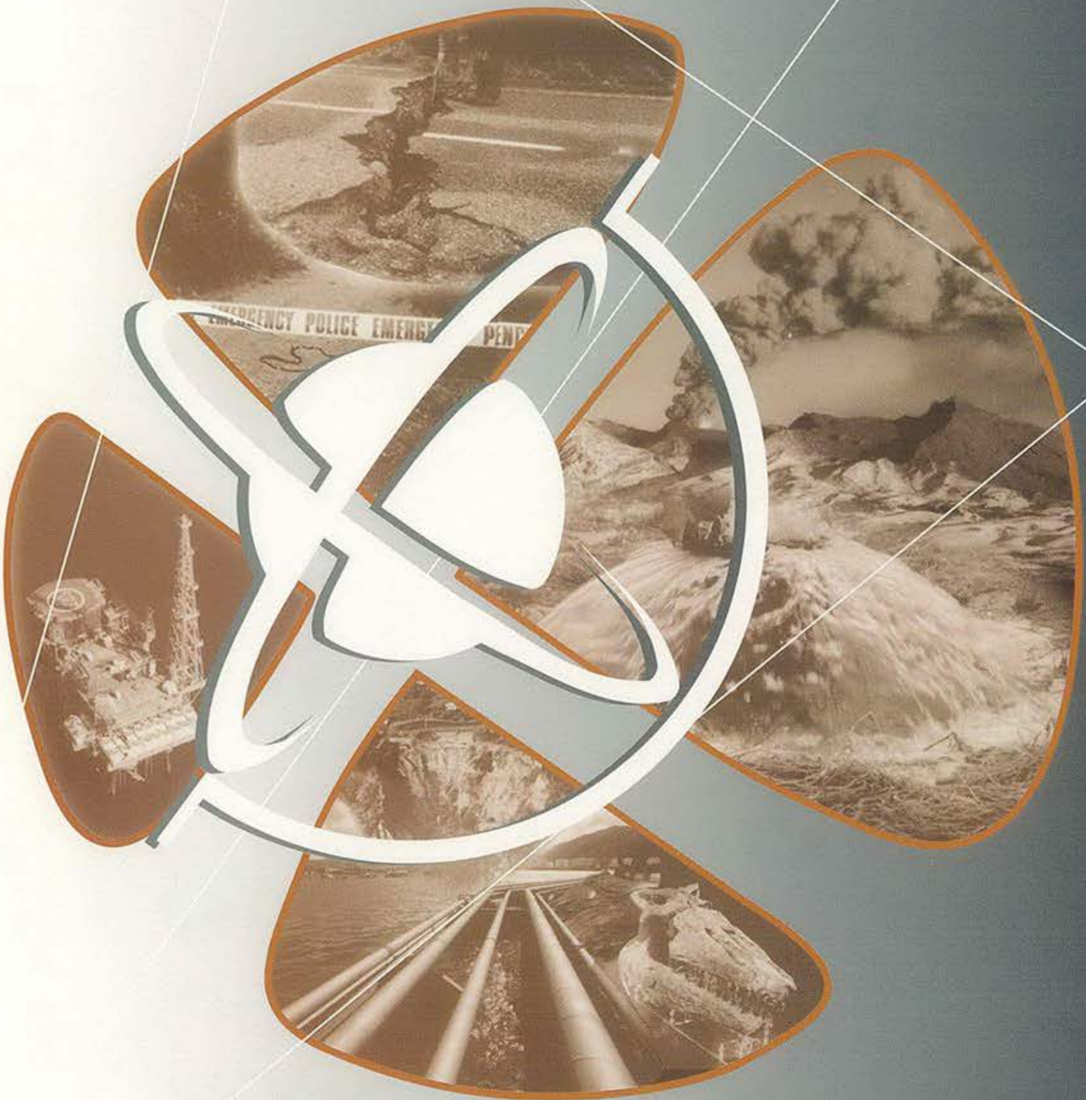
Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited



Use of precariously-balanced rocks to test the New Zealand seismic hazard model: A pilot study

by M. W. Stirling & R. Anooshehpoor

Confidential

Client Report
2004/158

November
2004

Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited

Use of precariously-balanced rocks to test the New Zealand seismic hazard model: A pilot study

by M. W. Stirling & R. Anooshehpoor

Prepared for

Earthquake Commission Limited

CONFIDENTIAL

Institute of Geological & Nuclear Sciences client report 2004/158
Project Number: 430W1018

The data presented in this Report are available to GNS for other use from
November 2004

Gracefield Research Centre, 69 Gracefield Road, Gracefield, PO Box 30368, Lower Hutt, New Zealand, Telephone: +64-4-570 1444, Facsimile: +64-4-570 4600
Web: www.gns.cri.nz

A Crown Research Institute

CONTENTS

EXECUTIVE SUMMARY

We undertake the first New Zealand-based pilot study to investigate the use of ancient precariously-balanced rocks, (rocks that are unstably balanced on top of a pedestal) as a criteria for testing the estimates of earthquake shaking from probabilistic seismic hazard models for long return periods. To date, research to test seismic hazard models in New Zealand have been restricted to the short historical record of earthquakes. Our survey of three sites in central Otago, a site in northwest Nelson, and a site in eastern Fiordland has yielded a total of 28 precariously-balanced rocks which, on the basis of established USA-based methodology, are used to provide estimates of the maximum ground motions that have occurred at the sites since the rocks became precarious. Estimates of the age of the precariously-balanced rocks (10,000 to 55,000 years) are made from considerations of the geologic and climatic history of the sites, and from a cosmogenic date obtained from bedrock removed from the pedestal of a precariously-balanced rock at one of the central Otago sites. Comparison of the maximum peak ground accelerations and ages of the precarious rocks to seismic hazard curves derived from the New Zealand National Seismic Hazard Model show that the central Otago rocks provide lower estimates of peak ground accelerations than the hazard model, for equivalent return periods. In contrast, the northwest Nelson rocks correlate well with the precarious rock data. No precarious rocks were found in eastern Fiordland, consistent with the obviously-active alpine erosion processes, and regular occurrence of large earthquakes in the region. The difference between the central Otago and northwest Nelson sites is that the former are all located within 5 km of active faults, whereas the northwest Nelson site is not. Peak ground accelerations calculated with the assumption of median ground motions for these faults produce hazard curves that compare favourably with the precarious rock data. The variability about the median estimates of PGA for the fault sources, and/or the median PGA for the fault sources may therefore be overestimated for the central Otago sites. The implications and limitations of the pilot study for providing constraints on seismic hazard estimates are such that we propose that several aspects of follow-up work be pursued.

1.0 INTRODUCTION

In this study we undertake a pilot study to take the first steps towards developing a methodology to test the long-term estimates of probabilistic seismic hazard (PSH) from the National Seismic Hazard Model (NSHM; Stirling et al. 2002a). To date, efforts to develop tests for PSH models in New Zealand have been limited to the short-term historical period (≤160 years; Dowrick & Cousins, 2003, Rhoades et al., 2002, Stirling et al. in prep.). However, the practical requirements of engineers and planners are estimates of hazard for return periods of 500 years (i.e. 10% probability in 50 years) or more, which are considerably longer than the historical period and are strongly influenced by prehistoric earthquakes constrained from active fault data. It remains a serious issue that no method of validation can be formally applied to these estimates of long-term hazard at the present time.

In this project we apply one of the few methodologies currently being developed to test the long-term estimates of PSH. In the western USA, ancient precariously-balanced rocks (PBRs; Fig. 1) appear to be strong ground-motion seismoscopes that have been operating on solid rock outcrops for thousands of years, thus providing a constraint on the maximum ground motion that could have occurred in that time (Brune, 1996; Brune, 1999; Shi et al. 1996; Bell et al. 1998, Anooshehpoor et al. 2004). Most precariously balanced rocks can oscillate about two rotation axes when set to rocking (Fig. 1). A pseudo-3D finite difference method developed by Shi *et al.* (1996) can be used to estimate the dynamic toppling acceleration of balanced rocks, subjected to inputs with various waveforms, from the quasi-static toppling accelerations measured in the field. The quasi-static static toppling acceleration for a rock (in terms of peak ground acceleration, PGA, in units of gravitational acceleration, g) is equal to the tangent of the angle ("alpha" in Fig. 1) between the vertical and the line through the centre of mass of the rock and the rocking point (Housner, 1963). Thus tall thin rocks may be more easily toppled than more slabby rocks. Field and laboratory (shake table) tests of toppling accelerations for rocks in the western USA by Anooshehpoor and Brune (2002) and Anooshehpoor et al. (2004) have given confidence in the estimation of toppling accelerations from quick field examination of the geometry shown in Figure 1 when the toppling accelerations are scaled up by 30% to take account of the dynamic component of toppling acceleration. This is the component of toppling acceleration needed to overcome inertia and initiate rocking motion (Anooshehpoor et al. 2004).

Comparison of the precarious rock data to the USA national PSH maps (Frankel et al., 1996, 2002) shows that the PSH maps predict accelerations that greatly exceed the toppling accelerations of the PBRs (Brune, 1999, Anooshehpoor et al., 2004). Recent studies by Stirling et al (2002b) show that unusual site effects (e.g. negative site effect due to exceptionally hard rockmass) do not account for the discrepancy between the PBRs and the PSH maps. Furthermore, according to the USA PSH model the probability of toppling the rocks in the time span that the rocks have remained precarious (over 10,000 years for rocks in the Mojave Desert, California; Bell et al, 1998) is 100% (Purvance, 2004) as a result of the large uncertainties in the USA model. Instead, Brune (1999) and Anderson and Brune (1999a, b) suggested that the ergodic assumption in PSHA may be the source of the discrepancy between the PBRs and the maps. In this case the ergodic assumption states that the random variability in ground motion from a single earthquake of magnitude ("M") and location ("L") at sites equidistant from the earthquake is equivalent to the distribution of ground motions at any one of the sites over time from repeated earthquakes of the same "M" and "L". The PBRs instead appear to correlate well with the median estimates of peak ground acceleration from the PSH models (i.e. PSH estimates that assume that sigma is equal to 0), suggesting that the uncertainty routinely built into PSH models may provide overestimates of the actual hazard. Similar conclusions have been reached in recent work on comparing the New Zealand Seismic Hazard Model (NSHM) against the historical record of felt intensities (Dowrick and Cousins, 2003).

