rock mass was particularly undercut with a C-shaped cavern beneath an overhanging face.

Much of the upper part of the ~60-65° failure plane was covered with brown soil and roots, indicating that much of this surface had evolved prior to the event. Root growth probably aided crack propagation, but the box thorn may also have helped to absorb some moisture from the crack.

[5] Wet (1.89-2.10 tm^{-3}) and dry (1.43-1.77 tm^{-3}) density measurements of Oamaru limestone are available in the National Rock and Mineral Collection database (http://pet.gns.cri.nz).

[6] This "back of the envelope" calculation assumes: water has percolated inwards from the cliff surface and the fracture surface; saturation of the rock pores is total; and uses the difference between wet and dry density measurements.

Figure 6 A thin layer of roots and soil covers part of the upper side of this block. It matches the upper right-hand (western) edge of the scar on the cliff (see Fig.3B) and corresponds to part of the failure crack. Note the prominent change in colour in the surface beneath the helmet – the upper half of the block (that was once beside the failure crack) is wet (dark) whereas the lower half is dry (light). Water has penetrated the block to a depth of ~25 cm from the failure crack. A similar phenomenon can be seen in the block behind – in this instance the left hand steep side of the block has roots and the wet/dry transition is near-vertical.

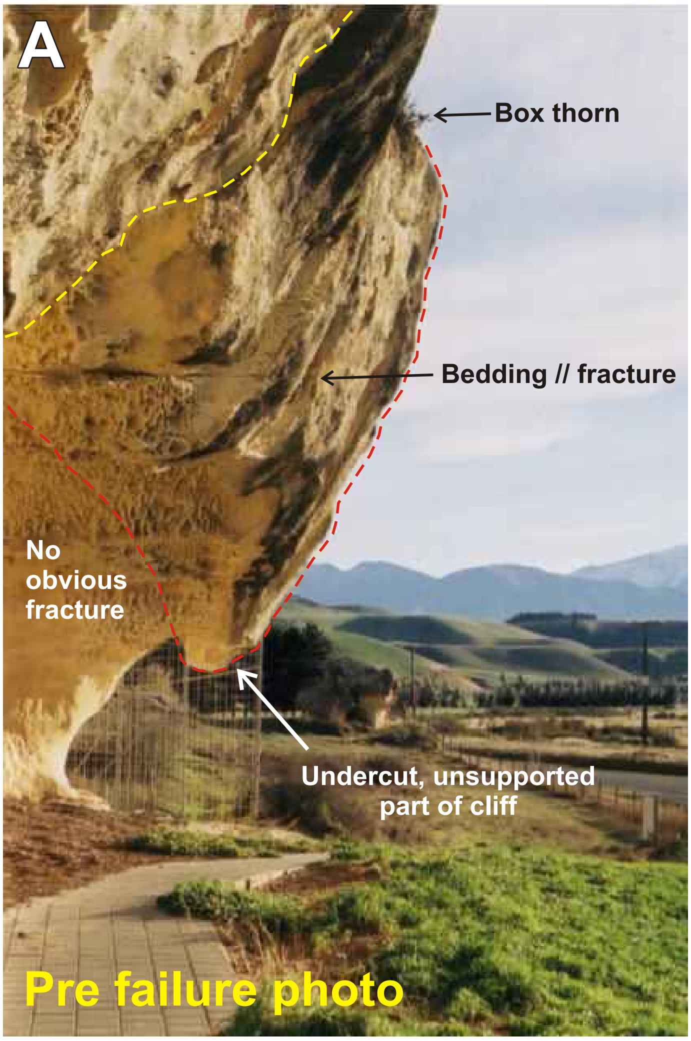
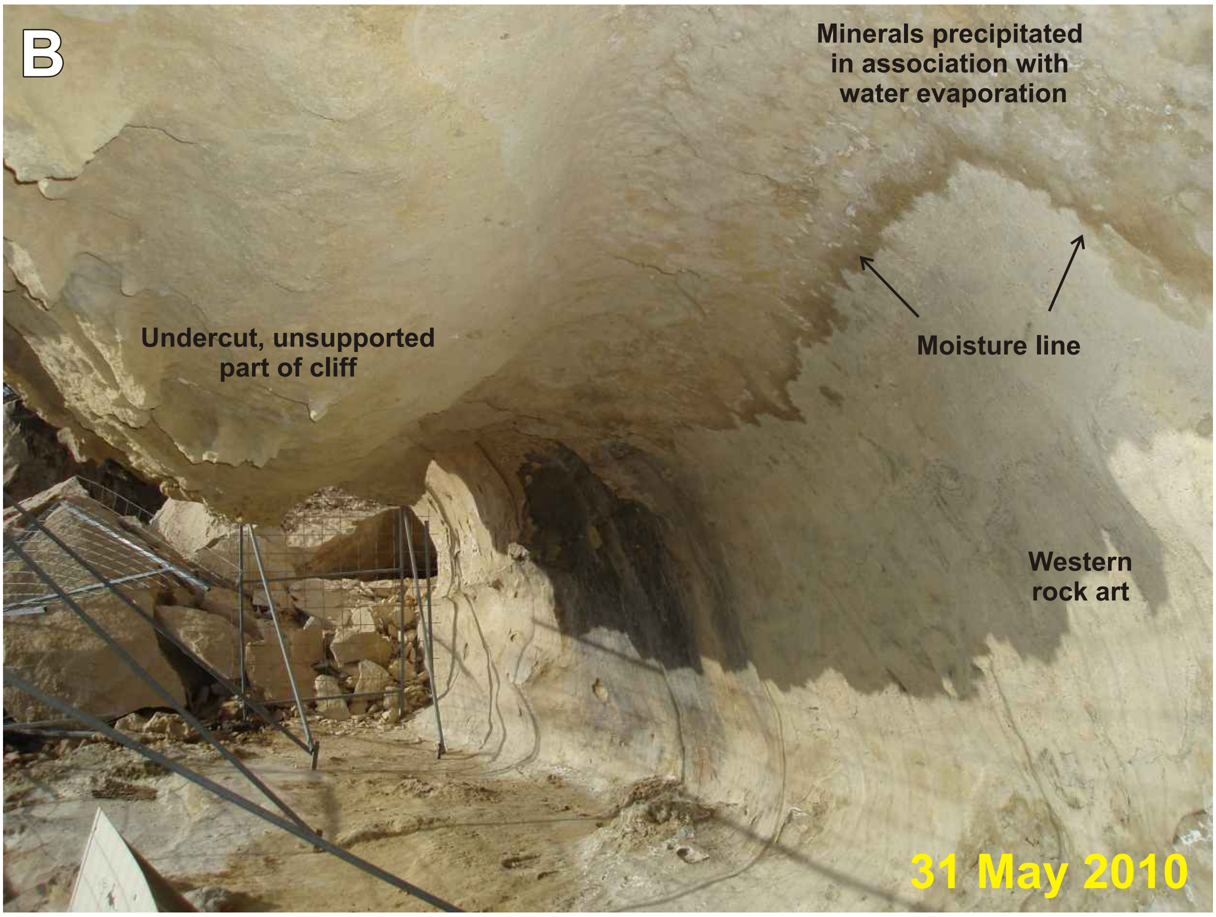


Figure 7

Unsupported parts of the cliff. (A) View of the under side of the rock fall area, prior to the failure in May 2010 (Photo supplied by Ngāi Tahu Māori Rock Art Charitable Trust). The failed area is annotated with a red dashed line. No fracture is visible beneath the overhang. (B) An area of focus for geotechnical assessment of safety is behind the cage protecting the western rock art (see also right hand side Fig.3B). This area of the cliff is deeply undercut and unsupported. Variations in moisture content (seen in this photograph) may reflect seepage behind the cliff. Photograph S Cox/GNS Science 31 May 2010.



5.0 REMARKS

A failure plane had been evolving in the Takiroa cliff for some unknown period prior to May 2010. Record storm rainfall then occurred throughout the region, surpassing monthly totals measured in the past 93 years. A sudden rock fall occurred during the intense rainfall, interpreted to be due in small part to a small (~5%) increase in weight due to the water and in large part to lowering of the rock-mass strength by water pressure in the crack. Over time, however, the crack had been slowly propagating and harbouring root growth. Eventual failure was inevitable, with or without an obvious trigger.