Our study builds on the previous USA-based research by providing the first field application of the PBR methodology outside of the western USA. It is important to establish whether the methodology has this broader applicability. Successful application of the methodology to New Zealand would have the purpose of verifying whether it holds the wider applicability to test PSH models outside of the western USA (in this case the New Zealand NSHM), and can indeed test the fundamental assumptions embodied in the modern methods of PSHA.

2.0 METHODOLOGY AND DATA

Our methodology comprises the following series of activities: (1) selection of study areas, (2) identification of PBRs in the study areas (3) estimation of the toppling peak ground accelerations of the PBR features according to the geometry shown in Figure 1 and methodology of Shi et al. (1996) and Anooshehpoor et al. (2004), (4) estimation of the age of the PBRs by way of cosmogenic dating of the surfaces of the rocks samples (Appendix 1), (5) comparison of the age and toppling peak ground accelerations of the precarious rocks to the peak ground accelerations predicted from the NSHM for the time period represented by the age of the rocks, and (6) evaluation of any discrepancies between the toppling accelerations of the precarious rocks and the accelerations predicted from the PSH maps for the time period represented by the age of the precarious rocks. We now describe these activities in more detail:

2.1 Selection of study areas

Sites were selected in central Otago, eastern Fiordland and northwest Nelson for our study, based on these areas having an abundance of rock outcrops of suitable morphology for the formation of PBRs (i.e. tor outcrops; Figs. 2 and 3). We replaced our original choice of Banks

Peninsula with eastern Fiordland and northwest Nelson, based on a brief reconnaissance of Banks Peninsula in early 2003 which showed it to be almost devoid of rocks outcrops that would yield PBRs. In central Otago, the ancient schist peneplain landscape (i.e. exhumed and uplifted "fossil" plain) is typically characterised by schist tors (Fig. 3). The tors are considered to be ancient remnants of unweathered bedrock that were exposed by uplift and erosion of the peneplain surface (e.g. Stirling, 1991). Specifically, the schist plateaux of Cairnmuir Flat and the western end of the Dunstan Trail (Fig. 2) were selected to search for PBRs, based on the large number and spectacular preservation of tors in these areas. We decided that the criteria for site selection would be the presence of at least five precarious rocks within an area of approximately 10 km by 10 km. This is an area small enough that ground motions from earthquakes would not vary significantly across the area due to attenuation with distance, but large enough that five or more rocks could be found. It is also the same area as the grid cell size usually used to construct PSH maps from the NSHM). However, these criteria were not strictly applied for all of our sites, as we also decided to examine a site in the Cardrona Valley with just two PBRs while travelling north at the end of our fieldwork (Fig. 2). We included a site in eastern Fiordland in our study, based on anecdotal evidence of the presence of PBRs on the summit ridges of Mt Titiroa, approximately midway between Lakes Manapouri and Monowai (R. Norris and G. McVerry pers comm.; Fig. 2). Finally, the Mackay Downs site in northwest Nelson was also examined in our study, based on anecdotal evidence of PBRs in the area (P. Kilgour, pers comm.). Mackay Downs is an area of plateaux north of the Heaphy Track in Kahurangi National Park (Fig. 2). The central Otago and eastern Fiordland regions were visited in February 2004 by vehicle and foot, and the northwest Nelson region was visited in April 2004 by foot.

2.2 Identification of precariously-balanced rocks (PBRs)

In general, the identification of PBRs was an intuitive process. In the Dunstan Trail and Cairnmuir Flats areas (Figs. 2 and 3), PBRs were located by driving to and walking amongst tor landscapes. At the Mt Titiroa and Mackay Downs sites, all surveying was done by foot, given the remote settings of the two areas. Binoculars, while useful at all stages of the fieldwork, were of greatest value when choosing outcrops to visit in the latter areas. Potential candidates for PBRs were usually rocked by hand to ascertain whether or not they were attached to the base rock (referred to as the pedestal) and unstable. Since the toppling accelerations are proportional to angle alpha, and angle alpha is proportional to the overall shape of the rock (Fig. 1), tall to equidimensional rocks (i.e. rock height $\geq$ width) were chosen for analysis where possible, whereas more slabby rocks (i.e. height < width) were generally ignored unless they were very unstable.

On Mt Titiroa, we were not able to find any PBRs. The granitic rock formations along the summit ridge were generally large, stable rock outcrops (Fig. 4). The steep alpine environment and associated erosional processes are probably very effective in removing unstable elements of the rockmass from the summit ridge. Furthermore, earthquake-induced mass movement of unstable rockmass and colluvium is commonplace in this region, and recent landslide scars resulting from the M7.2 21 Aug 2003 Fiordland earthquake were observed on the lower, bush-covered slopes of Mt Titiroa.

2.3 Estimation of the toppling peak ground accelerations of the PBRs

We applied the methodology of Shi et al. (1996) to estimate the toppling accelerations of the precarious rocks from the tangent of the angle (alpha) between the vertical and the line through the centre of mass of the rock and the rocking point (Fig. 1). Estimates of toppling accelerations were made on four PBRs from the Dunstan Trail area (identified as "DUNS" in Table 1), six from Cairnmuir Flat (identified as "CLYDE" in Table 1), two from Cardrona Valley (identified as "CAR" in Table 1), and on 16 rocks from Mackay Downs, northwest Nelson (identified as "MK" in Table 1). The static toppling accelerations, in units of g are listed in Table 1.

2.4 Estimates of the age of the PBRs

While our understanding of the age of the peneplain landscapes in central Otago and northwest Nelson gives us some confidence that the PBRs are ancient features (i.e. prehistoric), we applied some relevant rock surface dating techniques on the PBRs to test our assumptions. Our approach was to date the surface of the pedestal beneath the PBR, as close as possible to the rocking point of the rock (Fig. 1 and "CLYDE-6 in Fig. 3). This way, we were confident that our date would be as close as possible to the timing of PBR formation, rather than dating the rock outcrop before it became precarious. In contrast, dating the top of the PBR would be likely to overestimate the age of the PBR, since the top of the rock could have been exposed a long time before the rock became precarious. In order to date the pedestal surfaces we applied the Beryllium 10 (^{10}Be) cosmogenic dating technique. The technique is well established for dating of rock surfaces around the world, and is based on the time-dependent accumulation of ^{10}Be in the crystal lattice of quartz minerals due to exposure to solar radiation. We were only able to date one of the PBRs at the time of this report, this being CLYDE-6 from Cairnmuir Flats (Table 1, Fig. 3) which was sent to a well-established dating laboratory at the Australian National University (ANU). The date obtained for the CLYDE-6 sample is 55,000 $\pm$ 4,200 years before present (Appendix 1). The other two samples (CLYDE-8 and MK-14) were sent to a newly established dating collaboratory between the Institute of Geological and Nuclear Sciences (GNS) and Canterbury University (A. Zondervan, pers comm.), but the dates were unavailable at the time of writing this report.

Table 1 PBR identifications, locations, and measurements. The "CLYDE" PBRs are from the Cairnmuir Flat site, "DUNS" PBRs are from the Dunstan Trail site, "CAR" PBRs are from the Cardrona Valley site, and the "MK" PBRs are from the Mackay Downs site. See Figure 2 for the locations of the sites, and Figure 3 for pictures of the PBRs.

Rock	Location	$\tan \alpha_1$	Slope (degrees)
CLYDE-01	-45.18307, 169.29395	0.23	-
CLYDE-02	-45.18382, 169.29182	0.51	-
CLYDE-06	-45.18562, 169.28147	0.11	-
CLYDE-08	-45.19118, 169.28143	0.44	15
CLYDE-09	-45.19330, 169.28278	0.32	10
CLYDE-10	-45.19302, 169.28272	0.47	-
DUNS-01	-45.36573, 169.84613	0.53	-
DUNS-03	-45.36115, 169.82928	0.18	18
DUNS-04	-45.35877, 169.82187	0.19	-
DUNS-09	-45.31557, 169.79882	0.47	-
CAR-01	-44.87308, 169.06375	0.21	-
CAR-03	-44.87412, 169.07668	0.27	20
MK-01	-40.86, 172.24	0.32	-
MK-02	-40.86, 172.24	0.32	-
MK-03	-40.86, 172.24	0.47	-
MK-04	-40.86, 172.24	0.29	-
MK-05	-40.86, 172.23	0.32	-
MK-06	-40.86, 172.23	0.53	-
MK-07	-40.86, 172.23	0.40	-
MK-08	-40.86, 172.23	0.32	-
MK-09	-40.86, 172.24	0.53	-
MK-10	-40.87, 172.24	0.29	-
MK-11	-40.87, 172.25	0.73	-
MK-12	-40.87, 172.25	0.40	-
MK-13	-40.87, 172.25	0.58	-
MK-14	-40.87, 172.25	0.73	-
MK-15	-40.87, 172.25	0.73	-
MK-16	-40.87, 172.25	0.62	-

2.5 Comparison of the age and toppling accelerations of the precarious rocks to the peak ground accelerations predicted from the NSHM

Our method is to plot hazard curves calculated from the NSHM for the Dunstan Trail, Cairnmuir Flats and Mackay Downs sites (in this case graphs of the annual frequency of exceedance for a suite of PGA levels) and superimpose the precarious rock measurements on the same plots by plotting 1/age of the rocks against the toppling accelerations for the five or more measurements (Anderson & Brune, 1999a, b). Evaluation of the discrepancies between the hazard curves and the precarious rock estimates are then made.

2.6 Evaluation of the comparisons between the NSHM and the precarious rocks

If any discrepancies are observed between hazard curves and PBR data, we would identify the elements of the PSH model likely to give rise to the discrepancies, and discuss the implications of our findings.