Failure has highlighted a need for caution around the cliff, or any other cliff area. Cliffs are naturally unstable places, and rock falls are the major natural erosion process that forms and modifies them. Old blocks at the base of the cliff provide evidence that the May 2010 failure at Takiroa was not unique. However, for the most part these blocks have rounded, weathered, lichen covered surfaces encrusted with calcite precipitation, indicating they are not from recent failures. There are anecdotal reports that a significant rock fall may have occurred during the 1930's, but for the most part, little material has been observed or recorded to have fallen during European time. For the rock art to have been preserved, the cliffs must have stayed in much the same configuration since the art was created. It can therefore be argued that rock falls from the limestone cliffs at Takiroa are rare.

It is very difficult to predict or quantify the threat of subsequent catastrophic events. Overhanging and undercut sections of cliff, similar to that which failed, are still present on the site (Fig.7). The recent failure has changed stresses in the surrounding rock (increasing and decreasing them in different areas) and this may induce a short-term increase in frequency of rock falls. The 25-26 May 2010 failure removed at least one major hazard from the area, so that the site is now safer than it previously was. But, in retrospect, the site was exceedingly unsafe, so that being safer now does not indicate that it is now safe. Immediate field observations made for this report provide no information on future failure frequency or current safety margins.

Regardless of whether the frequency of failures has changed, rock falls are an inevitable natural process at this site. Possible future scenarios, some of which may not occur for a hundred or a thousand years, are depicted in Figure 8. It is likely that the chance of any future failure will be greater when the rock mass is wetted by heavy rainfall or runoff.

It would be possible to decrease the exposure of visitors to the rock-fall hazard by decreasing the amount of time they spend in the rock-fall runout zone below the cliff. The current layout of the paths has egress along the cliff base, parallel to the cliff in a position so that walkers are exposed to the path of anything that falls from the cliffs for much of the time of their visit. Small cobble and some boulder-sized pieces are currently balanced on ledges above the path, and along the top of the cliff, and could be removed to mitigate some of the hazard at the site[7] (rock scaling – see Fig.8). The path is now covered by debris from the 25-26 May collapse and needs to be rebuilt. It may be possible to redesign routes with more

---

[7] Rock-scaling will require access by abseil. At the same time consideration should be given to the removal of vegetation such as box thorn, thereby reducing the penetration of roots into fractures.

direct access to the art viewing areas that result in a shorter time spent by the visitor directly beneath the hazard. Signage should also be used to warn and remind visitors that hazards are known to exist around the cliffs. Visitors should be given the opportunity to consider whether the experience of seeing and appreciating the rock art in its natural setting is worth accepting exposure to a natural hazard, and may appreciate being reminded they can minimise their exposure to the hazard by not lingering unnecessarily.

Are remedial engineering solutions warranted or justified? To comment specifically and directly on engineering hazard solutions is beyond the scope and intent of this report. It is clear from the way in which development has been carried out during the past few years that Ngāi Tahu Māori Rock Art Charitable Trust and Te Rūnanga o Ngāi Tahu place strong spiritual and cultural value on Takiroa and their other rock art sites. It may be possible to undertake remedial work that could not only enhance public safety, but also improve protection and curation of the art, as well as the cul;tural experience. Protection fencing and water runoff are two topics particularly worthy of further discussion and investigation.

The rock art is currently protected from visitors by lightweight metal fences, although the western cage was damaged by the recent rock collapse (Fig.7). The western fence is situated where the cliff is particularly undercut and overhung. Consideration could be given towards the feasibility of replacing these fences with something that provides structural support to the rock face. It may be possible to design a structure that will fit in more naturally with the cultural setting – perhaps disguised by a Māori totem rather than as raw structural steel?

Any measures to reduce surface water runoff from the terrace above the cliff face would also be of benefit to both public safety and curation of the rock art. The Waitaki Valley is normally a low rainfall area and the only local runoff comes directly from the rain that falls on the cliff at Takiroa, but there is potential for irrigation to augment natural surface runoff and/or saturation of the rock mass. On the terrace immediately above the Takiroa cliff, there is a water race which leads back ~7 km to an intake siphon on the Otekaieke River (Fig.1A). An arm of the race ends and enters buried concrete pipe to descend the hill above the cliff (Fig.1B). It is possible that during the May 2010 storm the race acted like a drain, collecting runoff along its 7 km length and carrying it towards the cliff top. Any overflow of water, for example where the race enters the pipe, or if the pipe has lost some of its integrity underground, could have augmented the natural runoff onto the cliff. Given the role water played in the 25-26 May failure, examining the irrigation, runoff and drainage should be considered high priority. A change in irrigation design may minimise any contribution of extra water during extreme rainfall events or dampness to the rock art, whilst improving the use of water for the neighbouring farm. It may also be possible to implement field drainage above the cliffs that could decrease runoff down the cliffs.