3.0 RESULTS

We show our comparisons of hazard curves for PGA from the NSHM (Stirling et al. 2002) to our PBR data (Table 1) in Figure 5. All toppling accelerations have been scaled up by 30% before plotting on Figure 5 to take account of the dynamic component of toppling acceleration. Two hazard curves are shown on each graph: The hazard curves that use a 3-sigma cutoff for the uncertainty distribution of the attenuation model (i.e. consistent with the methodology used to undertake PSHAs from the NSHM; hereafter referred to as the "3-sigma curve") is shown as a thin solid line, and the hazard curve that is based simply on median estimates of PGA (i.e. with no uncertainty) from the attenuation model is shown as a thin dashed line in Figure 5 (hereafter referred to as the "median curve"). All calculations are made according to strong rock site conditions (Class A of the draft NZS1170-5 Loadings Standard) with the McVerry et al. (in prep) attenuation model, consistent with the rockmasses exposed at the sites. The precarious rock data are plotted on the graphs as horizontal thick and thin solid lines. These data are plotted with toppling acceleration on the x-axis and 1/precarious rock age on the y-axis.

For the Cairnmuir Flat, Dunstan Trail and Cardrona Valley sites we show two sets of precarious rock data on each graph. These two sets of data encompass the uncertainty in age of the PBRs, in that the lower, thicker line corresponds to 1/55,000 year age obtained for CLYDE-6, and the upper line corresponds to 1/10,000 years. For the former, we assume that our date for CLYDE-6 is representative of all of our schist PBRs. The 10,000 year figure is a minimum estimate of the age of the PBRs based on the assumption that the schist tors were shaped into the present form by Pleistocene cold-climate aeolian erosion (i.e. mechanical abrasion of the tors by impact of windblown sand and silt derived from glacial erosion in the Southern Alps), activity that would have largely ceased by the beginning of the Holocene (10,000 years ago). By accommodating the 10,000 year age into our graphs we are not simply relying on the single CLYDE-6 date for all of our PBRs. For Mackay Downs we assume a minimum 10,000 year age for the granite PBRs based on the same logic applied to the schist PBRs. Our rationale for interpreting the graphs is that if the NSHM is correct we would expect all PBR data to plot to the right of and above the hazard curves.

The graphs in Figure 5 show different results for each site. At Cairnmuir Flat, a wide range of toppling accelerations are shown, and the PBR data largely plot to the left of and below the 3-sigma and median hazard curves from the NSHM. A small part of the total range of toppling accelerations plot to the right of the PGAs for the median curve (where the median curve becomes vertical on the lower right of the graph) and to the right of the 3-sigma curve for the 1/10,000 year exceedance rate (upper horizontal line). Clearly, the PBRs yield toppling accelerations that are considerably less than the 3-sigma curve, but have some agreement with the median curve. For the Cardrona Valley, the toppling accelerations for the two PBRs intersect the left side of the median curve, but lie considerably to the left of the 3-sigma curve. Like Cairnmuir Flat, the PBR toppling accelerations at Cardrona Valley do not correlate well with the 3-sigma curve. For Dunstan Trail graph, the PBRs plot between the median and 3-sigma curve, indicating consistency with the former, but a small discrepancy with the latter, except for a small portion of the total distribution of PBRs for the 1/10,000 year exceedance rate which plot to the right of the 3-sigma curve. Lastly, the Mackay Downs graph shows the PBRs plotting to the right of both graphs, indicating overall consistency between the hazard curve and PBR data.

4.0 DISCUSSION

The comparisons of NSHM-derived hazard curves to toppling accelerations from the PBRs in Figure 5 almost exclusively show a tendency for the PBRs to correlate poorly with the estimates of PGA from the NSHM, when the standard methodology of incorporating attenuation uncertainty into PSHA is applied. In contrast the hazard curves based on median estimates of PGA correlate more favourably with the PBR data. The only notable exception is the Mackay Downs graph, which shows the PBRs to correlate well with the 3-sigma hazard curve (i.e. plotting to the right, and above the 3-sigma hazard curve in Fig. 5). We attempt to understand the differences between the Mackay Downs results and the other (central Otago) results by identifying significant differences between the input parameters of the hazard curves for the sites.

All three central Otago graphs in Figure 5 (Cairnmuir Flat, Cardrona Valley and Dunstan Trail) are sites very close to major active fault sources (Fig. 2) that wholly contribute the maximum PGAs on the hazard curves. The impact of these fault sources can be seen on the median curves for the three central Otago graphs where the median PGAs abruptly truncate at the maximum PGA (i.e. the dashed lines changes abruptly from sloping to vertical). For the Cairnmuir Flat site, this near-field fault source is the southwest Dunstan Fault, which produces M7.0 earthquakes with a recurrence interval of 8,000 years 2.9 km from the site in the NSHM. In a similar vein, the Cardrona Fault source produces M7.1 earthquakes with recurrence interval 7,500 years 4.4 km from the Cardrona Valley site, and the Ranfurly Fault source produces M7.0 earthquakes with a recurrence interval 8,000 years 3.6 km from the Dunstan Trail site. These are all fault sources that should have produced repeated large earthquakes in the assumed time span that the PBRs have been in existence (10,000 to 55,000 years). For example the Dunstan Fault has produced a minimum of four surface rupture events in the last 24,300 $\pm$ 3,900 years according to recent paleoseismic investigations (Van Dissen et al. 2004), a time-span only half that of the 55,000 year date for the CLYDE-6 PBR. In contrast, the Mackay Downs site is at a large distance from the nearest active fault (the White Creek Fault, 91 km to the south of the site), leaving the maximum PGAs to be derived from distributed seismicity sources alone. The discrepancies between the 3-sigma hazard curves and the PBR data for the central Otago sites is therefore due to the PGAs assumed for near-field fault sources in the NSHM in the 3-sigma curves as compared to the median curves. Alternatively, the recurrence intervals in the NSHM may be erroneously short for the three faults, but the error would have to be about a factor of 10 for the 3-sigma curves to correlate with the PBR data. This seems unlikely, given that the new paleoseismic studies on the Dunstan Fault have reconfirmed that the fault has a recurrence interval in the thousands, rather than tens of thousands of years (Van Dissen et al. 2004). Clyde-6 and other PBRs have simply not been toppled by any of the large earthquakes on the nearby faults. Possible explanation for the discrepancies at the central Otago sites are: (1) that the full variability in PGA about the median assumed in the attenuation relationship for the fault sources overestimates the actual variability for those sources; and (2) that the median PGA assumed in the attenuation relationship for the fault sources overestimates the actual median motions for the sources. Such explanations are conceivable in the case of hazard estimates dominated by one fault source, rather than estimates derived from numerous sources, as is the case for the Mackay Downs site. A relevant observation is that recent large earthquakes such as the M_w 7.6 20 September 1999 Chi Chi, Taiwan and M_w 7.4 17 August 1999 Izmit, Turkey earthquakes produced near-field ground motions considerably less than expected, and it is thought that this may be due to median motions being overestimated for such events in the past. Furthermore, recent comparisons of the NSHM against the historical incidence of Modified Mercalli felt intensities (MMI) in New Zealand have shown the rates of exceedance for the felt intensity levels to be around 20-30% less than the exceedance rates for those intensity levels predicted from the NSHM (Dowrick & Cousins, 2003). However, this is a relatively small discrepancy in terms of PGA (only about 10%), given the typical slope of the hazard curves in Figure 5.

Lastly, there is the question of whether we are using our PBR data correctly in Figure 5. We have plotted the complete range of PBR toppling accelerations for each site, and evaluated the hazard curves on the basis of whether they intersect the range of toppling accelerations. In using the range of toppling accelerations in this manner we eliminate any potential bias that might be introduced into the study by for instance basing the analysis on the PBR that provides the lowest toppling acceleration at each site. While a single PBR may indeed provide realistic upper bounds on the ground motions at a site, it is equally possible that it may be misleading if it has somehow survived strong earthquake shaking through other influences such as topographic effects. Topographic effects are poorly understood and quantified at the present time, and some observations of historical earthquakes, particularly in the last decade have revealed significant topographical effects across regions of relatively uniform site geology. Given the uncertainties in the methodology we have applied, we consider that our approach is a conservative one that may be improved with future work (see recommendations below).

5.0 CONCLUSIONS

Our pilot survey represents the first application of the PBR methodology to New Zealand, the first application of the USA-based methodology outside of North America, and a successful application of the methodology. The study of three sites in central Otago, a site in northwest

Nelson and a site in eastern Fiordland has yielded a total of 28 PBRs, which have been used to provide estimates of the maximum ground motions that have occurred at the sites since the rocks became precarious. No PBRs were found in eastern Fiordland, which is likely to reflect the combination of active alpine erosion processes and regular earthquake shaking. Estimates of the age of the PBRs (10,000 to 55,000 years) have been made from considerations of the geologic and climatic history of the sites, and from a cosmogenic date obtained from bedrock removed from the pedestal of a PBR at one of the central Otago sites. Comparison of the maximum PGAs and ages of the precarious rocks to seismic hazard curves derived from the New Zealand NSHM show that the central Otago rocks provide lower estimates of peak ground accelerations than the hazard model, for equivalent return periods. In contrast, the northwest Nelson rocks correlate well with the PBR data. The difference between the central Otago and northwest Nelson sites is that the former are all located within 5 km of active faults, whereas the northwest Nelson site is not. The variability about the median estimates of PGA for the fault sources, and/or the median PGA for the fault sources may therefore be overestimated for the central Otago sites. In contrast the good agreement between PBR data and hazard curves at the northwest Nelson site may reflect the appropriateness of these parameters in the cases where hazard is derived from multiple earthquake sources. The implications, together with the limitations of this pilot study for providing constraints on seismic hazard estimates are such that we propose that several aspects of follow-up work be pursued (see recommendations).