The conservation of cultural heritage is a very different issue from public safety. Following the 25-26 May collapse the art works may now have a slightly increased exposure to the weather. While protected from the Public by cages, they are potentially at risk from future collapse of the cliff. This risk cannot be reduced to zero, but it can be reduced, and so the life of the art can be prolonged. It is a matter for the legal owner of the art to determine how much they are prepared to pay to conserve it. Te Rūnanga o Ngāi Tahu may be able to persuade others to contribute to its conservation.

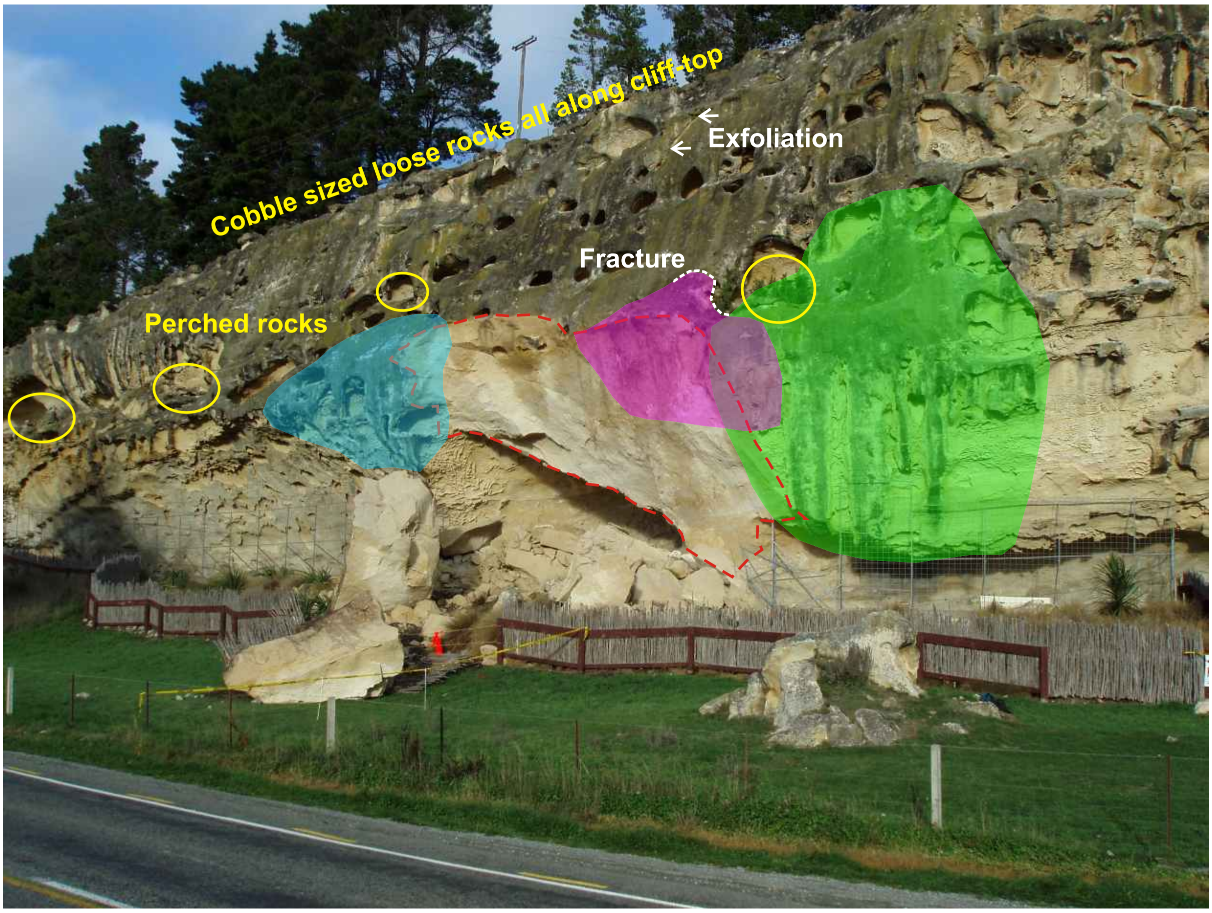


Figure 8 Hypothetical scenarios of rock fall at Takiroa in the future, include collapse of the cliff above the western rock art (green), a smaller collapse of the overhung cliff linking back to the open fracture observed near the ledge covered with box thorn (pink), or collapse of the overhanging nose (blue). Rock falls are a natural process at cliffs, but they can be highly infrequent and difficult to quantify. Cobble and some boulder-sized rocks perched on ledges or exfoliating along the cliff top could be relatively easily removed (rock-scaling) to improve public safety. It may be possible to rebuild damaged access paths in a position further out from the cliff face, thereby decreasing average time visitors are exposed to rock fall hazard.

6.0 CONCLUSIONS

A collapse of ~35 m^3 limestone from cliffs at Takiroa, Duntroon, North Otago occurred overnight on the 25-26 May 2010 during exceptional storm rainfall. Unwitnessed, the collapse beside State Highway 83 occurred from a 45 m^2 area of cliff between two areas of historic and culturally important rock art. The art was unaffected, but falling debris of between 40 and 77 tonnes damaged a path, garden and fences developed to enhance the visitor experience and protect the art. As the site is actively promoted and receives ~20,000 visitors per year, there have been concerns for visitor safety.

Roots and soil indicate that the steeply overhanging failure plane had been evolving in the Takiroa cliff for some lengthy period prior to May 2010. Limestone either side of the fracture appears to have been locally saturated. Photographs of the cliff prior to the rock fall show that the failed rock mass was undercut and steeply overhung, but with no obvious signs of fractures or an imminent failure. The main contributing factors in the collapse were the overhung nature of the cliff, low rock-mass strength and gravity, probably triggered by water from surface runoff on the cliff filling the crack during heavy rain.