6.0 RECOMMENDATIONS

The results of this brief pilot study indicate a discrepancy between the NSHM and the PBR data that has potential implications for the characterisation of ground motions at sites near active faults. However, as the study is a pilot, we have not been able to address numerous uncertainties in our study. Issues such as sample size of the PBR dataset, and uncertainty in the age and toppling accelerations of the PBR data severely limit the applicability of our study. We therefore recommend the following work to verify the results of our pilot, and take the study further towards providing criteria for testing PSH models:

1. Improve the age control of the PBRs identified in the pilot study. This study has unfortunately been limited to a single ^{10}Be date of CLYDE-6, so it is necessary to determine dates for a representative sample of PBRs from each of the sites.
2. Undertake simulations of hazard curves at the PBR sites that allow for epistemic (model) uncertainty (i.e. the various choices of parameters that influence the median estimates of PGA) to be kept distinct from aleatory (random) variability (i.e. the degree of scatter in data about the median). The central Otago PBR data may for instance correlate with hazard curves that allow for a range of median estimates of PGA, but reduced variability about any one of those median estimates.
3. Analyse the USA PBR laboratory and field data to understand the uncertainty between the

actual toppling accelerations for PBRs and the toppling accelerations derived from the tangent of angle alpha. This would allow us to place uncertainty bounds on the toppling accelerations given in Fig 5 and establish the significance of the discrepancies.

4. Conclusively verify that PBRs are definitely absent from areas of strong ground motions, by checking whether or not they are present in areas known to have been shaken by large historical earthquakes. PBRs presence versus absence on granite summits exposed along more gently-sloping mountain ranges in the maximum shaking intensity region of the M7.8 Buller and M7.2 Inangahua earthquakes would provide an opportunity to assess whether PBRs exist in areas of strong earthquake shaking. In this pilot study the steep upper slopes and summit ridge of Mt Titiroa in eastern Fiordland showed an absence of PBRs, which is probably due to a combination of alpine erosion processes rapidly removing unstable bedrock, and earthquake shaking (e.g. the M7.2 August 23 Fiordland earthquake, and others similar-sized events over the last 20 years). The relative importance of the latter in preventing PBRs being preserved is therefore unknown. A reconnaissance of some of these mountain summits in areas where the higher MMI isoseismals have been constructed (e.g. MM 7 and greater) would provide upper bounds on the shaking that PBRs can sustain. We would expect PBRs to be absent from the areas of maximum shaking intensity, and be present some distance away. The spatial distribution of PBRs in relation to the spatial distribution of strong shaking from the two earthquakes would therefore provide some constraints on the ground motions that PBRs can actually sustain. Where possible we would use strong motion accelerogram data, but would be largely reliant on converting MMI data to PGA in this study due to the absence of any recorded strong motion data for the Buller earthquake, and sparseness of accelerogram data for the Inangahua earthquake.
5. Integration of PBR studies, historically-based studies and other independent constraints on past ground motions into a comprehensive test of PSH models. After the above issues have been addressed (1-3 above), the PBR data should be used together with the results of historically-based tests (Rhoades et al. 2002; Dowrick & Cousins, 2003; Stirling et al. in prep) and earthquake-induced landslide and rockfall data to construct a multi-variable test of the NSHM. The proposed work would be to develop such a methodology, undertake the test at a series of New Zealand sites, and produce trial hazard curves and PSH maps that show hazard adjusted according to the constraints provided by the test.

7.0 ACKNOWLEDGEMENTS

We are indebted to the Earthquake Commission Research Foundation and Nevada Seismological Laboratory, University of Nevada Reno for providing financial support for our study. We also acknowledge the discussions with, and/or assistance in identifying prospective sites for PBR studies from the following people: Paul Kilgour, Graeme McVerry, Richard Norris, Jim Brune, Phil Tonkin, Mauri McSaveney, Kelvin Berryman, and Terry Webb. For field-based assistance and discussions we thank Paul Kilgour, Bruno Pace, Nicola Litchfield, Andrew King, Johanna King and Jenny Suckale. Derek Fabel is given a special thanks for providing the ^{10}Be date at short notice, and Albert Zondervan and Jamie Shulmeister are thanked for discussions on the sampling strategy. For field-based accommodation we thank Debbie Dowling for the stay at her place during our initial visit to the Dunstan Trail area, and the Department of Conservation for allowing us to stay in huts in the Mt Titiroa and Mackay Downs areas. Lastly, we greatly appreciate the thorough and insightful peer reviews of this report carried out by Graeme McVerry and Nicola Litchfield.

8.0 REFERENCES

Anderson, J.G. and Brune, J.N. 1999a. Probabilistic seismic hazard analysis without the ergodic assumption. *Seismological Research Letters 70(1):* 19-28.

Anderson, J.G. and Brune, J.N. 1999b. Methodology for using precarious rocks in Nevada to test seismic hazard models. *Bulletin of the Seismological Society of America 89(2):* 456-467.

Anooshehpoor, A. and J. N. Brune (2002). Verification of Precarious Rock Methodology Using Shake Table Tests of Rock Models, *Soil Dyn. Earthquake Eng. J.*, in press.

Anooshehpoor, A., J.N. Brune and Y. Zeng (2004), Methodology for obtaining constraints on ground motion from precariously balanced rocks, Bull. Seism. Soc. Am., 94, 285-303.

Bell, J.W., Brune, J.N., Liu, T., Zreda, M., and Yount, J.C. 1998. Dating precariously-balanced rocks in seismically active parts of California and Nevada. *Geology 26:* 495-498.

Brune, J.N. 1996. Precariously-balanced rocks and ground motion maps for southern California. *Bulletin of the Seismological Society of America 86:* 43-54.

Brune, J.N. 1999. Precarious rocks along the Mojave section of the San Andreas Fault, California: constraints on ground motion from great earthquakes. *Seismological Research Letters 70(1):* 29-33..

Dowrick, D.J., and Cousins, W.J. 2003. Historical incidence of Modified Mercalli Intensity in New Zealand and comparisons with hazard models. *Bulletin of the New Zealand Society for Earthquake Engineering 36,* 1-24.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M. 1996. National seismic hazard maps, June 1996, U.S. Department of the Interior, U.S. Geological Survey.

Frankel, *A.D.*, Petersen, M.D., Mueller, *C.S.*, Haller, C.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M. *and* Rukstales, *K.S.* [2002] Documentation for the 2002 Update of the National Seismic Hazard Maps. *U.S. Geological Survey Open-File Report 02-420.*

Housner, G.W. (1963). The behavior of inverted pendulum structures during earthquakes, *Bull. Seism. Soc. Am.,* **53**, 403-417.

McVerry, G.H. Response spectral attenuation models for New Zealand. (Manuscript in preparation).

Purvance, M. 2004. Parameters contributing to the toppling of precariously balanced rocks. 2004 *SCEC Annual Meeting September 19-23 2004. Proceedings and Abstracts 14*, 148.

Rhoades, D.A., Smith, W.D. and Stirling, M.W. 2002. Tests of seismic hazard models. *Institute of Geological and Nuclear Sciences Client Report 2002/99.*

Shi, B. Anooshehpoor, A., Zeng, Y., and Brune, J.N, 1996. Rocking and overturning of precarious rocks by earthquakes. *Bulletin of the Seismological Society of America 86:* 1364-1371.

Standards New Zealand 2004. Structural design actions Part 5. Earthquake Actions, New Zealand. Draft NZS 1170-5 Standard.

Stirling, M.W., 1991. Peneplain modification in an alpine environment of Central Otago, New Zealand. *New Zealand Journal of Geology and Geophysics, 34*, 195-202.

Stirling, M.W., McVerry, G.H., and Berryman, K.R. 2002a. A new seismic hazard model for New Zealand. *Bulletin of the Seismological Society of America 92:* 1878-1903.

Stirling, M.W., Anooshehpoor, A., Brune, J.N., Biasi, G., and Wesnousky, S.G. 2002b. Assessment of the site conditions of precarious rocks in the Mojave Desert, California. *Bulletin of the Seismological Society of America 92:* 2139-2144.

Stirling, M.W., Field, E.H, and Petersen, M.D. Comparison of the Historical Record of Modified Mercalli Intensities to Seismic Hazard Models for Southern California and New Zealand. *Bulletin of the Seismological Society of America* (in preparation).

Van Dissen, R.J., Barrell, D., Langridge, R., Litchfield, N. and Tonkin, P. 2004. Reassessment of seismic hazard at the Clyde Dam site, Central Otago. Progress report. *Institute of Geological and Nuclear Sciences Client Report 2004/149.*

Figure 1 Schematic diagram of a precariously-balanced rock (PBR; diagram extracted from Anooshehpoor et al. 2004). The PBR is unattached to the pedestal, and the tangent of angle alpha (shown) is proportional to the toppling acceleration (peak ground acceleration, in g). See the text for further explanation.

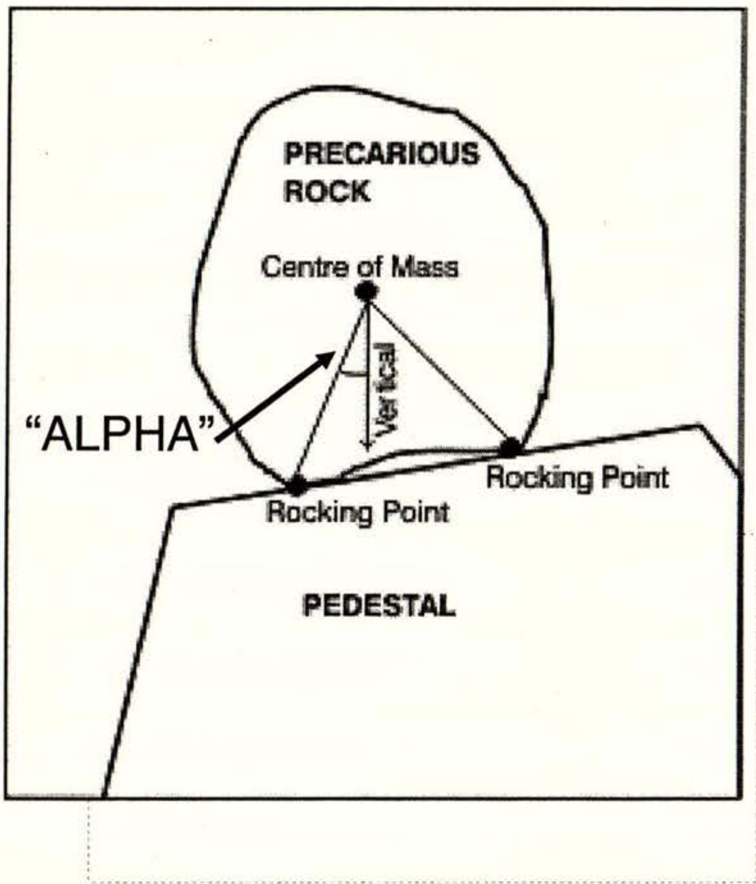


Figure 2 The PBR sites examined in our study. The maps show the active faults as red lines on the topographical maps, and we also show the sites in relation to a typical example of earthquake hazard from the national seismic hazard model (Stirling et al. 2002).

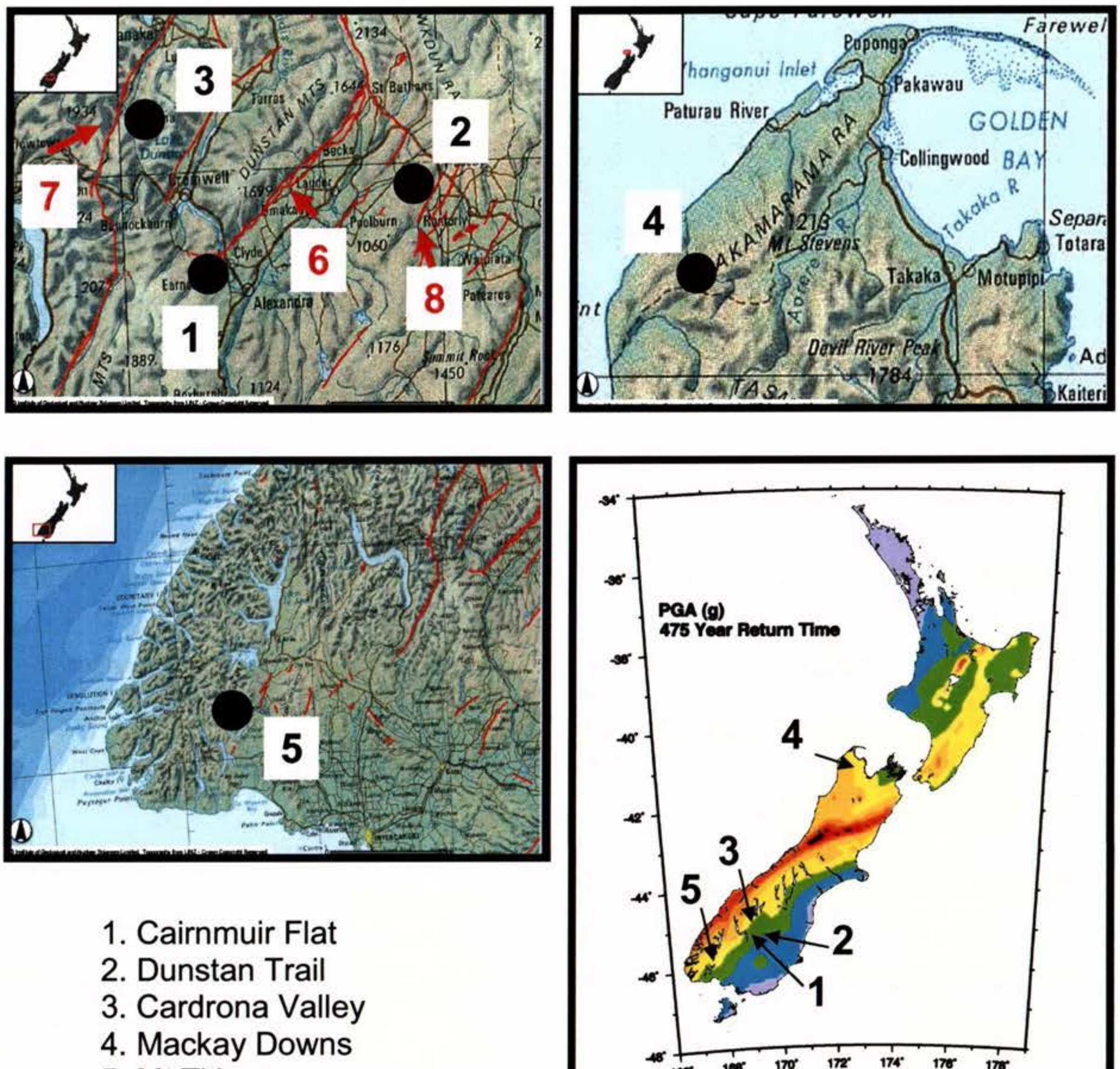


Figure 2 (cont) Schist tor-studded landscape of central Otago (Cairnmuir Flat, Cardrona Valley, and Dunstan Trail sites; top left picture), granitic outcrop and boulder-covered plateaux of northwest Nelson (Mackay Downs site; top right picture), and the steep terrain of eastern Fiordland (bottom left picture).

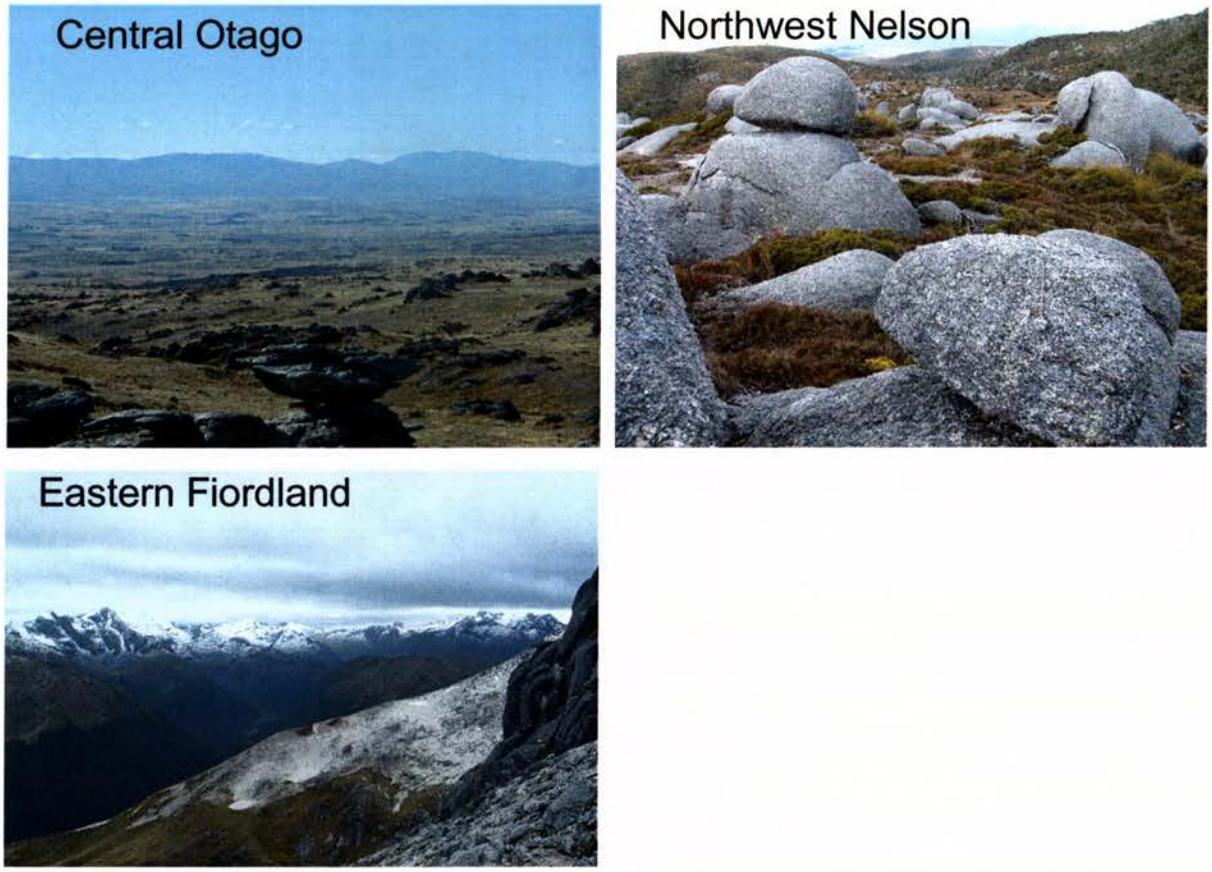


Figure 3 PBRs examined in this study. The PBRs shown on this page are from the Cairnmuir Flats site, and are (clockwise from top left) CLYDE-1, CLYDE-2, CLYDE-8 and CLYDE-6. A sample taken from the pedestal of CLYDE-6 has been dated by cosmogenic methods (see location of sample), and the results are discussed in the report. Refer to Table 1 for estimates of toppling accelerations (accelerations necessary to topple the rocks). In all cases these rocks are detached from the pedestal.