Failure highlights the need to treat the cliff, or any cliff area, with caution. Cliffs are naturally unstable places. Older debris indicates that the May 2010 collapse was not unique and future rock falls are an inevitable natural process at the site. A small fracture is present in the cliff immediately above failure scar and may provide a surface for a future failure, but there are also overhung and undercut areas of the cliff that have similarities to the area that recently fell. Loose cobble- and some boulder-sized rocks perched on ledges and the top of the cliff also present a hazard for visitors to the site.

Decisions need to be made as to what degree of risk is acceptable for public access, although the frequency of rock fall (either absolute or relative) is difficult to quantify. Points raised in this report to be considered by a full geotechnical review and hazard assessment include: improved signage and natural-hazard warning; repositioning of the access path; engineering support; and management of water/runoff on the cliff. The public have always been exposed to a degree of risk at this site, and it is potentially less following the rock fall than before. The risk is relatively low, but it is not negligible. It cannot be reduced to zero by "appropriate remedial work" such as scaling the slope, or engineering support.

ACKNOWLEDGEMENTS

This report is an output of the GeoNet immediate landslide response facility, funded by the Earthquake Commission (EQC) and the Institute of Geological and Nuclear Sciences Ltd (GNS Science). The author would like to thank the Ngāi Tahu Māori Rock Art Charitable Trust and Amanda Symon (Curator) for encouraging this work and providing assistance. Photographs not taken by the author were supplied by Amanda and neighbouring landowners Geoff and Jan Keeling. Technical assistance was provided by Delia Strong and Brian Ferris. Rainfall and runoff data were collected by Environment Canterbury, Otago Regional Council and NIWA. Grant Dellow, David Barrell, Jane Forsyth, Mauri McSaveney of GNS Science, Lee Paterson of MWH New Zealand Ltd and Markus Hanz of OPUS Consultants Ltd provided helpful perspectives on issues of rock stability and public safety. The report was reviewed by David Barrell and Mauri McSaveney.

REFERENCES

Forsyth, P.J. 2001 Geology of the Waitaki area : scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. Institute of Geological & Nuclear Sciences 1:250,000 geological map 19. 64 p. + 1 fold. map

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657