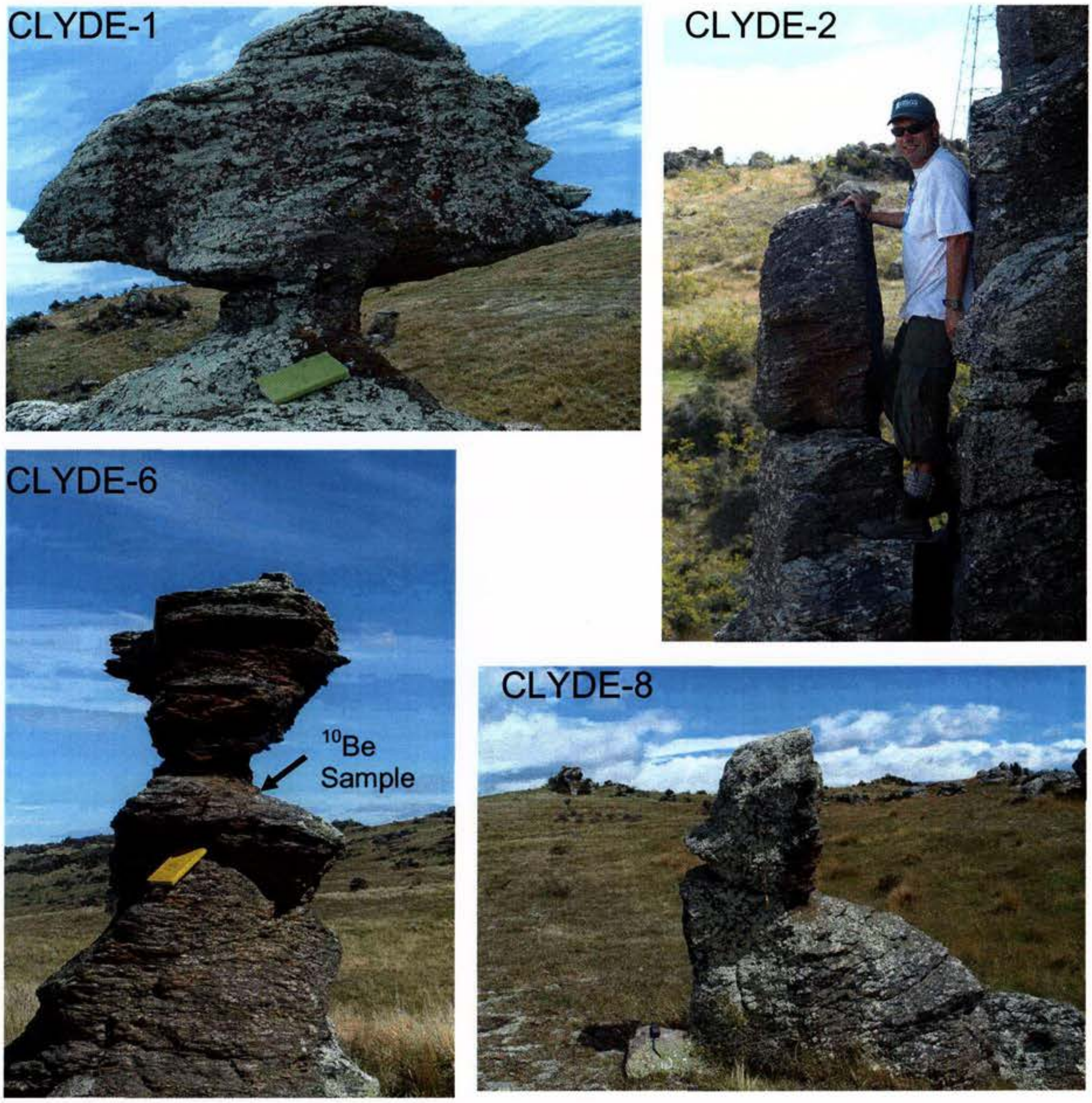


Figure 3 (cont) PBRs examined in this study. The PBRs shown on this page are from the Cairnmuir Flat and Dunstan Trail sites, and are (clockwise from top left) CLYDE-9, CLYDE-10, DUNS-02 and DUNS-01. Refer to Table 1 for estimates of toppling accelerations (accelerations necessary to topple the rocks). In all cases these rocks are detached from the pedestal.

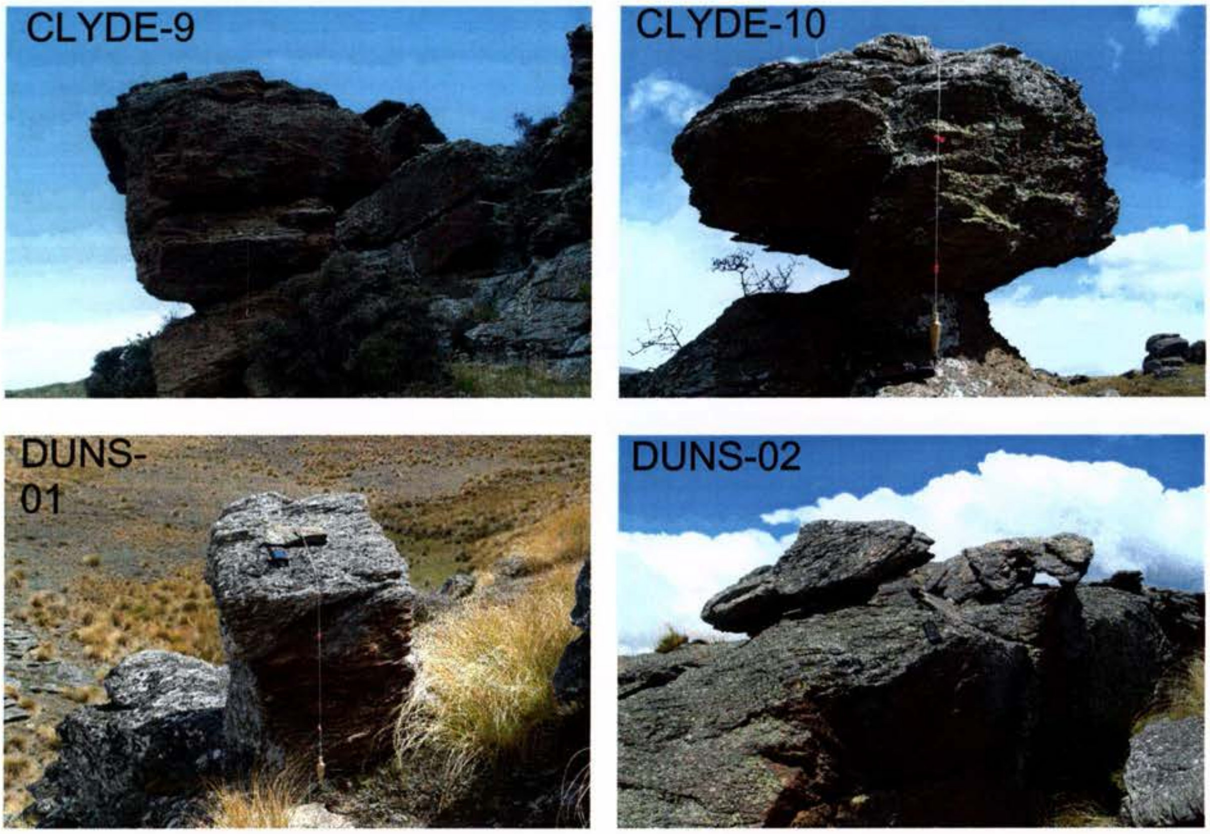


Figure 3 (cont) PBRs examined in this study. The PBRs shown on this page are from the Dunstan Trail and Cardrona Valley sites, and are (clockwise from top left) DUNS-03, DUNS-04, CAR-01 and DUNS-09. Refer to Table 1 for estimates of toppling accelerations (accelerations necessary to topple the rocks). In all cases these rocks are detached from the pedestal.

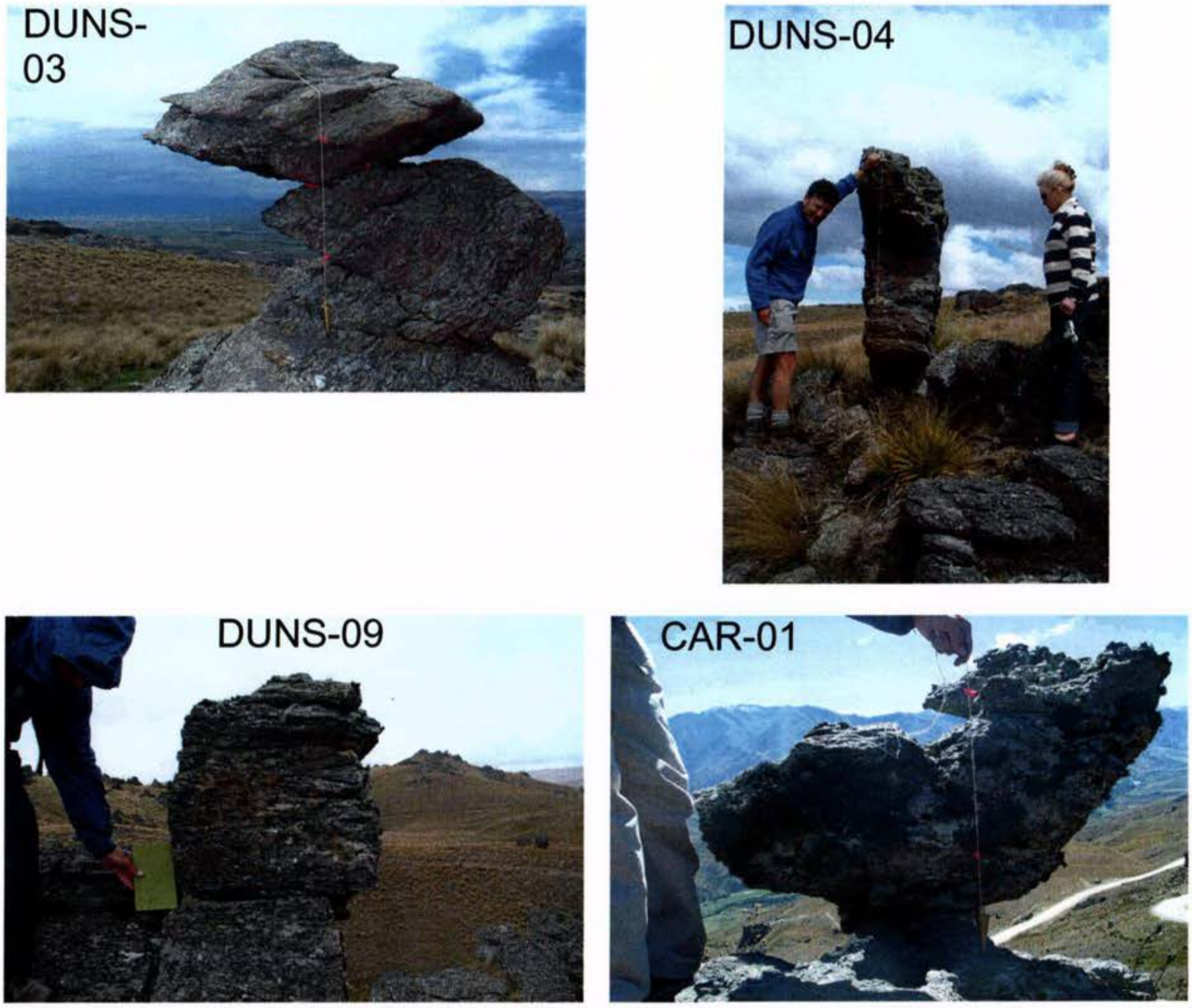


Figure 3 (cont) PBRs examined in this study. The PBRs shown on this page are from the Cardrona Valley and Mackay Downs sites, and are (clockwise from top left) CAR-02, MK-01, MK-03, and MK-02. Refer to Table 1 for estimates of toppling accelerations (accelerations necessary to topple the rocks). In all cases these rocks are detached from the pedestal.

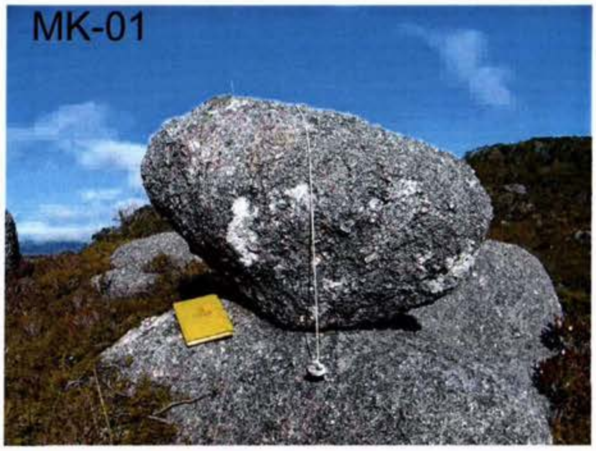


Figure 3 (cont) PBRs examined in this study. The PBRs shown on this page are from the Mackay Downs site, and are (clockwise from top left) MK-04, MK-05, MK-07, and MK-06. Refer to Table 1 for estimates of toppling accelerations (accelerations necessary to topple the rocks). In all cases these rocks are detached from the pedestal.

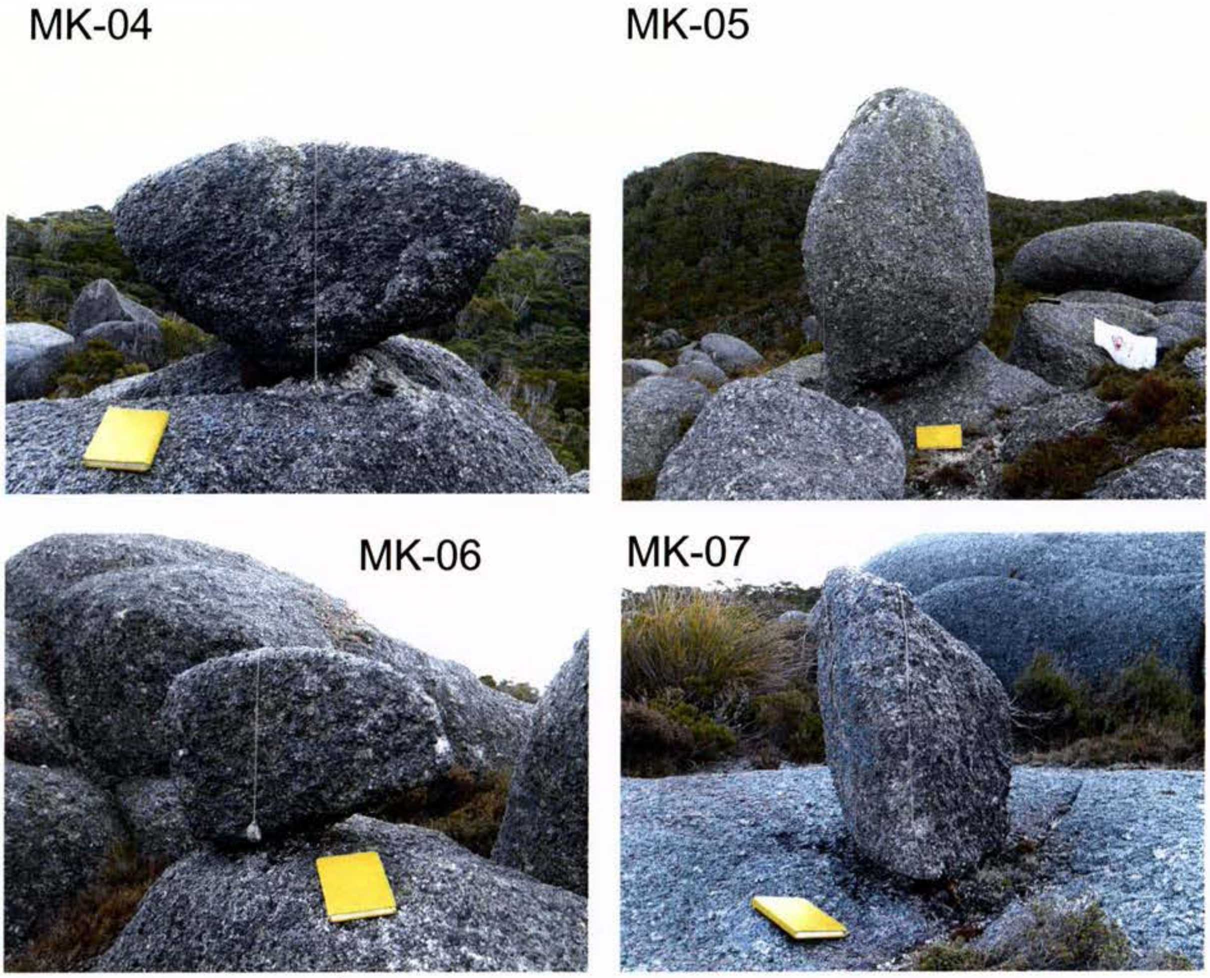


Figure 3 (cont) PBRs examined in this study. The PBRs shown on this page are from the Mackay Downs site, and are (clockwise from top left) MK-08, MK-09, MK-11, and MK-10. Refer to Table 1 for estimates of toppling accelerations (accelerations necessary to topple the rocks). In all cases these rocks are detached from the pedestal.

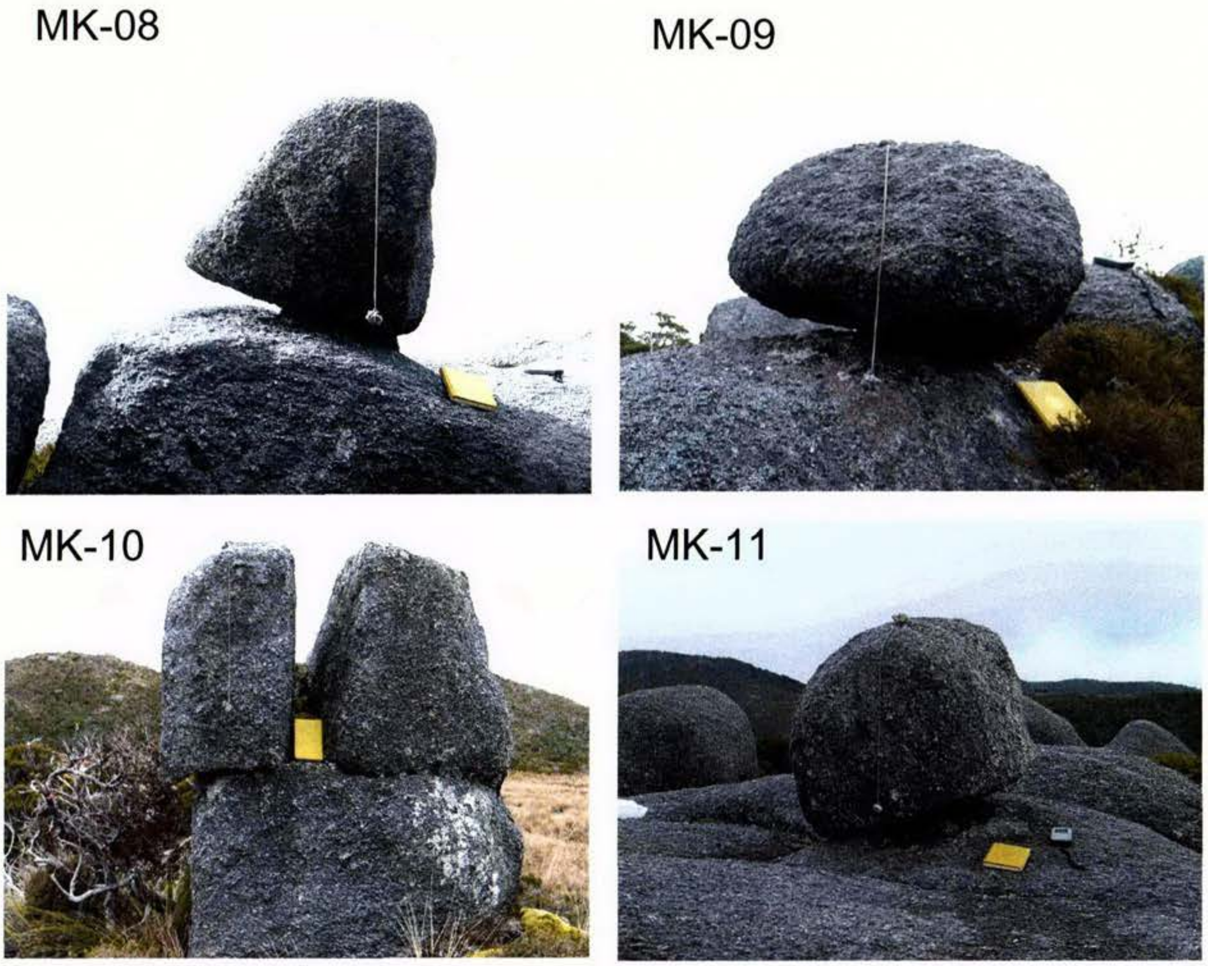
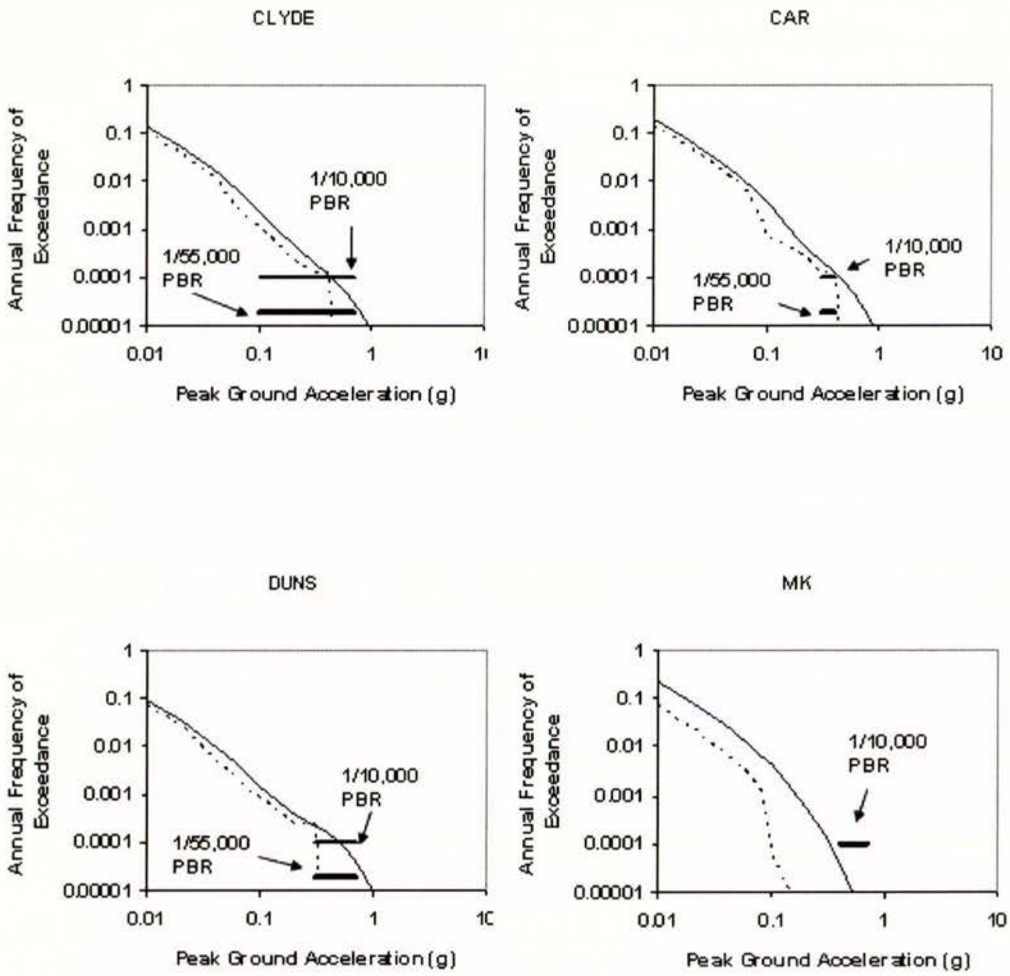


Figure 3 (cont) PBRs examined in this study. The PBRs shown on this page are from the Mackay Downs site, and are (clockwise from top left) MK-12, MK-13, MK-16, and MK-14 & 15 (i.e. two in one picture). Refer to Table 1 for estimates of toppling accelerations (accelerations necessary to topple the rocks). In all cases these rocks are detached from the pedestal.

Figure 4 Granitic summit rocks at Mt Titiroa, eastern Fiordland. Though the granitic rock is ideal for the formation of PBRs, none were found in our foot survey. The granitic landforms are generally large and stable outcrops (i.e. all attached to the underlying bedrock; top pictures and bottom right picture). The absence of PBRs is probably due to the rapid erosion of the granitic rockmass in the steep and harsh mountain environment of Fiordland (bottom left picture).

Figure 5 Hazard curves for peak ground acceleration on strong rock from the national seismic hazard model (Stirling et al. 2002; thin solid lines for 3-sigma hazard, dashed line for median hazard) and the range of toppling accelerations and age estimates for the PBRs (horizontal solid lines that span the range of toppling accelerations, plotted and labelled according to the 1/age estimates) from Cairnmuir Flat ("CLYDE"), Cardrona Valley ("CAR"), Dunstan Trail ("DUNS") and Mackay Downs ("MK"). The toppling accelerations are taken from the PBRs shown in Fig 3 and documented in Table 1 but scaled up by 30% to take account of the dynamic component of toppling acceleration (Anooshehpoor et al; 2004).



APPENDIX 1

Beryllium 10 results from Australian National University for CLYDE-6 pedestal

Derek Fabel

Research School of Earth Sciences
The Australian National University
Canberra, ACT 0200, Australia
Ph. +612 61255518
Fax. +612 61255443
Email. derek.fabel@anu.edu.au

Tuesday, July 20, 2004

Mark Stirling
GNS
PO Box 30368
Lower Hutt
New Zealand

Dear Mark,

The in-situ produced cosmogenic ^{10}Be and ^{26}Al results for sample "CLYDE-8" are shown in Table 1 and 2. I have calculated three scenarios (A, B, and C) for different topographic shielding (Table 1).

Scenario A: No topographic shielding. This is an underestimate and provides the minimum exposure age

Scenario B: Topographic shielding for a sample location at the base of an infinitely high and wide vertical wall. This probably overestimates the shielding.

Scenario C: Topographic shielding by a rectangular obstruction that blocks incident cosmic rays from the sample surface up to a constant inclination angle of 100°, and that extends through an azimuth of 100°. These values were estimated from the photo you sent and provide the most accurate exposure ages.

The cosmogenic nuclide data are provided in Table 2. The ^{10}Be and ^{26}Al results agree very well, indicating a simple exposure history. For Scenario C, the nuclide concentrations can be interpreted either as a minimum exposure age of 55.5 ± 4.2 ka (mean of ^{10}Be and ^{26}Al) **or** as a steady-state erosion rate of 10.2 ± 0.8 mm/ka.

Note: it is incorrect to state that the sample has been exposed for 55.5 ka and that the erosion rate has been 10.2 mm/ka. The two values are mutually exclusive. The minimum exposure age is calculated by assuming zero erosion, while the steady-state erosion rate is calculated by assuming an infinite exposure time. Therefore if you use the steady-state erosion rate you have lost the ability to comment on the duration of exposure, and vice versa.

Please do not hesitate to contact me if you have any questions about the results.

Regards,

Derek Fabel

Table 1 Production rate data

Lab ID	Scenario	Elevation (m)	Latitude (degrees)	Longitude (degrees E)	Shielding factor	Sample thickness (cm)	Thickness correction factor	^{10}Be scaling factor	^{26}Al scaling factor	^{10}Be production rate (atom/g)	error	^{26}Al production rate (atom/g)	error
CLYDE-6	A	580	45.1911	169.2814	1	3	0.975	1.65	1.652	8.2	0.5	50.1	3.1
	B	580	45.1911	169.2814	0.5	3	0.975	1.75	1.752	4.3	0.3	26.6	1.6
	C	580	45.1911	169.2814	0.7333	3	0.975	1.75	1.752	6.4	0.4	38.9	2.4

Thickness correction calculated using a rock density of 2.75 g cm^{-3} and a cosmic ray attenuation coefficient of 150 g cm^{-2}. Altitude latitude scaling factor calculated according to Stone (2000).

Table 2 Cosmogenic nuclide data, minimum exposure ages, maximum erosion rates and nuclide ratios

Lab ID	Scenario	[^{10}Be] (atom/g)	error	^{10}Be minimum exposure age (ka)	error	^{10}Be maximum erosion rate (mm/ka)	error	[^{26}Al] (atom/g)	error	^{26}Al minimum exposure age (ka)	error	^{26}Al maximum erosion rate (mm/ka)	error	^{26}Al/^{10}Be	error
CLYDE-6	A	220486	6152	43.7	2.9	13.2	0.9	1301541	49730	42.7	3.1	13.3	1.0	5.9	0.3
	B	415773	11600	83.1	5.5	6.9	0.5	2454505	49730	82.1	5.5	6.8	0.5	5.9	0.2
	C	283495	7910	56.3	3.7	10.2	0.7	1673602	93782	55.3	4.7	10.2	0.9	5.9	0.4

Total Al concentration in quartz determined by ICP-AES and assigned 2% uncertainty. Data are normalized to NIST SRM 4325 using ^{10}Be/^{9}Be = 3.02 x 10^{-11}. Exposure ages are calculated using sea level, high latitude ^{10}Be and ^{26}Al production rates of 5.1 ± 0.3 and 31.1 ± 1.9 atoms g^{-1} yr^{-1} (Stone, 2000). Calculated nuclide concentrations include AMS and production rate uncertainties, but do not include uncertainties in altitude and latitude scaling (~5%) or temporal variations in geomagnetic field intensity.

Institute of Geological & Nuclear Sciences Limited

Gracefield Research Centre
69 Gracefield Road
PO Box 30 368
Lower Hutt
New Zealand
Phone +64-4-570 1444
Fax +64-4-570 4600

Rafter Research Centre
30 Gracefield Road
PO Box 31 312
Lower Hutt
New Zealand
Phone +64-4-570 4637
Fax +64-4-570 4657

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand

Phone +64-3-477 4050
Fax +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road, SH1
Wairakei
Private Bag 2000
Taupo
New Zealand
Phone +64-7-374 8211
Fax +64-7-374 8199

For more information visit the GNS website
http://www.gns.cri.nz

A Crown Research Institute

Cover photographs from GNS photo library